27.07.2023

Carbon driven energy equilibrium at the municipal scale –

Energy Equilibrium

GoA 1.1 - Performing multi-dimensional assessment of different RES development scenarios in municipalities

D 1.1 Final report

Thermopolis Ltd.
Sauli Jäntti
Tel. +358 (0)40 047 1740
sauli.jantti@thermopolis.fi

Interreg Baltic Sea Region
Co-funded by the European Union
ENERGY TRANSITION
Energy Equilibrium

Table of contents

1 Introduction

1.1 Energy Equilibrium

Variability and non-controllability of seasonally generated renewable energy (fluctuations in solar radiation intensity, wind speed, etc.) in regions requires for more adaptive and flexible energy system infrastructure. Therefore, enhancing system flexibility and focusing on energy storage solutions will play major role in transforming renewable energy supply potential into reality. To ensure an uninterrupted supply of energy to all the main energy consumption groups in the economy (households, industry, commercial sector, agriculture), there should be a perfect balance - equilibrium point - between the produced energy and the consumed energy.

The storage of renewable energy has been highlighted as a key element in accelerating the decarbonization of the local energy systems. However, local public authorities that are responsible for setting direction and creating an enabling policy environment for RES infrastructure development encounter numerous challenges in deploying energy accumulation. Since energy accumulation technologies are emerging technologies, their implementation at municipal scale incorporates numerous uncertainties. Local governments face several questions that often remain unanswered due to a lack of knowledge and on-site capacity, which in turn significantly hinders the regional path to climate neutrality.

This project defines energy storage as a key attribute of the energy equilibrium that links renewable energy production with consumption. The determination of the energy equilibrium in the municipalities will be analysed in close interaction with the balancing factors of sustainable development, where the economic, technical, environmental, and social factors are of particular importance for local public authorities. The project directly addresses the evolving challenge of BSR countries to enable the development of public support policies to promote broader renewable energy generation, distribution, and storage. As a result of the project, local public authorities and other target groups defined in Section 3.3. will be able to make well-informed, rational decisions and develop well-structured municipal action plans. The project will help to reduce uncertainty for local public authorities and help authorities to avoid costly mistakes in choosing inappropriate development strategies, thus also strengthening EUSBSR governance, coordination, and communication.

This project aims to support local and regional public authorities and energy suppliers in decision making and answer several questions, such as:

(1) Given territorial potential, available budget, natural resources, and socioeconomic needs of residents, which accumulation technology is most appropriate for a given municipal region?

(2) What policy instruments and mechanisms should be created to promote the use of the identified RES accumulation technologies in the specific municipal region?

(3) What risks (technological, economic, social, and political) should municipalities consider in RES infrastructure development projects and what are the specific risks associated with energy storage?

(4) What are the key steps that municipalities need to take today to create an enabling environment for the development of sufficient RES infrastructure, including the necessary energy storage capacity?

In most countries in the BSR, the focus has been on advancement of RES generation technologies rather than energy storage. Due to Europe's recent decisions to strengthen energy security and move away completely from dependence on Russian fossil energy imports, the importance of energy storage in European energy systems is now being emphasised more than ever.

This project aims to develop an Energy Equilibrium Platform – an interactive and easily applicable tool to support municipalities and energy suppliers in decision-making related to the development of efficient action plans to accelerate local RES utilization in the region. Energy Equilibrium Platform will help municipalities to:

(1) Identify the most optimal RES storage development strategy and its impact on energy flexibility in the region;

(2) Help to determine the key factors affecting energy equilibrium (balance between the produced and the consumed energy) in the region;

(3) Help to develop policy mechanisms and action plans to enhance local RES in the region;

(4) Help to anticipate risks and avoid making expensive mistakes (e.g., investing in inappropriate technological solutions).

The Energy Equilibrium Platform will be built using system dynamics modelling method. System dynamics (SD) is a mathematical modelling approach that is used to reproduce a real-world system, in the case of this project – the real structure and function of a municipality. It is applied to investigate dynamic development of complex systems which in turn contribute to solving problems of high complexity such as development of future energy strategies in the region.

1.2 Aim of the activity

The focus of this activity was to develop a conceptual framework of Energy Equilibrium Platform which was done by conducting PESTLE (political, economic, social, technical, legal, environmental) analysis on RES storage solutions for five different energy accumulation alternatives defined in the project:

(1) Batteries - for electricity

(2) Accumulation in the form of thermal energy

(3) Accumulation in the form of hydrogen

(4) Accumulation in the form of biomethane

(5) Accumulation in the form of potential energy

Technical analysis includes technology characteristics, technical potential, and capacity assessment, including technology impact on system flexibility. The analysis identify success and failure criteria of the technology performance levels, technology risk and uncertainty, including the identification of best practice examples, demonstration projects, field work and case studies from abroad. Economic analysis includes cost-benefit analysis considering economic feasibility constraints and financial implications of each technology.

Economic analysis outlines financial framework of RES energy systems in the BSR countries, as well as identify opportunities for capital access to finance the investments, and funding gaps for municipalities.

Social analysis considers and list the social conditions that impact successful implementation of RES infrastructure development projects in municipalities of BSR region such as public acceptance, knowledge, adaptability to innovations and new technologies, and others, as well positive impact aspects such as the provision of employment opportunities.

Environmental analysis list all the environmental factors influencing the sustainability level of future energy systems - risk of environmental damage and creation of indirect environmental damage, insufficient provision of life cycle, risk of not achieving the reduction of carbon footprint.

Political and legal analysis identify the existing political instruments and support mechanisms of RES storage and infrastructure development in municipalities, as well as opportunities for inclusion of new stimulative instruments, including an in-depth review of policy instruments that are crucial for RES development, especially to enhance investments in RES storage solutions.

1.3 Deliverables of GoA 1.1 multi-dimensional assessment of different RES development scenarios in municipalities

The main deliverable of this activity was the development of an outlook on multidimensional (economic, technical, environmental, social, political, and legal) performance indicators (KPIs) and benchmarks characterizing RES storage solutions for all five different energy accumulation alternatives defined in the project. These indicators and benchmarks were identified based on the PESTLE assessment and lead to collected data on the identified KPIs to create an input database. As a result, an outlook on the RES development and KPIs of storage technologies were created and the collected data is serving as input values for Energy Equilibrium platform creation.

The aim of this deliverable was to develop a knowledge base of RES accumulation solutions, therefore addressing the challenges that the local public authorities face in energy planning and enhancement of RES in the regions. Some of these challenges are uncertainty, lack of capacity and knowledge in identifying the most optimal strategies for RES infrastructure development that would include RES generation technologies and energy accumulation technologies. Local public authorities admit that energy accumulation is one of the most important aspects that should be anticipated in seasonally generated variable energy since it directly impacts region's ability to substantially increase the utilization of local RES. Therefore, this deliverable will serve as the first step towards the development of solution for local public authorities.

The outlook will describe different RES accumulation solutions for municipalities, including the comparative assessment of available technologies and the review of the main driving forces and critical factors affecting the flexibility and sustainability of RES in the municipalities in the long term.

1.4 List of created documents

To track the evaluation of different RES development scenarios, the following baseline papers have been prepared (see Table 1).

Table 1: List of created documents

PART	DESCRIPTION	AUTHORS
Part 1 – One Pagers	Part 1 is a collection of all descriptions for each selected technology	by all technology partners
Part 2 – PESTLEs	Part 2 is an overview of the PESTLE analyses. The original PESTLE analyses are attached to the report as an appendix (as a separate document).	by all technology partners and partners involved in GoA 1.1.
Part 3 – Final Report	Final report as a summary of the individual aspects developed.	Thermopolis Ltd with ZEBAU and support by all partners

2 Part 1 – Descriptions of selected technologies

The first step in the analysis is the description of the individual technologies. Here, not only the specific technical aspects are relevant, but the differentiation between the technologies and the positioning between the elements of generation and distribution.

Analysis was made for five different energy accumulation alternatives defined in the project:

TECHNOLOGY	AUTHORS
Batteries	Thermopolis Ltd, Sustainable Business Hub Scandinavia AB (SBH)
Thermal Energy	Lithuanian Energy Institute (LEI)
Hydrogen	Sustainable Business Hub Scandinavia AB (SBH)
Biomethane	Institute of Fluid-Flow Machinery Polish Academy of Sciences (IMP PAN)
Potential Energy	Institute of Fluid-Flow Machinery Polish Academy of Sciences (IMP PAN)

Numerous stakeholders were involved in the preparation of the documents. These include representatives of DH providers / grid owners, municipal decision, and policy makers as well as energy agencies and different types of associated partners.

Quality control of the report performed by ZEBAU, supervision of GoA 1.1. performed by RTU.

.

2.1 Batteries

2.1.1 Lithium-ion battery for grid-scale storage

A lithium-ion battery or Li-ion battery (abbreviated as LIB) can store electric energy as chemical energy. A LIB contains two porous electrodes separated by a porous membrane. A liquid electrolyte fills the pores in the electrodes and membrane. Lithium salt (e.g. LiPF6) is dissolved in the electrolyte to form Li+ and PF6- ions. The ions can move from one electrode to the other via the pores in the electrolyte and membrane. Both the positive and negative electrode materials can react with the Li+ ions. The negative electrode in a LIB is typically made of carbon and the positive of a Lithium metal oxide. The battery is fully discharged when nearly all the Lithium have left the negative electrode and reacted the positive electrode.

The first lithium batteries were developed in the early 1970s and Sony released the first commercial lithium-ion battery in 1991. During the '90s and early 2000s the LIBs gradually matured via the pull from the cell-phone market. The Tesla Roadster was released to customers in 2008 and was the first highway legal serial production all-electric car to use lithium-ion battery cells. Further, around 2010 the LIBs expanded into the energy storage sector.

Lithium Nickel Manganese Cobalt Oxide (NMC) is the most widely used Li-ion battery for energy storage. The NMC battery has a high energy density but uses cobalt. Other batteries that are used for this purpose is Lithium Iron Phosphate (LFP) and Lithium Titanate (LTO). The LFP battery do not use cobalt in the cathode but have higher price due to lower volumes. LTOs are the most expensive of the three using a lithium titanate anode.

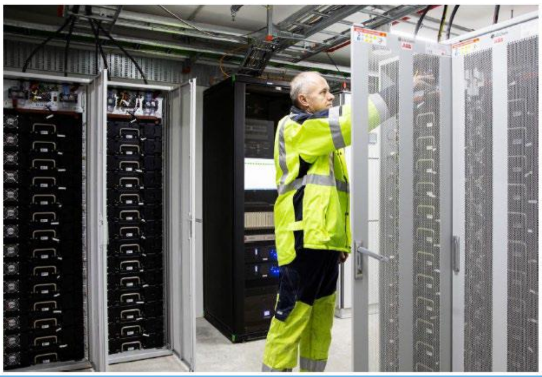
In LIB storage systems battery cells are assembled into modules that are assembled into packs. The battery packs include a Battery Management System (BMS). The BMS is an electronic system that monitors the battery conditions such as voltage, current, and temperature and protects the cells from operating outside the safe operating area. A Thermal Management System (TMS) regulates the temperature for the battery and storage system. The TMS depends on the environmental conditions, e.g. whether the system is placed indoor or outdoor. Further an Energy Management System (EMS) controls the charge/discharge of the grid connected LIB storage from a system perspective.

View concise technology information in Table 2, and practical instances of this technology in Table 3.

Table 2: Technology Data Lithium-ion batteries

Level of technological readiness:	TRL 9
Storage time:	hours to days, the self-discharge rate makes storage periods of several months unfeasible.
Storage reaction time:	Immediate charge and discharge of electricity.
Investment price range:	Around 1 M€ per MWh
Maintenance costs:	540 €/MW and 2€ / MWh
Capacity and power output:	Vary a lot, 6 MWh in a standard unit (40 feet container, 30m2), 18 MW power output
Lifetime:	25 years
Charging cycles:	14 000
Efficiency:	All: 91 % AC, All: 95 % DC, Charge efficiency 98 %, Discharge efficiency 97%. Energy loss during storage: 0,1%/day

Table 3: Examples of Lithium-ion batteries

1		Energylab Nordhavn, Copenhagen, Denmark Technique: NMC Year: 2017 Capacity: 430 kWh; 630 kW Use: Frequency regulation, peak shaving, voltage regulation, harmonic filtering Provider: ABB for Radius Elnet /Ørsted
2		Neoen's Hornsdale Wind Farm, South Australia Technique: Probably NMC Year: 2017 Capacity: 129 MWh; 100 MW Use: Peak shaving Provider: Tesla

Information and images on lithium-ion batteries were retrieved and compiled from Technology Data Catalogue on Energy storage published by Danish Energy Agency [1].

3	 *Warsaw University of Technology*	The important invention of Polish scientists - three times longer battery life for electricians. As we can read on the website of the Warsaw University of Technology, a research team from this university led by *prof. Leszek Niedzicki* have developed the world's first battery electrolyte, which extends the life of an electric car battery three times. The compound used in the batteries is a chemical compound called LiTDI. The electrolyte made of LiTDI salt has interesting properties from the point of view of electric cars and not the only. First, it does not contain the fluorine present in all other electrolytes. This highly toxic compound is dangerous to human life and the environment. Its elimination guarantees that in the event of a failure and fire, it will not have a negative impact on nature and, for example, in the event of a fire, will not lead to human poisoning. And besides, an electric car with such an electrolyte is simply even more ecological. Secondly, the use of the electrolyte invented by Poles allows the battery to operate at much higher temperatures than those currently used, without any damage to the battery itself. Batteries with LTDI salts can work even at a temperature of 90 °C. Thanks to this, it is not necessary to use an expensive cooling system in electric cars. This extends the life of the battery and increases the range of the vehicle. The invention of Polish researchers, by reducing the production costs of batteries, may significantly affect the development not only of the electric car market. The invention is already in production. As it turns out, the invention of scientists from the *Warsaw University of Technology* is not only a discovery that, as is often the case, lies dusty in University Offices. This electrolyte is already produced under the license of the *Warsaw University of Technology* by the *French Chemical Company Arkema*. It is already used in the production of car batteries, but also batteries for smartphones or in the house with PV photovoltaic [21].

4		The Polish company *Griffin Group Energy* has launched in cooperation with the Swiss manufacturer *Leclanche* an energy storage facility at the GPZ 110kV/15kV *Cieszanowice station* that can provide 3 MW of power in both directions of the power system operation. The energy storage was launched for one of the leading system operators (DSO) in Poland - *Tauron Dystrybucja S.A.* This technology uses lithium-ion (Li-Ion) cells, which give the possibility of charging and discharging the device with a current five times higher than the nominal one. Thanks to this, both processes can take place in less than a quarter of an hour. The device is characterized by a high level of security. The modules are equipped with liquid cooling and fire protection systems. The energy storage is integrated with the SCADA class systems of *Tauron Dystrybucja S.A*. The system operates in various strategies, including co-operation with a wind farm. The devices bring numerous benefits, including stabilizing the electromagnetic network [47].

2.1.2 NA-S batteries

Na-S batteries are rechargeable batteries and are designed for system level applications. They are both power-intensive and energy-intensive. Larger installations (34 MW – 50 MW) are used for time shifting of production from renewable or conventional production plants. Smaller installations (400 kW – 8 MW) are used as back-up power, for off-grid applications and for ancillary services. Na-S battery cells consist of a molten sodium anode, a molten sulfur cathode and a β-alumina oxide solid state electrolyte (BASE), incased in a single tube. A temperature of 300 °C or more is required to ensure sufficient Na ion conductivity through the BASE. Cells are arranged in modules with thermal enclosures to minimize heat loss. The production of BASE has large impact on both battery performance and cost. An alternative research route is to use the Na-S chemistry in a flow battery. Due to the similarity with Na-NiCl2 batteries, synergies in research and development efforts can be expected. A Na-S battery installation consists of one or more Na-S battery units containing the battery modules, a battery management system and a power conversion system required to connect the batteries to the grid.

The heat loss amounts to approximately 1 % per hour and the Na-S batteries are thus not ideal for long term storage. The heat loss should thus not be treated as an independent source of energy loss during operation as it is included in the battery efficiency. Simple air cooling is sufficient for maintaining temperature and build into standard battery units. The battery temperature should be maintained to prevent the electrodes from solidifying since freeze-thaw cycles significantly reduce battery lifetime.

Individual battery cells have been measured with efficiencies at 89 %. The efficiency of a grid size battery unit including auxiliary losses has been measured to be 83 % for an Italian installation primarily used for time shifting.

Na-S battery installations come in two typical sizes. The larger installations used for time shifting have 34- 50 MW capacity. Smaller installations of up to 8 MW capacity have been installed during the last 20 years in 200 different locations. As the batteries are highly modular, the installation size can easily be varied according to demand.

View concise technology information in Table 4, and practical instances of this technology in Table 5.

Table 4: Technology Data NaS

Level of technological readiness:	TRL 7-9
Storage time:	minutes to hours, with charge/discharge times of 6-8 h the normal storage period will be on this scale for optimal battery storage utilization.
Storage reaction time:	Immediate charge and discharge of electricity.
Investment price range:	370 k€ for 1 MWh
Maintenance costs/year:	1,5% of total investment and 1,8€ per MWh
Capacity and power output:	Larger installations: 300 MWh, 50 MW power output
Lifetime:	19 years
Charging cycles:	5 600
Efficiency:	83 %

Table 5: Examples of NaS

1		Buzen City, Fukuoka, Japan Year: 2016 Capacity: 300 MWh; 50 MW Energy density: 26 kWh/m³ Specific energy: 56 Wh/kg Total land use: 47m²/MWh
2		Campania Region (3 sites), Italy Year: 2015 Capacity: 250 MWh; 34,8 MW Energy density: 41 kWh/m³ Specific energy: 76 Wh/kg Total land use: 77m2/MWh

Information and images on Na-S batteries were retrieved and compiled from Technology Data Catalogue on Energy storage published by Danish Energy Agency [2].

2.1.3 Vanadium redox flow batteries

Vanadium redox flow batteries also known simply as Vanadium Redox Batteries (VRB) are rechargeable batteries. VRB are applicable at grid scale and local user level. VRB are the most common flow batteries. A flow battery consists of a reaction cell stack where the electrochemical reactions occur. At least one storage tank is filled with electrolyte (anolyte) consisting of reactants in solution for the negative battery electrode, the anode. At least one more storage tank is filled with electrolyte (catholyte) consisting of reactants in solution for the positive battery electrode, the cathode. Piping is connecting the storage tanks with the reaction cell stack, and mechanical pumps are used to circulate the electrolytes in the system. Flow batteries are different from other batteries by having physically separated storage and power units. The volume of liquid electrolyte in storage tanks dictates the total battery energy storage capacity while the size and number of the reaction cell stacks dictate the battery power capacity. The energy storage capacity and power capacity can thus be varied independently according to desired application and customer demand. A VRB installation consists, as a minimum, of a VRB unit as described above, a battery management system, and a power conversion system connecting the battery unit to the grid.

Electrolyte left in the cell stack during idle periods will self-discharge over time resulting in an energy loss. As the electrolyte volume in the cell stack is generally small compared to the total electrolyte volume, the total energy loss from self-discharge will be at most 2 % of stored energy during any idle period. The mechanical pumps require energy. The energy used by the mechanical pumps is included in determination of battery efficiency and should thus not be treated as a separate loss.

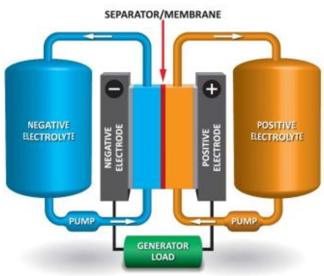
For individual VRB reaction cells the energy conversion efficiency can be as large as 90 % at low current densities. The grid-to-grid efficiency is reported by multiple sources to be approximately 70 % at constant rated discharge power. UniEnergy Technologies reports 75 % energy efficiency for frequency regulation application and 70 % energy efficiency for peak shaving application. Vionx Energy reports a DC efficiency of 78 % and an AC efficiency of 68 % for their units operating at rated capacity.

View concise technology information in Table 6, and practical instances of this technology in Table 7.

Table 6: Technology Data Vanadium redox flow batteries

Level of technological readiness:	TRL 8-9
Storage time:	hours to days, the self-discharge rate makes storage periods of several months unfeasible.
Storage reaction time:	The typical storage period depends on operation. It ranges from minutes to hours for grid scale installations. The storage time is not technologically limited. Energy can be stored for extended periods of time as is the case in small local user level VRB units used for emergency power.
Investment price range:	600 k€ for 1 MWh
Maintenance costs:	2 % of total investment and 0,9 € per MWh
Capacity and power output:	Vary a lot, from 1 MWh, 325 kW to 60 MWh, 15 MW power output but both smaller and larger facilities are constructed.
Lifetime:	20 years
Charging cycles:	Unlimited cycles over 20 years lifetime
Efficiency:	Up to 78 %

Table 7: Examples of Vanadium redox flow batteries

1	 Picture: [3]	Hokkaido, Japan Year: 2016, Capacity: 4x15 MWh=60MWh, 15 MW Provider: Sumitomo Electric Industries
2	 Picture: How VRB battery work [4]	Braderup, Germany Year: 2014 Capacity: 1 MWh, 325 kW Provider: UniEnergy Technologies

Information and images on vanadium redox flow batteries were retrieved and compiled from Technology Data Catalogue on Energy storage published by Danish Energy Agency [4].

2.2 Accumulation in the form of thermal energy

Thermal energy storage (TES) technologies can help to integrate high shares of renewable energy in heat/power generation, industry, and buildings. TES technologies offer unique benefits, such as helping to decouple of heating and cooling demand from immediate power generation and supply availability. The resulting flexibility allows far greater reliance on variable renewable sources, such as solar and wind power. Thermal storages are useful for the production and use of renewable electricity, because the (surplus) electricity can be used by power-to-heat to supply district heating grids. To make this more efficient and to be more independent from the fluctuating electricity production, thermal storages are useful.

Thermal energy can be stored either directly as heat or converted into electricity for later use. Additionally, an important aspect of thermal energy utilization is the possibility of waste heat utilization, where excess or unused heat generated during certain processes can be captured and put to practical use, thereby increasing overall energy efficiency and reducing wastage.

From an energy demand perspective, TES can provide solutions for the overall energy system rather than focusing on power, heat or cold. Energy demand in end-use sectors such as buildings is strongly affected by seasonality. Thermal storage can store energy for short and/or long term, helping to address seasonal variability in supply and demand. TES technologies such as thermal tanks (using water), solid state (using storage media such as sand, rocks, concrete, and ceramic bricks) and underground TES (UTES) can store excess power generation in summer and then supply space heating during the colder seasons. Also, chilled water tanks and UTES can be used on a seasonal basis to provide district cooling. This helps to cover electricity demand peaks when consumers require the most heating or cooling.

In industry, water tanks are wider used for low-temperature heat generation and storage in conjunction with solar thermal plants. Innovative technologies for sensible, latent, and thermochemical TES are also undergoing trials to store high-grade heat. TES can already be used to store low-temperature heat generated either through electrically powered heat pumps or by on-site solar thermal plants. Decoupling heat use from generation would permit flexibility and smart energy use and would allow continuous demand to be met by intermittent renewable generation.

Recently new sand-based storage tanks appear on the market enabling the higher temperatures available for seasonal storage using clean and environmentally secure technology.

Molten-salt storage is commonly deployed in the power sector. This is due to its advanced technological readiness and its application with concentrated solar power (CSP) plants. Molten salts are already in use today to allow CSP plants to consistently generate power by charging during the day and discharging at night.

Other TES technologies, such as solid-state thermal storage using concrete as the raw material could reduce the capital cost of CSP applications. Solid-state technologies could offer a low-cost form of storage to provide both electricity and heat to industrial processes in a similar fashion to co-generation plants today. High energy density PCMs and salt hydration storage solutions could help to reduce the spatial footprint of TES systems, potentially expanding their range of applications.

In the longer-term further research is needed to understand the potential for chemical looping and other thermochemical storage systems integrated into manufacturing processes to help meet higher-temperature process heat requirements.

In the near-term, other TES technologies are likely to become commercially viable, including solid-state and liquid air options that store surplus energy from CSP, solar photovoltaics (PV) and wind. Investments in technological development combined with measures to enhance market pull can unlock rapid growth in TES deployment. Such initiatives can form part of a holistic energy policy aimed at scaling up renewables and decarbonizing energy use.

Analysis of thermal storage technologies

Thermal energy storage (TES) systems have the potential of making the use of thermal equipment more effective and are important means of offsetting the mismatch between thermal energy availability and demand. It may be used to store surplus energy from the power plants, usually in the form of wastewater, waste energy from air conditioners, waste energy from industrial processes, and so on. It becomes a sort of energy sink into which we can throw any form of energy which is not needed for the moment. The energy storage systems can contribute significantly to meeting society`s need for more efficient, environmentally benign use in building heating and cooling, space power, and utility applications.

Depending on the specific technology, it allows excess to be stored and used hours, days, months, from the individual building, district, town, or region. Usage examples are the balancing of energy demand between daytime and night-time, storing summer heat for winter heating, or winter cold for summer air conditioning. Storage media include water or ice-slush tanks, masses of native earth or bedrock accessed with heat exchangers by means of boreholes, deep aquifers contained between impermeable strata; shallow, lined pits filled with gravel and water and insulated at the top, as well as eutectic solutions and phase-change materials.

TES systems are achieved with rather wide range of different technologies, which can be divided into several categories. Thermal energy storage solutions may be classified by:

1. Status of energy storage:

- Sensible heat storage in hot liquids and solids;
- Latent heat storage in melts and vapor;
- Thermochemical heat storage in chemical pounds.

2. Time length of stored thermal energy:

- Short term (used hours, days),
- Seasonal or long-term (used months).

3. Temperature level of stored thermal energy:

- Heat storage,
- Cool storage.

The following technological solutions were selected for the purpose of municipal level TES systems, as well developed to commercial level of with existing and operating prototype:

1. Sensible thermal water-based energy storage
2. Sensible heat sand-based energy storage.
3. Sensible heat molten-salt storage.
4. Latent Phase-Change Material (PCM).
5. Thermo-chemical heat storage.

2.2.1 Sensible Thermal Energy storage (water based)

Thermal energy storage in the form of sensible heat is based on the specific heat of a storage medium, which is usually kept in storage reservoirs with high thermal insulation. The most popular and commercial heat storage medium is water, which has a few residential and industrial applications. Water makes a good medium of heat storage due to its high specific heat capacity. Water can store greater heat per unit weight in comparison with other substances. Moreover, water is low cost and non-toxic [5].

Hot water stores are today based on water contained in tanks made of steel, stainless steel, concrete, or plastic or by water volumes placed in envelopes consisting of different water-tight materials. Equipment such as heat exchanger spirals, electric heating elements, stratification devices for enhancement of thermal stratification in the hot water stores, baffle plates, etc., can be built into the stores. The hot water stores are normally insulated with an insulation material with a low thermal conductivity to reduce heat losses of the stores [6].

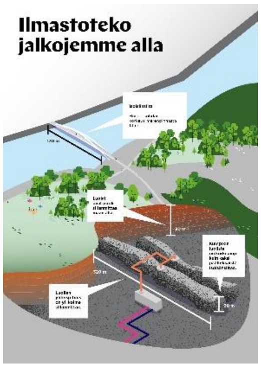
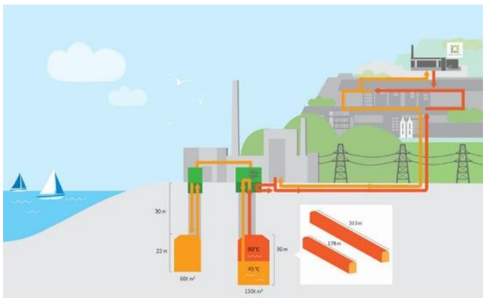
Energy storage systems are designed to accumulate energy when production exceeds demand and to make it available at the user's request. They can help exploit the variable production of renewable energy sources, increase the overall efficiency of the energy system, and reduce CO_2 emissions. Underground storage of sensible heat in both liquid and solid media is also used for typically large-scale applications. These applications can be Tanks, Concrete and Water pits, Borehole Rock cavern, Caves Thermal Energy Storage (TES) systems. Hot water tanks serve the purpose of energy saving in water heating systems based on solar energy and in co-generation energy supply systems. Underground Thermal Energy Storage (UTES) – is also a widely used storage technology, which makes use of the underground as a storage medium for both heat and cold storage, and include borehole storage, aquifer storage, cavern storage and pit storage. Which of these technologies is selected strongly depends on the local geological conditions. At present, TES systems based on sensible heat are commercially available [7].

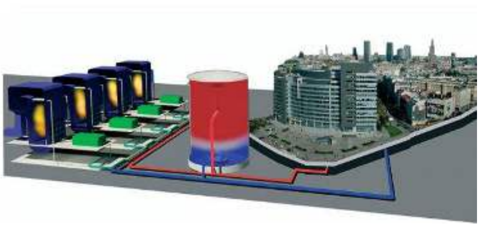
View concise technology information in Table 8, and practical instances of this technology in Table 9.

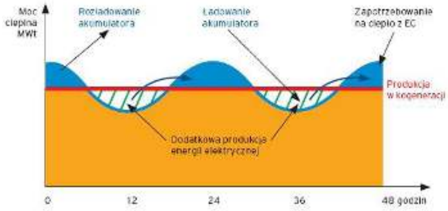
Table 8: Technology Data Water based sensible thermal energy storage

Level of technological readiness:	TRL 9
Storage time:	may be both – Seasonal (long-term) as well as short time storage. Thermal energy storage can provide to DHC networks different technical capabilities mainly in two different time scales: short and long-term energy storage. Peak Shaving and increasing the penetration of intermittent renewable energy sources through Power-to-heat technologies are some of these capabilities allowed with TES [8].
Storage reaction time:	must be rather quick for short time (hours) and days/months for seasonal storage
Investment price range:	Investment cost 2560-3387 €/kW, total production cost 60-83 €/MWh. €50-200/m3 of water equivalent, which makes specific investment cost for tanks from €0.5-3.0/kWh. The price of complete system of UTES sensible heat storage ranges €0.1-10/kWh. [7]
Maintenance costs:	90 €/kW/a [7]
Capacity and power output:	Capacity 10 – 50 kWh/t and power output 0.001-10 MW [8], kWh to 1 GWh for tanks and MWh to GWh for underground [9]
Lifetime:	15-50 years [9]
Charging cycles:	Due to big variety of types, sizes, etc., as well as short- or long-term of use, charging cycles may vary significantly.
Efficiency:	55-90 % depending on specific heat of storage medium, and thermal insulation technologies [8]
Temperature range (thermal storage):	In the best systems, water charging temperature is about 80-95°C and discharging 45°C, use of heat pumps can reduce discharge temperatures to 5°C. Underground heat storages are frequently used for seasonal storage in combination of heat pumps [7] [8] [9]

Table 9: Examples of Water based sensible thermal energy storage

1		20 m³ accumulation water tank short-term storage installed together with 1.5 MW biomass boiler-house at Matuizai settlement (Lithuania). Storage tank operates as short-term storage and ensures constant and continuous heat supply. Storage photo was provided by the owner of the installation - UAB "Varėnos šiluma" [10].
2		The Heliostorage borehole thermal energy storage (Finland) solution provides large-scale underground energy storage that enables the long term, energy efficient and eco-friendly storage of heat. One of the biggest challenges with any sensible heat storage solution is overcoming losses. Through multiple iterations and variations of drilling patterns over an 8-year period, the Heliostorage team have created an optimized borehole configuration that effectively charges and discharges the earth converting it into a heat battery [11].
3		The heat caverns located under Mustikkamaa (Finland), filled with water, and used as UTES even out the consumption peaks of the district heating network all year round. For example, waste heat from wastewater and properties can be stored in the heat cavern and released for use as needed. In the future, the temperature of the water in the heat cavern will vary between +45 and +100 degrees, depending on the operating situation [12].
4		In 2020, the largest thermal energy storage (TES) facility in Finland was put into operation in Vaskiluoto, Vaasa. It will diversify the region's thermal energy generation both now and in the future. The power plant will carry out charging, and heat will be discharged from the TES system to be used in the region's district heating network. The caverns used for thermal energy storage will act as an optimisation tool within EPV's energy generation portfolio. The total volume of the TES facility is 210,000 m3 and it will have a charging and discharging capacity of 100 MW [13].

5		75,000 m^3 water pit at Marstal solar heating plant (Denmark). More than half of the heat is supplied by solar energy – and have done so since 2013. The system consists of more than three hectares of solar collectors, two pit heat storages, a heat pump, and a biomass CHP plant. Today, 12 GWh or 50% of the district heating in Marstal is covered by solar heat and the heating costs of the small island town have decreased [14], [15].
6		Hybrid energy generation and accumulation system at Kaunas University of Technology (Lithuania), including Solar PV plant, underground concrete Seasonal heat accumulation and storage (500 m^3), and heat pumps. Installation of the system reduced annual heat demand from 1020 MWh to 490 MWh, electricity demand by 30%, as system generates appr. 350,000 kWh of electricity during the year. Annual energy savings will be appr. 200,000 €. Storage photo was presented by Kaunas University of Technology [16]. Project was implemented by Smart grid competence hub for boosting research, innovation, and educational capacities for energy transition (SMAGRINET) project, co-funded by the Horizon 2020 Programme of the European Union.
7		In October 2021, a heat accumulator was commissioned at the Karolin CHP plant, thanks to which the Poznań City (in Poland) heat distribution system will gain greater flexibility, and by storing above 1.1 GWh of energy. The nominal water temperature in the heat accumulator is 98^{O}C. The investment will reduce coal consumption in the production process by 11.5 thousand. tonnes per year and light fuel oil by 310 tonnes per year and reduce carbon dioxide emissions into the atmosphere by 24,000. tons per year (this is like planting 4 million mature trees) [17]
8		In March 2009, the operation of the first and largest heat accumulator in Poland, used in such a large municipal heating system at the Siekierki Heat and Power Plant in Warsaw began. The accumulator balances the operation of the CHP plant in a daily cycle, enabling shifting production to more efficient units and increasing production in cogeneration. The heat accumulator was designed and manufactured by Polish companies based on Scandinavian experience. The amount of energy that can be stored in it is 1.6 GWh. This energy is enough to simultaneously heat approximately 25,000 apartments in Warsaw around the clock. The investment cost approx. 12 M€.

	 *Operation of the heat accumulator in the municipal District Heating System of Warsaw*	Basic technical data: Capacity - 30,400 m3 (more than 40 million 0.75 l thermoses) Tank height - 47 m Tank diameter - 30 m Thermal capacity - 1.6 GWh Thermal power - 300 MWt Insulation thickness - 500 mm Loading / unloading speed - 4,500 t/h Mains water temperature - 40-99°C Tank type - non-pressurized Corrosion protection - steam cushion [18]

2.2.2 Sand and ceramics based Thermal Storage Systems

Enduring mechanism uses electricity from surplus solar or wind to heat a thermal storage material — silica sand or ceramic bricks. Particles are fed through an array of electric resistive heating elements to heat them to 1,200°C. The heated particles are then gravity-fed into insulated concrete silos for thermal energy storage. The baseline system is designed for economical storage of up to a staggering 26,000 MWh of thermal energy. With modular design, storage capacity can be scaled up or down with relative ease. When energy is needed, the hot particles are gravity-fed through a heat exchanger, heating and pressurizing a working gas inside to drive the turbomachinery and spin generators that create electricity for the grid. The system discharges during periods of high electricity demand and when limited solar photovoltaic or wind power are available, such as early in the morning and evening, during dinner preparation, and when TVs are on. Once discharged, the spent, cold particles are once again fed into insulated silos for storage until conditions (and economics) are appropriate again for charging.

As a storage medium, abundant silica sand is stable and inexpensive, and has a limited ecological impact both in extraction and end of life. Particle thermal energy storage is a less energy dense form of storage but is very inexpensive. The energy storage system is safe because inert silica sand is used as storage media, making it an ideal candidate for massive, long-duration energy storage [22].

Dry bottom ash handling system provider produces green thermal energy — steam or hot air — which can be used directly in industrial plants or for the generation of electricity using steam turbines. The system consists of a blower, a fluidization air blowing system, a fluidization air suction system, an air filter and fan, an air pre-heater, and an integrated thermal energy storage module. Silica sands are the system's storage media [23].

First commercial sand-based high temperature heat storage is now in operation at Vatajankoski power plant area [8]. The system, which is adjacent to a power plant. It has 100kW heating power and 8MWh capacity and can heat the sand up to 500-600°C through renewable energy. The system is based around a large steel container that holds hundreds of tonnes of sand. Vatajankoski uses the system to ready the waste heat recovered from data servers to feed into the district heating network[24].

A brick energy and heat warehouse has just entered the market. The bricks store heat energy at 1500°C all day long. Depending on the demand, the system converts heat into electricity and returns it to the grid. The project is supported by *Breakthrough Energy Ventures, founded by Bill Gates*. Brick energy and heat storage is a simple alternative to complicated energy storage systems based on the latest technologies. In November 2022, the system was introduced to the market by the *American company Rondo Energy.* Available in two variants, the battery stores energy from RES in the form of heat. Heated to a temperature of 1500 ° C, the bricks can keep warm for whole days. One cubic meter of bricks can store up to 1 MWh which is more than other available storage technologies [20].

View concise technology information in Table 10, and practical instances of this technology in Table 11.

Table 10: Technology Data Sand based Thermal Storage Systems

Level of technological readiness:	TRL 7-8
Storage time:	Seasonal (long-term). Proper insulation between the storage and environment ensures long storing period, up to months, with minimal heat losses. Sand is a very effective medium for storing heat and loses little over time. The developers say that their device could keep sand at 500C for several months [25].
Storage reaction time:	Storing cycle takes from hours to months [25].
Investment price range:	As a storage medium, abundant silica sand is stable and inexpensive at €25-€42/ton. Particle thermal energy storage is a less energy dense form of storage but is very inexpensive (€1.7-€3.4 per kWh of thermal energy at a 900°C charge-to-discharge temperature difference) [6]; < 10 €/kWh of storage capacity[25].
Maintenance costs:	Minimal, no consumables, fully automized [25].
Capacity and power output:	Nominal power - up to 100 MW, Capacity - Up to 20 GWh [25].
Lifetime:	Tens of years [25].
Charging cycles:	1 to 2 weeks
Efficiency:	Up to 95 %. Resistive heating of sand is essentially 100% efficient, but the efficiency is inevitably lowered by heat loss through the boundaries of the system. The large 1 GWh storages will have the efficiency of around 95% when used for normal wind-power oriented storing cycles of 1 to 2 weeks [25].
Temperature range (thermal storage):	up to 600–1000 °C [10], up to 1000 – 12000C [26], up to 1500 bricks [20].

Table 11: Examples of Sand based Thermal Storage Systems

1		First commercial sand-based heat storage to Vatajankoski, an energy utility based in Western Finland. It will provide heat for Vatajankoski's district heating network in Kankaanpää, Finland. The storage has 100 kW heating power and 8 MWh capacity. The full-scale utilization of the storage will begin during the year 2022 [24].
2	 *The Magaldi Green Thermal Energy Storage (MGTES) system. Image:* [27].	The MGTES – Magaldi Green Thermal Energy Storage system develops an accumulation technology based on a fluidized sand bed (Energy from the sand), powered exclusively by renewable energy. The system can be charged either with excess electrical or thermal energy, managing to store it for an interval ranging from 4 to over 10 hours up to weeks. The sand fluidization system has significant advantages: large thermal storage capacity (up to the order of GWh); high thermal efficiency; fast response times; no environmental impact thanks to the use of natural materials. The technology has reached a high technological maturity (TRL7) and the first industrial module is currently under construction at the Magaldi production site in Salerno, which will soon be open to visits by the largest international energy companies [28].
3	 *A brick storage of energy and heat, source:* [19] A brick storage of energy and heat may turn out to be a bull's-eye. It takes just four hours to "charge" the warehouse, which is simply to heat a pile of bricks. They are heated evenly and provide a constant source of energy 24 hours a day. The thermal batteries are manufactured in plants in California. Rondo Energy, which called its technology a "brick toaster", has already started commercial deliveries of kits. The creators of the thermal battery claim that their method could be used to manage 90% of the heat generated in the world in industrial processes. Their warehouses are scalable, easy to configure and can be adapted to any type of building. No need to rely on complex components and rare materials means that the system can operate for up to 40 years without a decrease in performance. – Rondo's mission is simple: *to reduce the cost of heat and energy for large industrial processes.*	Energy from zero-emission sources can then be used, e.g., for industrial processes, such as the production of steel, cement, although the number of possible applications is basically not limited. However, a brick energy and heat storage can find a particular application in industry, as it allows you to replace coal-fired furnaces and boilers with fuels that pollute the atmosphere. Such a solution, due to the ease of installation and cooperation with local RES, may reduce the costs of energy production and storage compared to the technologies currently available on the market. The thermal battery is fault-tolerant, power loss is not a problem either. The energy store is made entirely of bricks and iron, so it eliminates the risks associated with other energy storage technologies, such as battery explosion. As a result, the thermal battery provides electrification at the absolute lowest cost and causes no additional peak loads on the electricity grid. This enables the integration of more electricity generation from renewable sources. Rondo heat accumulators maintain continuous output 95% of the time. Operation with input power accounts for only 15% of the battery life (about 4 hours a day needed to heat the bricks) [20]. *Deep emission reductions are now both possible and affordable for many of the world's most energy-intensive facilities. Our studies of customer facilities show emission reductions of 50% to 90% and operating cost reductions of 30% or more,"* said Jeremy Keller of Rondo Energy [19].

2.2.3 Molten salt energy storage systems

Molten salt can function as a large-scale thermal storage method that would allow other energy sources, such as nuclear and solar, to become more feasible by smoothing out the fluctuations in demand and weather. Molten salts have high boiling points, low viscosity, low vapor pressure, and high volumetric heat capacities. A higher heat capacity corresponds to a smaller storage tank volume. Salts used for storage (such as sodium nitrate $NaNO_3$ and potassium nitrate KNO_3) have melting points between 300-500°C and volumetric heat capacities between 1670 - 3770 kJ/m3 °C. Commercially available "HITEC" salt used in solar plants consists of potassium nitrate (53% by weight), sodium nitrite $NaNO_2$ (40% by weight), and sodium nitrate (7% by weight) with a liquid temperature range of 149 - 538°C. The salts are heated and stored in an insulating container during off-peak hours. When energy is needed, the salt is pumped into a steam generator that boils water, spins a turbine, and generates electricity. The conversion of thermal energy to electricity can proceed by different cycles such as the Rankine, Brayton, and Air-Brayton cycles [29].

There are two different configurations for the molten salt energy storage system: two-tank direct and thermocline. The two-tank direct system, using molten salt as both the heat transfer fluid (absorbing heat from the reactor or heat exchanger) and the heat storage fluid, consists of a hot and cold storage tank. [13] The thermocline system uses a single tank such that hot and cold salt are separated by a vertical temperature gradient (due to buoyancy force) to prevent mixing. [14] There are two cycles in the thermocline system: charging and discharging. To charge, salt flows out of the cold side, is heated by the heat exchanger (reactor), and flows into the tank's hot side. To discharge, salt flow out of the hot side, transfers heat to generate power (turbine), and flows into the tank's cold side [30], [31] .

View concise technology information in Table 12, and practical instances of this technology in Table 13.

Table 12: Technology Data Molten salt energy storage systems

Level of technological readiness:	TRL 9
Storage time:	Seasonal
Storage reaction time:	Storage duration at full power – minutes, hours [30], 6-10 hours [32]. Storage period hours to days [9].
Investment price range:	CAPEX [1] 100-300 €/kW, Average CAPEX 2016 - 20-40 €/kWh [32]
Maintenance costs:	Operation & maintenance costs - €12.9-92/kWh[2] [29]
Capacity and power output:	Range of capacities MWh to 5 GWh [9]
Energy density	70-200 kWh/m³ [9]
Lifetime:	> 20 years [9]
Charging cycles:	The annual number of charging cycles depends on the efficiency of technologies applied for charging and discharging processes.

[1] CAPEX is an abbreviated term for Capital Expenditures.
[2] Since information was originally provided in $, conversion to € was performed using Average exchange rate of the year, when information was released

Efficiency:	Round-trip efficiency > 98 % [9]
Temperature range (thermal storage):	Charging temperature 62-200oC depending on common salt hydrate chemical reaction, operating temperature 265 - 565°C [9], [30]

Table 13: Examples of Molten salt energy storage systems

1		Sweden-headed energy utility major Vattenfall AB together with compatriot SaltX Technology Holding AB, an energy storage technologies developer, will test how renewable wind and solar power can be stored in salt. In experiments, SaltX's patented technology has proven to be able to store up to ten times more energy and for much longer periods than water. It will now be tested for the first time on an industrial scale at a pilot unit in Vattenfall's Reuter-C CHP plant in Berlin, Germany. Charged with electricity from the grid, the 0.5 MW pilot plant at Reuter-C has a total storage capacity of 10 MWh of high-quality heat that it can discharge into the Berlin district heating network. Technology is based on nano-coated salt (NCS). The technology enables this "salt battery" to be charged several thousand times and that the energy can be stored for weeks or months without losses [33].
2	 Image: [34]	Archimede Solar Power Plant. The solar thermal power plant consists of a field of about 30,000 m^2 of mirrors (the parabolic collectors) that concentrate sunlight onto 5,400 m of pipe carrying the molten salt fluid. Molten salt is used as the heat transfer fluid in solar field and is heated to 550°C. The thermal energy is then stored in a hot tank and is used to produce high pressure steam to run steam turbines for electricity generation, reducing the consumption of fossil fuels [35]. Thermal Energy Storage type – 2-tank direct, capacity 8 hours, Total of 1,580 tons of molten salt. 60% sodium nitrate, 40% potassium nitrate. Capacity 100 MWh (thermal). Tanks are 6.5 m high and 13.5 m in diameter [36].

3	 *A prototype with "cabinets", each of which is a separate thermal battery module* [37].	The accumulator system consists of a heat exchanger, fan, evaporator/condenser, and salt particle tank. Despite its simplicity, this system was able to provide heating for an average family of four for two days. Engineers upgraded it to a fully working prototype, the size of a large wardrobe, that could be used in the real world. With almost 30 times more storage capacity, the system could heat a house for up to two months. 'It's not the final product yet, but everything is ready for the first real-world tests,' said Professor Olaf Adan from Eindhoven University of Technology. "The potential is huge, but we've also seen a lot of great technology that hasn't been introduced. So, we're going to keep our feet on the ground and do it step by step," he added. A pilot project is already being prepared, under which the technology will **be tested in homes** in Poland, France and the Netherlands later this year [37].

2.2.4 Phase changing material heat storage

Thermal energy storage (TES) with phase change materials is a promising approach for combined heat and power plants to enhance the electricity peak regulation capability and maintain stable heat-supply at the same time [38].

Phase change material (PCM) as thermal energy storage (TES) has been used in various building applications. It changes phase at a certain temperature or temperature range, and simultaneously absorbs or releases a large amount of latent heat. Due to its high latent storage/release ability during its phase transition period, the material is used for building or solar energy storage, as well as for cooling applications, acting as a heat sink during a summer night, and removing excess heat in the building during the day [39].

Phase change materials (PCMs) can offer a higher storage capacity that is associated with the latent heat of the phase change. PCMs also enable a target-oriented discharging temperature that is set by the constant temperature of the phase change [7].

The main criterion for selecting a PCM is the phase change temperature range needed for the application. Other thermophysical properties, such as the latent heat of fusion and thermal conductivity, should also be considered during selection. Classification of families of PCMs:

- Sub-zero PCMs: with a congruent phase-change temperature below 0°C, e.g., salt-water mixtures.
- Ice: which has a phase-change temperature to water of °C.
- Low-temperature PCMs: with a phase change temperature of 0-120°C, e.g., paraffin waxes and salt hydrates.
- High-temperature PCMs: with a phase change temperature above 120°C, e.g., inorganic salts and their eutectic mixtures, including those stored in ceramic supporting materials known as composite PCMs (cPCMs).

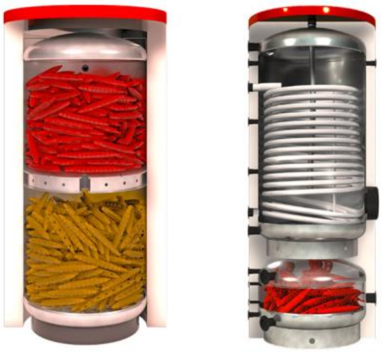
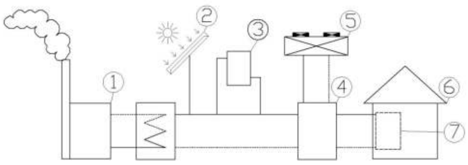
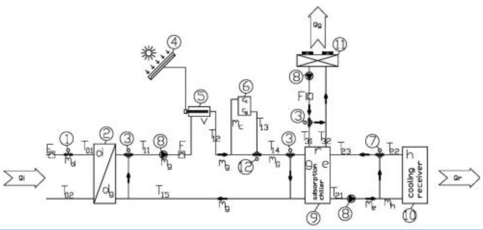
PCMs have a higher energy density compared to sensible heat storage materials, meaning that their physical footprint is smaller. PCMs can charge and discharge at an almost constant temperature, meaning that a PCM can be specifically chosen to provide a specific output temperature according to the engineering need [9].

View concise technology information in Table 14, and practical instances of this technology in Table 15.

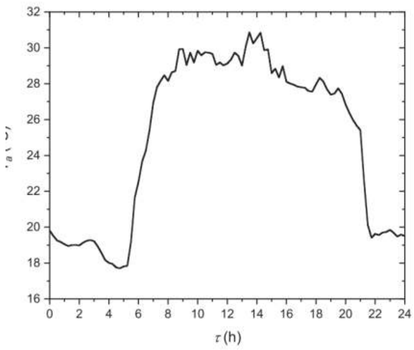
Table 14: Technology Data Phase changing material heat storage

Level of technological readiness:	TRL 9
Storage time:	may be both – from hours in short-term storage to Seasonal (long-term) [9].
Storage reaction time:	short time (hours) and days/months for Seasonal storage.
Investment price range:	Investment cost 4,517-11,292 €/kW, average production cost 90-226 €/MWh [7]. For cold Chain – Sub-zero PCM 55.8-194.4 €/kWh; for District Heating & Cooling – High Temp PCM and Buildings – both Low Temp and High Temp PCM 50.7-194.4 €/kWh[9]
Maintenance costs:	188 €/kW/a [7]
Capacity and power output:	Storage capacity 50-150 kWh/t, load factor 80 % [7] For Ice PCM – 334 kJ/kg; for Low Temp PCM (paraffin wax) – 200 kJ/kg [9]
Energy density	Sub-zero temperature PCM – 30-85 kWh/m^3; low-temperature PCM – 56-60 kWh/m^3; high-temperature PCM – 30-85 kWh/m^3 [9]
Lifetime:	In average technical lifetime 10-30 years, depending on storage cycles, temperature and operating conditions, economic lifetime – 20 years. For cold Chain – Sub-zero PCM – 5-20 years; for District Heating & Cooling – High Temp PCM – 10-20 years (over 5000 cycles); and Buildings – both Low Temp and High Temp PCM – > 10 years [9]
Charging cycles:	vary significantly depending on the material used, quantity of capsules [9], [39]
Efficiency:	> 90 % [9]
Temperature range (thermal storage):	for cold Chain – Sub-zero PCM – -115 - +80C years, for District Heating & Cooling – High Temp PCM and Buildings – both Low Temp and High Temp PCM – 0 – 750°C [9]

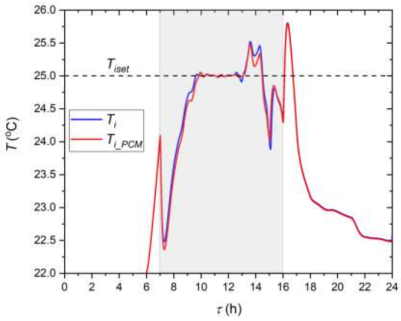
Table 15: Examples of Phase changing material heat storage

1		The storage tanks are filled with over 55,000 Axiotherm HeatSels®. These are patented high-performance macro-encapsulations made of specially developed plastics. They are designed in such a way that, in addition to providing a large surface area, the PCM layer thickness are thin enough for the entire PCM to participate in the phase change process and for heat to be transferred quickly even at very low temperature differences. To achieve this, a heat transfer medium, in this case water, flows around the heatsels in the storage tank [8], [40].
2		Futurium in Berlin - stage, museum, laboratory, and forum; Kerosene latent heat storage tank based on the HeatSels®– technology, consisting of 55,000 heatsels, 5 tanks with a total volume of 50,000 l, storage capacity is over 1 MWh, storage tank for the absorption cooler has a constant loading and unloading temperature of 12 °C [22]. In addition to the extensive use of solar thermal energy and photovoltaics, only highly efficient combined heat and power and cooling systems are used to provide energy. Thanks to latent cooling and electricity storage systems, demand and generation peaks can be balanced out. As a result, the installation of peak-load boilers could be completely dispensed with. In the annual balance, the building provides a primary energy surplus of 8 kWh/sqm or 99,000 kWh/a (in relation to the demand according to EnEV) [23], [41].
3	 *General scheme of the cooling system: 1 – district heating system, 2 – solar heating system, 3 – thermal energy storage, 4 – adsorption chiller, 5 – recooling system, 6 – office building, 7 – air cooler.* 	Implementation the phase change material (PCM) thermal energy storage for air conditioning system in the office building located in Ostrołęka (Poland). The implemented system was designed to provide AC for the office building located in Ostrołęka (Poland) in which 7 rooms is cooled. The system uses low-grade heat from district heating to produce chilled water for air conditioning in an office building. The cooling load of the conditioned rooms originates from the heat transferred from three sources: the environment, workers, and electric appliances (essentially personal computers).

The scheme of the cooling system configuration: 1 – regulating valve, 2 – district heating heat exchanger, 3 – 3-way on/off valve, 4 – photovoltaic panels, 5 – electric heater, 6 – LHTES, 7 – 3-way mixing valve in cooling circuit, 8 – circulating pump, 9 – adsorption chiller, 10 – office building, 11 – drycooler, 12 – 3-way mixing valve in driving (hot) circuit, F – flowmeter, T – temperature [42].



Daily ambient temperature profile on July 22, 2020 [42].



Evolution of the calculated temperature inside the office with (Ti_PCM) and without (Ti) LHTES. (The shaded area indicates the period when the air conditioning system was on) [42].

The requirements of the AC system were met by the chiller of refrigeration power up to 16 kW and maximum coefficient of performance (COP) of 0.65. It operates with the hot water temperature 50–95◦C and recooling temperature 22–40◦C, producing chilled water of 8– 21◦C. Nominal flow rates are 2.5 m3/h in the hot water circuit, 5.1 m3/h in recooling and 2.9 m3/h of chilled water. The adsorption chiller for cooling the office driven by district heat and supported by phase change heat storage containing 1000 kg of RT62HC. Provided tests and simulation of the system operation for cooling the office building in Ostrołęka (Poland) during an exceptionally hot summer days (see Fig) showed that the storage with the selected PCM allowed to stabilize the indoor air temperature in the comfort zone during the occupied period and also to improve the performance of the adsorption chiller [42].

2.2.5 Thermo-Chemical Heat Storage

One of three possible approaches to thermal energy storage is to use reversible thermo-chemical reactions. The most important advantage of the thermo-chemical storage method is that the enthalpy of reaction is considerably larger than the specific heat or the heat of fusion. Therefore, the storage density could be much larger. In chemical reactions, energy is stored in the chemical bonds between the atoms that make up the molecules. Energy storage on the atomic level includes energy associated with electron orbital states. Whether a chemical reaction absorbs or releases energy, there is no overall change in the amount of energy during the reaction. That's because of the law of conservation of energy, which states that: Energy cannot be created or destroyed. Energy may change form during a chemical reaction [43].

The endothermic reactions of the chemical compounds can be triggered by supplying thermal energy accumulated or captured from any heat source. As a result, the chemical compounds are decomposed into individual ingredients with the supply of heat. Meanwhile, the thermal energy is stored in the form of chemical potential energy. The individual reactive components can be stored separately, which makes it possible to store thermal energy for long periods. On the other hand, thermal energy can be retrieved again via the recombination of the reactive components in an exothermic reaction. The thermal energy stored and released is equivalent to the chemical reaction enthalpy. The reaction enthalpy can be much larger than the transition heat of latent heat storage or sensible heat stored over a rational temperature span. Hence, the energy storage density of thermochemical heat storage can be much larger than latent or sensible heat storage. Latent or sensible heat storage loses thermal energy gradually by heat conduction and radiation owing to the temperature difference between the stored materials and the ambient air; however, thermochemical heat storage can store thermal energy in the form of chemical potential energy with negligible heat loss [44].

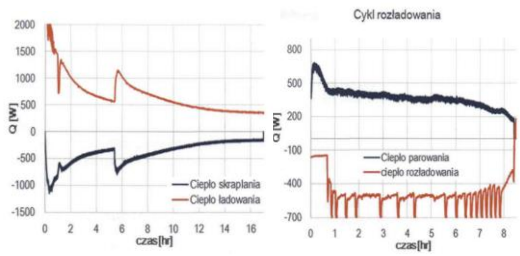
View concise technology information in Table 16, and practical instances of this technology in Table 17.

Table 16: Technology Data Thermo-Chemical Heat Storage

Level of technological readiness:	TRL 9
Storage time:	Seasonal [7]
Storage reaction time:	Storage duration at full power – hours, days [7], [32].
Investment price range:	investment costs 753-2258 €/kW , production costs 18.8-56.5 €/MWh [7]
Maintenance costs:	20-60 €/kW/a [7]
Capacity and power output:	energy capacity 120-250 kWh/t, power installed capacity 0,01-1 MW, load capacity factor 55 % [7], [32]
Lifetime:	technical 10-30 years, depending on storage cycles, temperature, and operating conditions; economic – 20 years [7]
Charging cycles:	~ 200 cycles per year [7]
Efficiency:	75-100 % [7], [32]

Temperature range (thermal storage):	150-180oC - the sorption TES (using zeolite/water) is charged at 150°C, transported over seven kilometres and discharged at 180°C, new up to 350°C and even higher [7]

Table 17: Examples of Thermo-chemical Heat Storage

1		Hungary-based Sinergy Kft is the recipient of Wärtsilä's first EPC energy storage project in Europe. The Finnish technology group commissioned the engine plus storage hybrid installation, its first globally, on August 22, 2018. The VPP can now provide frequency and secondary regulation to the Hungarian national grid. For the project, it integrated a 6 MW/4 MWh battery storage plant, complete with inverters and power electronics, with its GEMS energy management system, provided by subsidiary, Greensmith Energy, next to an existing power plant, which runs on three Wärtsilä W34SG engines. The system can analyse changes in market conditions and rate structures, said Wärtsilä [45].
2	 Container with project demo installation „MERITS"  *A set of thermochemical batteries*  *Charging and discharging cycles*	The world's first prototype installation for thermo-chemical storage of heat from the sun, which cooperates with the heating, cooling, and domestic hot water installation, was established in 2015 in Warsaw (Poland). The system includes: Installation of heat preparation for heating purposes with a weather control system Installation for preparing heat for domestic hot water. Ice water preparation system using an absorption chiller. Conventional short-term heat storage system Unconventional system of long-term (seasonal) heat storage in 2 thermochemical batteries with a capacity of about 350 MJ. The third research segment was performed simulating the behaviour of a small single-family low-energy house. This part of the container is insulated with 15 cm thick polyurethane foam. On the south side there are 2 energy-saving windows. An under-floor heating system was installed and chilled beams system under the ceiling. Fig. 3 and Fig. 4 show, for example, the results of thermal power measurements during the charging and discharging cycle for the one thermochemical battery [46].

5	 Image: [48]	Energy Dome. One of the new proposals is the storage of electricity of any origin using compressed carbon dioxide (CO_2). The solution was proposed by the Italian company Energy Dome, which developed a modular system for long-term storage of electricity. The concept with liquefied CO_2 is analogous to the method of energy storage using liquefied air developed by research units and companies in the USA, Israel, and Canada, among others. The use of CO_2 by the Energy Dome results from the physical properties of this gas - lower pressures are required to liquefy it than to liquefy air, less efficient compressors, less energy, and thus lower costs. The technology developed by the company makes it possible to locate warehouses in any place. The inventors emphasize that the devices are de facto emission-free - when energy is needed, CO_2 is evaporated, energy is consumed and then the released CO_2 can be reabsorbed into the storage. Engineers say they have developed a closed-cycle device and no CO_2 from the storage facilities is released into the atmosphere. According to the company, ultimately the devices may have a modular structure with a storage capacity of up to 200 MWh and an efficiency of 80%. The construction costs of the warehouses are not yet known. The company raised USD 11 million and intends to build the first "pilot" storage facilities with a capacity of 2 MW/4 MWh in Sardinia [48].

Information on accumulation in the form of thermal energy were retrieved and adapted from [5]–[9], [22]–[26], [29]–[32], [38], [39], [43], [44], [49]–[51].

2.3 Accumulation in the form of hydrogen

Interest in hydrogen has been growing greatly. The main interest is on producing hydrogen by excess renewable electricity, or even renewable energy produced solely to produce hydrogen, via electrolysis of water. Hydrogen can be stored as hydrogen or converted to another compound via power-to-x processes. The actual use of hydrogen in the energy system as an energy storage will be only a fraction of its uses. Here the focus is on the use of hydrogen in the energy system as an energy storage. The chosen technologies:

- Hydrogen in pressure containers
- Liquid organic hydrogen carrier (LOHC)

2.3.1 Hydrogen in pressure containers

Hydrogen is currently being used in a wide range of applications, mainly for industrial purposes in chemical production and refining. However, hydrogen has been seen as a mean for energy storage of renewable energy surplus since the 1920s. It has recently drawn a lot of attention due to the rapid spreading of the renewable energy industry all around the world and due to the steady growth of the hydrogen fuel cells industry. Large scale hydrogen production from surplus of renewable energy sources is believed to help sector coupling in the energy-supply system with power-to-gas and power-to-fuel technologies. Moreover, technologies running on hydrogen (applications in the transportation sector, energy production sector etc.) will be a significant part for the green energy transition.

Pressurized hydrogen storage is the only storage method currently in use on a significant scale world-wide. The technology and the materials of the hydrogen vessels have seen improvements as the demand of hydrogen storage is growing. However, hydrogen storage in pressurized tanks is a means of small and medium scale storage. Due to the limitations regarding material properties and operating costs, large scale storage on volumetric terms in pressurized tanks exceeding 200 bars at ambient temperature is not feasible, as the desired volumetric densities for a large-scale storage cannot be achieved. Tanks are categorised I-IV depending on construction and pressure limits, where IV is the most advanced.

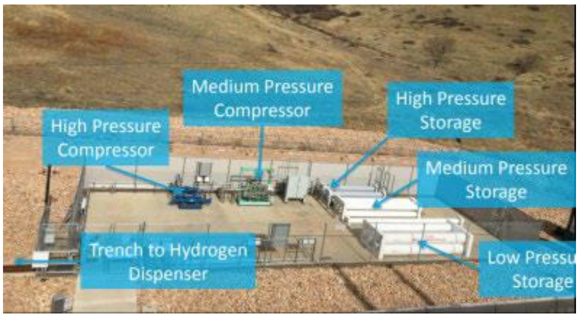
The technology medium-scale hydrogen storage tanks are the more frequently used technique for short to medium term storage. This technology fits the purpose of storage of hydrogen in a sustainable energy sector, i.e. production and storage of hydrogen gas from renewable energy production in large scale electrolysers. The pressure tanks need to withstand pressures from 50 bar to 1000 bar for hydrogen storage, over many cycles where they are being filled and emptied. As a result, different materials are used to support the tank and make its mechanical strength higher. Hydrogen embrittlement is the process in which metals like steel react with hydrogen, making them brittle and susceptible to cracking. This is one of the main factors that determines the tank's lifetime from the manufacturer. A phenomenon called hydrogen permeation can occur when hydrogen go through the walls of a container. This is a more common problem for materials like polymers and less common for metallic materials.

View concise technology information in Table 18, and practical instances in Table 19.

Table 18: Technology Data Hydrogen storage in pressure containers

Level of technological readiness:	TRL 9
Storage time:	The exact storage time depend on the materials of the tanks and how susceptible they are to hydrogen permeation and embrittlement. Hydrogen can be stored for month to years.
Storage reaction time:	Using hydrogen in a fuel cell will result in electricity production very fast. Seconds to minutes to produce electricity from stored hydrogen in a fuel cell.
Investment price range:	To store hydrogen in pressure containers will cost about 1M€ for a 500 kg H_2 system (about 8 MWh electricity and 7 MWh heat from fuel cell on grid)
Maintenance costs:	8 250€ per year per 500 kg storage unit. (0,009 M€/MWh)
Capacity and power output:	16,7 MWh in a standard unit of 500 kg H_2. Out of this about 8 MWh will be electricity and 7 MWh heat in a fuel cell (on-grid). Units can be built together to increase storage capacity. Fuel cells are available with different output (MW).
Lifetime:	25 years
Efficiency:	88 % for hydrogen, whole system about 40-45 % (electricity-hydrogen-electricity).

Table 19: Examples of Hydrogen storage in pressure containers

<table>
<tr><td>1</td><td>
</td><td>HyBalance Hobro, Denmark
Technology: 18 Type IV tanks, 450 bar, 500 kg H_2
Year: 2018
Use: Stationery and transport ready storage of hydrogen from electrolyzer output.
Provider: Air Liquide</td></tr>
<tr><td>2</td><td>
</td><td>Denver, USA
Technology: Multiple Type I tanks, 200 bar + Type II tanks, 850 bar, 310 kg H_2
Year: 2016
Use: Stationary storage for hydrogen fueling station for research purposes
Provider: Air Products</td></tr>
</table>

Information and images on hydrogen pressure containers were retrieved and compiled from Technology Data Catalogue on Energy storage published by Danish Energy Agency [1].

2.3.2 Liquid organic hydrogen carrier

Hydrogen is currently being used in a wide range of applications, mainly for industrial purposes in chemical production and refining. However, hydrogen has been seen as a mean for energy storage of renewable energy surplus since the 1920s. It has recently drawn a lot of attention due to the rapid spreading of the renewable energy industry all around the world and due to the steady growth of the hydrogen fuel cells industry. Large scale hydrogen production from surplus of renewable energy sources is believed to help sector coupling in the energy-supply system with power-to-gas and power-to fuel technologies. Moreover, technologies running on hydrogen (applications in the transportation sector, energy production sector etc.) will be a significant part for the green energy transition.

Energy carrying compounds are chemical substances that are in an energy rich state. If this energy rich state is achieved through hydrogenation (addition of hydrogen to the compound) of a liquid organic compound, then it is characterized as a Liquid Organic Hydrogen Carrier, or a LOHC. LOHC storage systems are fairly like conventional fuels, as they are stored in a liquid form in atmospheric pressure and environmental temperature until needed. Due to their high volumetric energy density compared to the compressed hydrogen gas, they are considered a viable alternative fuel not only for energy transport, and automotive purposes but for stationary applications as well.

LOHCs are essentially liquids or solids which are accompanied by the reversible hydrogenation and dehydrogenation at elevated temperatures with the help of catalysts. The organic compound retains its initial structure upon dehydrogenation. LOHC operation on small scale is accompanied by challenges with new process for hydrogen implementation regarding catalysts. The advantages lie in the compatibility of blending with the existing fuel infrastructure since the initial LOHC structure after hydrogen release remains the same. Especially, for transporting hydrogen over 1500 km, shipping hydrogen as LOHC is cost effective. Furthermore, no storage losses during transportation of hydrogen, as well as in a high hydrogen purity. Additionally, LOHCs are characterized by the ease of transportation. This, however, is impeded by the process of hydrogen liberation prior to use which is energy and cost consuming.

View concise technology information in Table 20, and practical instances in Table 21.

Table 20: Technology Data Liquid organic hydrogen carrier

Level of technological readiness:	TRL 7 system prototypes are available on market, but further research and development are being done.
Storage time:	Can be stored for a long period of time under ambient temperature and pressure. Loss of hydrogen during storage is negligible. Economically, 60 days is an optimum time span for storage when compared to compressed hydrogen storage.
Storage reaction time:	Will take time to add and free the hydrogen from the LOHC.
Investment price range:	The prices are uncertain, and market is volatile regarding LOHCs and data on the use of DBT-based LOHC system with solar power in Erlangen has been observed to result in H2 delivery cost of €5

	to €55 euros per kg H2. Additionally, H2 transport is more economical than conversion into electricity. For short distances, LOHCs are not economical.
Maintenance costs:	Estimated maintenance cost is 4 % of CAPEX/MW AND 1 % of CAPEX/MWh
Capacity and power output:	Depends on the size of storage tank. LOHC can be stored in room temperature in conventional storage equipment. 7 MWh is an available standard unit today but could be very much larger, LOHC could be freight by tanker boats for example.
Lifetime:	20 years
Efficiency:	72% for storing hydrogen alone

Table 21: Examples of Liquid organic hydrogen carrier

1		Hydrogenate capacity: 792 Nm³ hydrogen/day Year: 2016 Use: Mid to large-scale transport and stationery applications. Provider: Hydrogenious
2		Hydrogenate capacity: 94 Nm³ hydrogen/day Year: 2018 Use: Stationary system connected with electrolyser and fuel cell for smart grid applications Provider: Covalion

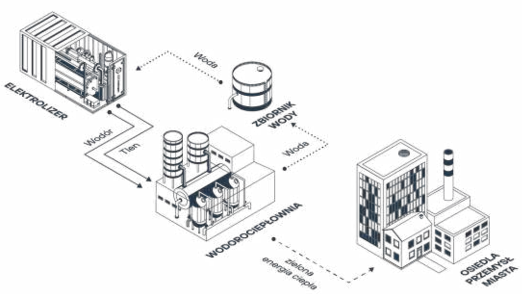
Information and images on liquid organic hydrogen carrier were retrieved and compiled from Technology Data Catalogue on Energy storage published by Danish Energy Agency [1].

2.3.3 Other devices, systems, and ways of using hydrogen

The hydrogen used today (the majority) is the so-called "black" hydrogen, obtained by steam reforming natural gas and other hydrocarbons. For example, Poland is one of the largest hydrogen producers in the European Union (see Table 22). However, black hydrogen technology spoils the market and hinders the development and implementation of electrolysis technology, i.e. production of "green" hydrogen (so it is no coincidence that there are no concrete plans to build large electrolysers in Poland).

Fortunately, there are examples of the initiated process of building a hydrogen economy (N.B. in port cities): an already existing HYPORT® – "green" hydrogen plant in Ostend (Belgium), German ventures – Hamburg Green Hydrogen Hub and HyTechHafen Rostock, as well as Belgian Power-to-Gas installation in Zeebrugge. However, one also needs to think about the entire hydrogen value chain (upstream, midstream, downstream), examples of which (storage) have been presented above, i.e. midstream.

Table 22: Polish examples of hydrogen downstream

1		Shunting hydrogen locomotive (SM42-6Dn) Technology: this locomotive is equipped with two hydrogen fuel cells with a total power of 170 kW (hydrogen is taken from tanks with a total capacity of 175 kg); the traction battery powers four asynchronous traction motors with a power of 4x180kW, which allows for a speed of up to 90 km/h Year (approval): 2023 Provider: PESA Bydgoszcz
2		Hydrogen boiler Technology: fully zero-emission heating device for the Power-to-Gas systems in the market; it is a compact unit of hydrogen and steam generation consisting of two components – a hydrogen boiler (based on the controlled combustion of hydrogen in pure oxygen in a closed circuit with the high efficiency of the device) and a hydrogen and oxygen source in the form of an electrolyser Year: 2021 Provider: SES Hydrogen (Sescom Group)

Information and images on other devices, systems, and ways of using hydrogen were retrieved and compiled from [52],[53], [54], [55].

2.4 Accumulation in the form of biomethane

Biogas provides a flexible clean and efficient form of energy. Enriched biogas may generate large volumes of biomethane allowing its usage as an alternative to natural gas via existing natural gas networks (or being used directly as fuel). The environmental impacts and high long-term costs of waste disposal have pushed the industry to realize the potential of turning this problem into an economic and sustainable initiative. Anaerobic digestion and the production of biogas can provide an efficient means of meeting several objectives concerning energy, environmental, and waste management policy. Biogas contains methane (60%) and carbon dioxide (40%) as its principal constituent.

Other gases than methane contained in biogas are considered contaminants. Removal of these impurities, especially carbon dioxide, will increase the biogas quality and enable its transport (volume flow) using gas pipe system. The integration of biological processes in the biorefinery that effectively convert carbon dioxide into methane is becoming increasingly important. Such process integration could significantly improve the sustainability of the overall bio-refinery process. The biogas upgrading by utilization of carbon dioxide rather than removal of it (presently most common) is a suitable strategy in this direction. The CO_2 transformation into methane requires significant amount of hydrogen, which may be generated by water electrolysis or biological methods (dark fermentation). The mentioned electrolysis can take part in the ancillary services of the power system.

There are two broad categories of upgrade techniques – biological and chemical, where traditional methods focus on ex-situ upgrading, utilizing catalytic conversion, membrane gas-permeation, physical and chemical scrubbing, absorption, and adsorption.

The technology based on H_2 production and addition to biogas strongly depends on:

- Feedstock types and preparation.
- Bioreactor types and configurations.

Barriers, advantages, and economics of biomethane deployment

The main barriers to the development of the biogas/biomethane sector in the European Union are high capital expenditures, long lead times (investments), and a strong conventional energy lobby. The most important advantages of biogas/biomethane technology include environmental aspects, high biomethane potential and support for agriculture. The development of biogas/biomethane technology will slowly reduce environmental pollution, reduce carbon dioxide and methane emissions, and allow for partial independence from the importing of natural gas.

Sources of financing for biogas plants are subsidies, credits, including from public and EU funds, bank credits and funds of the entities implementing the project. Without financial support, many of the existing and built biogas plants in the European Union would probably not have been constructed. Depending on the status of the beneficiary, appropriate financial assistance may be received.

When trying to estimate capital expenditures (CAPEX) and operating costs (OPEX) for biomethanation, three conditions must be considered (in the current turbulent situation):

1. these technologies do not exist commercially at the Technology Readiness Level (TRL) 8/9,
2. impact of technological development from a microeconomic point of view,
3. macroeconomic phenomena – mainly monetary policy and growing imbalance in the global economy.

Environmental and ecological aspects of biogas/biomethane plants

The most important environmental benefits achieved through the biogas/biomethane production include:

1. reduction of methane emissions from the natural decomposition of organic substances,
2. economy using distributed energy systems, thanks to which energy-transmission losses are minimised,
3. sanitary aspects,
4. the reduction of CO_2 emissions from diesel and petrol combustion.

The biogas/biomethane plants allow for the controlled management of waste organic matter. The natural processes of bio-waste decomposition produce methane, which, if released into the atmosphere, increases the greenhouse effect. For example, according to the data of the National Centre for Emission Management and Balancing (2020), in Poland, methane accounts for 11.8% of the emitted greenhouse gases – highest in agriculture, comprising one third of emissions. There are also significant methane emissions from municipal waste, sewage sludge, agro-industrial effluents, or agricultural residues. Anaerobic digestion of bio-waste limits methane emissions, which are up to 23 times more harmful than CO_2.

View concise technology information in Table 23, and practical instances in Table 24.

Table 23: Technology Data for biogas production in biomethanation

Level of technological readiness:	TLR 9 for biogas production and TRL 6/7 for biomethanation
Storage time:	long term storage (one year)
Storage reaction time:	Using biomethane in gas engines or turbines will result in fast electricity production. Practically electricity generation will start in range of minutes.
Investment price range:	Estimated cost of 1 MW biomethanation system is of the order 5M€
Maintenance costs:	not known yet
Capacity and power output:	Standard power systems based on biogas/biomethane production were in the range 1 MWe, due to sustainable delivery of sub-strates. However, there are systems with more than 10 MWe.
Lifetime:	25 years
Efficiency:	88 % for hydrogen, whole system about 40 % (electricity-bio-methane-electricity)

Table 24:Technology example of a methane production plant

1	 Image: [56]	GICON (Großmann Ingenieur Consult GmbH, Dresden) developed in-situ tech-niques based on trickle bed reactor (ready to market): • add-on for biogas and wind energy plants for doubling methane genera-tion, • option for existing infrastructure (vehi-cles, biogas plants, wind wheels), • controllable, stable, demand oriented process: a) high efficiency and product quality, b) very low self-energy demand, • utilization of CO_2 instead of its separa-tion, biogas upgrading using generated hydrogen. • economy feasible depending on: c) full load hours and individual costs of electricity, d) CAPEX Electrolyser, e) greenhouse gases quota mar-ket. • Monitoring and data management [56].

2.4.1 Biological Processes

Biomethanation complement chemical options, using the aptitude of microorganisms to convert CO_2 into useful products. Biological fixation of CO_2 is a sustainable solution to reduce CO_2 content in biogas. One of the biological methods to utilize CO_2 in biogas relies on the utilization of H_2, generated by water splitting (e.g. electrolysis), for conversion of CO_2 to CH_4 based on the action of hydrogenotrophic methanogens (process of hydrogenotrophic methanogenesis). The chemical reaction is shown in Eq. (1):

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad \Delta G = -130.7\ \text{kJ/mol} \tag{1}$$

To ensure the method is sustainable, electricity needed in the hydrolysis process should be produced by renewable sources, such as solar or wind. One of the disadvantages of H_2 was its low volumetric energy density, resulting in storage difficulties. This H_2 assisted biogas upgrading can occur in a so-called in-situ and ex-situ biogas upgrading. Ex-situ upgrading requires the CO_2 to be separated first by using e.g. absorption, adsorption, membrane separation or cryogenic methods and then utilised in methanation process in another reactor. Ex-situ upgrading technique will not be discussed here. In contrast, the process of in-situ upgrading does not require the CO_2 to be separated and removed first, rather it is converted into CH_4 – leading to a significant biogas purity.

In-situ biological biogas upgrading uses the injection of H_2 inside a biogas reactor during anaerobic digestion to react with CO_2, resulting in CH_4 production by the action of autochthonous methanogenic archaea. This can be operated through two different pathways: hydrogenotrophic methanogenesis or Wood–Ljungdahl pathway. Hydrogenotrophic methanogenesis leads to direct conversion of CO_2 to CH_4 with the addition of H_2 as a source of electrons, according to Equation (1). But the Wood–Ljungdahl pathway indirectly converts CO_2 to CH_4 via two reactions (2) and (3):

$$4H_2 + 2CO_2 \rightarrow CH_3COOH + 2H_2O \qquad \Delta G = -104.5\ \text{kJ/mol} \tag{2}$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \Delta G = -31.0\ \text{kJ/mol} \tag{3}$$

CO_2 is converted to acetate acid with the help of homoacetogenic bacteria. Then the acetate acid is converted into CH_4 by the acetoclastic methanogenic archaea. H_2 plays a crucial role in the whole process of anaerobic digestion. Exogenous addition of H_2 results in the increase of both hydrogenotrophic methanogens and homoacetogenic species, producing acetate from H_2 and CO_2. The downside of adding H_2 to the process is the inhibition of syntrophic acetogens which are involved in propionate and butyrate degradation and syntrophic acetate oxidizers (SAO). It is important to control the concentration of H_2 to ensure the equilibrium of biochemical reactions. The process is illustrated in Fig. 1.

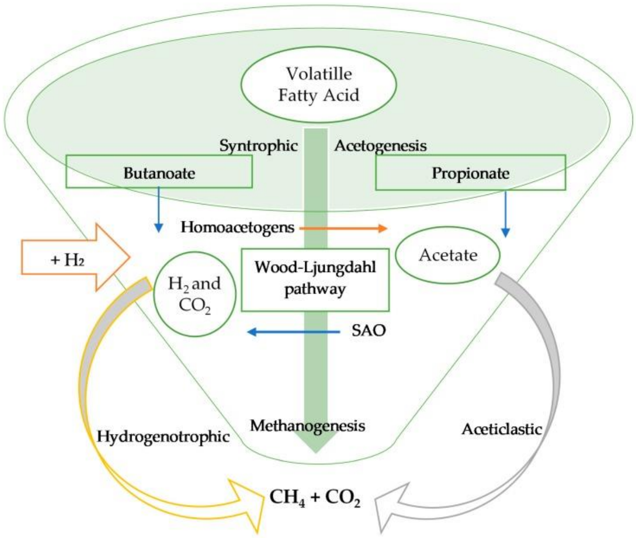


Figure 1: Metabolic pathways for hydrogen assisted methanogenesis. Image: [57]

2.4.2 Chemical Processes

Using CO_2 as a feedstock for the synthesis of commodity chemicals and fuels has the potential to be beneficial for the economy and environment. Methanation reaction, also called a Sabatier reaction, is a reaction between CO_2 and H_2 to produce CH_4 and water (H_2O). As with biological processes, access to renewable electricity and/or 'green' hydrogen is critical.

Although the reaction is between CO_2 and H_2, there is the potential of using biogas directly as feedstock for CO_2 methanation as CH_4 content in the biogas has only a little influence on the reaction at high pressure. The research has found that the methanation of CO_2 above 0.8 MPa will be ideal to decrease the effect of CH_4 on the conversion process. The process of hydrogenation of CO_2 to CH_4 using Ni catalyst can be described by Sabatier reaction (4):

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O, \quad \Delta H = -165 \text{ kJ/mol.} \quad (4)$$

The search for more efficient catalytic processes is continued. Challenges that need to be confronted include the development of catalysts that can operate at lower temperatures where the reaction is more promising and preventing of deactivation of the nickel-based catalysts due to sintering and oxidation. Sintering occurs due to the high temperature and water while oxidation is due to the presence of H_2. On the other hand, changing the nature of catalysts to less reactive catalysts result in the production of methanol.

2.4.3 Biomass Gasification

Biomethane can be also produced from biomass through gasification. Woody biomass, agricultural residues, and municipal solid waste can be used as feedstocks for gasification. Steam gasification is the preferred conversion scheme for biomethane production. Different gasifying agents can be used to improve biomass gasification performance.

In thermal gasification of solid biomass, woody biomass is first broken down at high temperature (between 700-800 °C) and high pressure in a low-oxygen environment. Under these conditions, the biomass is converted into a mixture of gases, mainly carbon monoxide, hydrogen, and methane (sometimes collectively called syngas). To produce a pure stream of biomethane, this syngas is cleaned to remove any acidic and corrosive components. After gasification, the methanation process (which is required to achieve high purity CH_4) then uses a catalyst to promote a reaction between the hydrogen and CO or CO_2 to produce methane. Any remaining CO_2 or water is removed at the end of this process.

Göteborg biomass gasification project (GoBiGas) is the world's first demonstration plant for large-scale production of biomethane through the gasification of forest residues [58], [59].

Information and images on accumulation in the form of biomethane were retrieved and adapted from [57]–[80].

2.5 Energy accumulation in the form of potential energy

Pumped hydropower storage (PHS), also known as pumped storage power plant (PSPP) is a kind of plant to store electricity, mainly with the aim of supply-demand balancing. During off-peak periods and times of high production of energy by renewable power plants, low-cost electricity is consumed to pump water to a highly elevated reservoir. In this way, the surplus electrical power is stored in the form of gravitational potential energy. When electricity demand increases, the stored water is released to drive the hydraulic turbines of the system and actuate a coupled electricity generator to produce power. The outlet flow from the higher reservoir can be controlled to provide variable output power. The roundtrip efficiency of a PHS plant can reach up to 90%, which is the highest percentage among mechanical energy storage (MES) technologies. Also, the capacity of such plants can be extremely large, up to a few thousand megawatts.

The main disadvantages of PHS systems are the limitations in water availability and topography challenges as well as high capital cost. Furthermore, appropriate sites for this technology seem to be available in the natural environment and therefore there are also ecological and social concerns to overcome. Even considering these challenges and drawbacks, PHS is by far the most widely implemented energy storage technology in the world due to the previously mentioned advantages, its considerable economic benefits via facilitating the supply of cheap electricity at times of expensive energy, spot prices and high efficiency. Among the several existing and developing MES technologies, the pumped hydropower storage system is the most mature one. This has made it the most broadly implemented energy storage system worldwide.

By 2017, PHS systems provide more than 95% of the total 184GW in-service electricity-storage capacity of the globe. Until 2011, around 40 PHS facilities were operating globally (mostly in the United States), while just two compressed air energy storage facilities (one in Germany and one in the United States) were in operation.

The PHS systems can be divided into two main configurations: open-loop and closed-loop systems. In the former, the plant is coupled to a natural water system such as a river (the lower reservoir is a dam connected to a natural water source). In the latter configuration the reservoir is not linked to any natural water flow, and there are only the upper and lower reservoirs between which the mechanical components of the system are placed and work. Fig. 2 illustrates the schematic diagram of a PHS system in a closed-loop configuration (the lower reservoir is not connected to any river or natural water stream). The operating principle of a PHS system is quite simple. As shown in the figure, a PHS consists of a few main components, namely, an upper reservoir, a hydraulic turbine/pump that is connected to a motor/ generator, a lower reservoir, the flow canal/piping system, and control systems (e.g. flow control valve). In the charging mode, the surplus power that is to be stored is used by the motor to drive the turbine/pump, which works on its pump mode at this stage. The pump transfers water from the lower reservoir to the upper reservoir to store the surplus electricity in the form of increased potential energy in the system. In the discharge mode, the direction of water flow and operation of components is reversed. The control valve opens, depending on the level of power needed to be produced, and water from the upper reservoir at high pressure flows through the hydraulic turbine/pump (which is in turbine operation mode) and produces rotational work that is fed to the generator. Finally, the discharged water is stored in the lower reservoir.

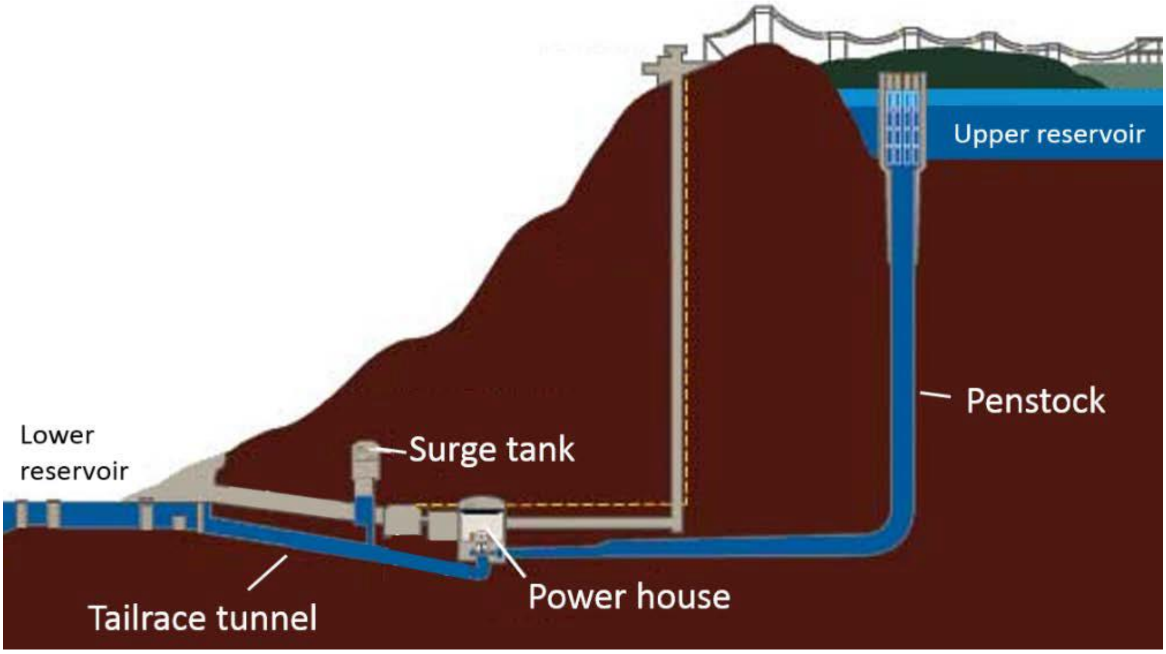


Figure 2: Schematic diagram of a PHS system, Image: [81]

PHS technology is mature, offers the greatest roundtrip efficiency among all MES systems, is fast in responding to demand and operation mode alteration, and is flexible in MW capacity. Also, the production cost of PHS systems is quite low due to the nature of how a PHS unit operates. However, the capital cost of PHS systems is very high. Moreover, there is no hope for significant reduction of the capital cost because, as previously mentioned, this technology is quite mature and has been under development for decades. This along with the environmental concerns associated with PHS systems, the long time required for constructing a PHS plant, and technical challenges such as sediments are the drawbacks of this technology.

Considering all its positive and negative points, PHS technology will continue to be a key component of energy systems around the world. This is especially important now after the sharp growth of renewable energy systems worldwide and the planned roadmap towards pure renewable energy systems. However, the undeniable fact is that there is still a gap between the technology reality and market needs. That is why studies and efforts to address remaining challenges are continuing, including: PHS plants with underground reservoirs or undersea PHS systems.

The most critical needs in this field are as follows:

1. Advances in designing the turbine and pump are required to further improve the cost-effectiveness and roundtrip efficiency of the system.
2. Digitalizing of PHS technologies is required. It is expected that development and advances in automation and information technology will shape the future of PHS plants.
3. Environmental impact is one of the main concerns and limitations of the development of PHS

plants mainly due to finding or creating water reservoirs with height difference. Technical developments in environmental sciences will directly affect the methodologies by which the ecological impacts of existing and new PHS plants are assessed.

4. Optimization of the system but also the trading and operation strategies of PHS plants in electricity markets when integrated with renewable power plants (such as wind turbines and solar power plants) could be effective in obtaining a better economic performance.

However, there is another important problem – the existing pumped-storage power plants, both in the European Union, associated countries, as well as in the USA, UK, Japan, etc., are mainly large-scale facilities. The Energy Equilibrium project, related to municipal activities, focusses on facilities with much lower installed capacity (below 100 MW), possible to be implemented and operated by the city. Such facilities generally do not exist, the technology has not been implemented on such scale, except for the Gaildorf storage facility as a pioneer (fig.3.).

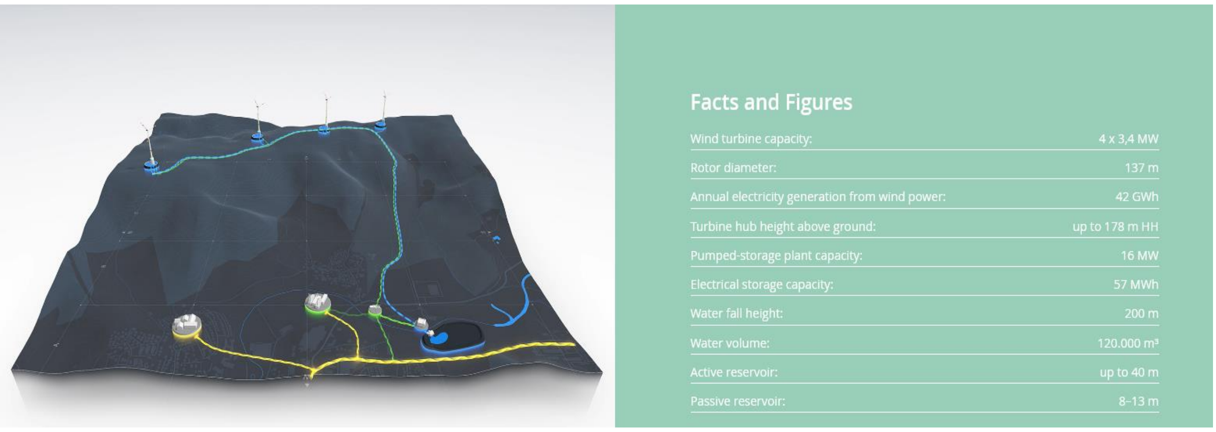


Figure 3: Schematic diagram of Naturstromspeicher Gaildorf with Facts and Figures, Image: [82]

The pilot project in Gaildorf near Stuttgart, Germany, demonstrates new concept – Water Battery. In this project, the foundations of the wind turbines are used as upper reservoirs. They are connected via an underground penstock to a pumped-storage power station in the valley that can provide up to 16 MW in power. The electrical storage capacity of the power plant is designed for 70 MWh (total, according to the project operators, which corresponds to more than five hours of storage operation for all wind turbines at nominal output). CAPEX is around EUR 75 million.

During times when the wind blows strongly, surplus renewable energy is often generated in other wind power plants that cannot be fed into the public electricity grid or stored. Instead, the energy production is throttled back, and the wind turbines are shut down. In the pilot project in Gaildorf, on the other hand, the electricity is temporarily stored in the upper basin.

The German Federal Ministry for the Environment, Nature Conservation, Construction and Reactor Safety (BMUB) has supported the project in Gaildorf with funds from its environmental innovation programme amounting to EUR 7.15 million. This is a clear mark of recognition for this innovative technology, which is being demonstrated for the first time in a large-scale technical application.

Therefore, when trying to estimate capital expenditures (CAPEX) and operating costs (OPEX) for pumped hydropower storage, four conditions must be considered (in the current turbulent situation):

1. this technology (small PHS) hardly exists commercially at the Technology Readiness Level (TRL) 8/9,
2. construction and operation of a pumped storage power plant, and consequently CAPEX and OPEX, are very dependent on local geographical, hydrological, and geological conditions,
3. impact of technological development from a microeconomic point of view,
4. macroeconomic phenomena – mainly monetary policy and growing imbalance in the global economy.

The data in Table 25 and Table 26 are mainly for existing large-scale objects (with one exception).

Table 25: Technology Data of hydro storage systems

Level of technological readiness:	TRL 9
Storage time:	Several hours to weeks.
Storage reaction time:	Using pumped hydro will result in electricity production very fast – it takes minutes to produce electricity.
Investment price range:	up to 75 M€ for 57 MWh storage capacity and 16 MW power
Maintenance costs:	not known yet
Capacity and power output:	100-3000 MW
Lifetime:	50-100 years
Efficiency:	74-90%

Table 26: Examples of hydro storage systems

1		Żarnowiec Pumped Storage Power Station, Poland Technology: open loop pumped hydro storage Year: 1973 - 1983 (modernised 2006 - 2011) Installed capacity: 716 MW Efficiency: 90% Provider: PGE

2		Żydowo Pumped Storage Power Station, Poland Technology: pumped hydro Year: 1964 - 1971 (modernised 2013) Installed capacity: 167 MW Provider: ENERGA
3		Naturstromspeicher Gaildorf, Germany Technology: a wind farm is combined with a pumped storage power plant Year: 2017 - 2022 Installed capacity (pumped hydro): 16 MW Provider: Naturstromspeicher GmbH (Max Bögl Gruppe)

Information and images on accumulation in the form of biomethane were retrieved and adapted from [81]–[89].

3 Part 2 – PESTLE analyses and conclusions of energy storage systems in municipalities

The general drivers behind the interest in energy storage are related to several factors. These include international, EU and national climate targets, which are also mirrored by climate targets at the municipal level. Energy storage has the potential to significantly improve energy self-sufficiency and increase the share of electricity produced from renewable energy sources. Many renewable energy sources face the challenge of fluctuating energy production and the resulting price volatility in the energy market. Energy storage can mitigate energy price volatility and ensure energy availability. As societies have become increasingly energy dependent, it is important to ensure energy availability in all circumstances. Energy storage can contribute to meeting these objectives.

The following tables summarise the advantages and disadvantages of each technology and the main findings of the PESTLE analyses.

Perspectives on the multidimensional key performance indicator (KPI) measurements of the carbon-neutral energy system in the municipalities' analysis have been made with the help of PESTLE analysis. In general, PESTLE analysis is a broad fact-finding activity around the external factors that could affect an organisation's decisions, helping it to maximise opportunities and minimise threats. PESTLE audits six external influences on an organisation: P for Political, E for Economic, S for Social, T for Technological, L for Legal, and E for Environmental. It will give an overall view of the environment under study, from many different angles, when considering a particular idea or plan.

The PESTLE analyses were made for five different energy accumulation alternatives:

TECHNOLOGY	AUTHORS
Batteries	Thermopolis Ltd, Sustainable Business Hub Scandinavia AB (SBH)
Thermal Energy	Lithuanian Energy Institute (LEI)
Hydrogen	Sustainable Business Hub Scandinavia AB (SBH)
Biomethane	Institute of Fluid-Flow Machinery Polish Academy of Sciences (IMP PAN)
Potential Energy	Institute of Fluid-Flow Machinery Polish Academy of Sciences (IMP PAN)

ZEBAU - Centre for Energy, Construction, Architecture, and the Environment Ltd. was responsible for the overarching aspects of environmental and political criteria and social acceptance.

In the PESTLE analyses for political, legal, social, and environmental factors country-context analysis were made for all five different energy accumulation alternatives. In total six countries were analysed in PESTLE analysis:

COUNTRY	AUTHORS
Sweden	Sustainable Business Hub Scandinavia AB (SBH)
Finland	Thermopolis Ltd
Latvia	Riga Technical University (RTU)
Lithuania	Lithuanian Energy Institute (LEI)
Poland	Institute of Fluid-Flow Machinery Polish Academy of Sciences (IMP PAN)
Germany	Zentrum für Energie, Bauen, Architektur und Umwelt (ZEBAU)

PESTLE analyses are very comprehensive and are therefore included as an annex to this report.

3.1 Battery storage technologies

Table 27: Advantages and disadvantages of Li-ion, Na-S and Vanadium redox flow batteries

Technology	Advantages	Disadvantages
Li-ion	Relatively high energy density, no requirement for a scheduled cycle to maintain battery life, commercially available in many sizes	Tendency to overheat and even combust, can be damaged by high voltage, aging, Challenges related to availability and mining of lithium, cannot store energy for several months
Na-S	Unexpensive and abundant raw materials, suitable for energy intense applications, commercially available (limited availability)	High temperature (300-350C), limited amount of freeze –thaw cycle (~20), not suitable for idle storage
Vanadium redox flow batteries (VRB)	Flexible installation size, Storage capacity and power capacity can be varied independently, use of full battery capacity without degradation, possibly unlimited cycle lifetime (up to 20 years)	High initial investment (Relatively high and volatile price of vanadium), low grid-to-grid efficiency

Table 28: Summary of PESTLE results for Li-ion, Na-S and Vanadium redox flow batteries

Political	Circular battery economy, material recovery, e-mobility, some countries offer financial support for energy storage including batteries
Economic	Raw material costs often high, expected for prices of applications to come down, operation and maintenance cost vary
Technical	RES integration, peak shaving, emergency back-up, time shifting, black starting, good power quality, many types available commercially
Social	Usually well accepted, concerns related to raw material mining etc.
Environmental	Impact of materials used both in manufacturing and in recycling
Legal	EU level: Recycling rates for batteries and their materials, digital battery passport (usage history)

The acceptance of battery storage has increased significantly in recent years as it is seen as an efficient and environmentally friendly solution for energy storage:

- Environmental friendliness: Battery storage is a clean alternative to conventional energy storage such as diesel generators. They use rechargeable batteries to store excess energy and release it when needed. As a result, they reduce the need for fossil fuels and help reduce greenhouse gas emissions.

- Grid utility: Battery storage can help stabilize the power grid and reduce the need for grid expansion. They can store excess energy from renewable sources when it's available and release it on demand when demand is high. This helps to reduce the use of conventional power plants and use the electricity grid more efficiently.
- Cost reduction: The cost of battery storage has fallen sharply in recent years, which has further increased its acceptance. Thanks to technological advances, economies of scale and improved production technology, battery storage has become more affordable. This has led to wider availability and use.
- Independence: Battery storage enables households and companies to become less dependent on external energy sources. With battery storage, they can store excess energy and use it when needed, which is particularly beneficial in regions with unreliable power supplies or high electricity costs.
- Funding Policies: Many governments and energy companies have introduced programs and incentives to encourage battery storage. Subsidies, tax breaks, and other financial incentives have helped increase battery storage adoption and deployment.

Despite these positive developments, however, there are still challenges for the widespread acceptance of battery storage:

- Energy Density and Capacity: Batteries have limited energy density and capacity, which means they can only store a certain amount of energy. This can limit the possible uses of battery storage, especially when it comes to storing large amounts of energy or long-term storage. There is a need for batteries with higher energy density and capacity.
- Life and performance: Batteries wear out over time and lose capacity. Battery life is limited and depends on factors such as charge and discharge cycles and ambient temperatures. To ensure the economic viability of battery storage, it is important to develop batteries with a long service life and high performance.
- Sustainability and environmental impact: Batteries often contain materials such as lithium, cobalt and nickel that must be degraded. Mining and extracting these materials can have environmental impacts such as landscape degradation and water pollution. It is important to develop sustainable methods for the extraction and disposal of battery materials.
- Grid integration: The integration of battery storage into the power grid is a technical challenge. Battery storage must be seamlessly integrated into the existing grid to ensure a reliable and stable power supply. This requires advanced control systems and communication technologies to run the batteries efficiently and maintain grid stability.
- Scalability: While battery storage is already deployed on a small scale, scaling it to larger systems is a challenge. The integration of large battery systems into the power grid requires extensive planning and coordination to overcome the challenges in terms of capacity, siting, grid connection and infrastructure.

Nevertheless, the general tendency towards acceptance of battery storage is very positive, as they play an important role in the transition to renewable energy and a sustainable energy supply.

3.2 Thermal energy storage technologies

Table 29: Advantages and disadvantages of thermal energy storage technologies

Technology	Advantages	Disadvantages
Water-based	High heat capacity, low cost, easily available, scalable	Temperatures higher than 100° C require pressurization to prevent boiling
Sand based	Low-cost material, easily available, high melting point (1.700° C), high temperature range (600-1.200° C), seasonal storage possible	only a few commercial applications, low heat capacity
Molten salt	Temperature range (e.g., 62-560° C)	To keep salt mixture molten "cold" side must have a high enough temperature, corrosion
Phase-change materials	Temperature range depends on used material	Some materials have a high cost, cycle limitations possible
Thermo-Chemical	Negligible heat loss, high energy density temperature range depends on chemicals used, compact	Few commercial applications, high costs, technically complex

Table 30: Summary of PESTLE results for thermal energy storage technologies

Political	Waste heat, solar energy, and district heating related policies. Some countries offer subsidies for thermal heat storages
Economic	The initial investment and operational costs vary significantly between the different types of thermal energy storages, often having a use for energy in thermal form is beneficial
Technical	There are many commercially available technologies and some still on their way to be commercialized
Social	Consumers expect any investment should reduce energy costs eventually
Environmental	The impact on the environment depends heavily on the chosen technology and the scale of the implementation
Legal	Thermal storage follows national legislation in terms of environmental impact, health, and safety issues. Innovative technologies bring new challenges

The acceptance of power-to-heat and thermal energy storage systems depends on various factors:

- Energy efficiency: Power-to-heat systems can help to use excess electrical energy that would otherwise be wasted. This can improve the energy efficiency of the overall system and promote the use of renewable energy. Therefore, the acceptance of power-to-heat is generally assessed positively.
- Costs: The profitability of power-to-heat systems plays a significant role in acceptance. If the cost of building and running such systems is high compared to other heat generation or storage technologies, this could hamper uptake. However, state subsidies or incentive programs can reduce the cost burden and increase acceptance.
- Flexibility: Power-to-heat systems can help make the power grid more flexible by balancing out fluctuating power generation from renewable energies. By converting excess electricity into heat, the demand for electrical energy can be reduced when the power grid is overloaded. The acceptance of power-to-heat therefore also depends on the willingness of the energy supply companies to integrate flexible loads and to make the necessary adjustments in the power grid.
- Environmental Impact: Power-to-heat systems can help reduce greenhouse gas emissions, especially when the electricity used comes from renewable energy sources. This can increase adoption as power-to-heat is seen as a green option to use excess renewable energy.
- Regulatory framework: Creating a favourable regulatory framework can influence the acceptance of power-to-heat. Clear and stable legislation and incentive mechanisms can promote investments in such systems and thus increase acceptance.

However, there are some challenges to be aware of:

- Heat losses: When storing thermal energy, there are always some losses due to heat transfer and thermal radiation. The longer the heat must be kept in storage, the greater these losses. It is important to use materials with low thermal conductivity and good insulation to minimize heat loss.
- Storage capacity: The storage capacity of heat storage tanks is limited. Creating storage facilities large enough to store large amounts of thermal energy over long periods of time can be a challenge. This is particularly problematic when the thermal energy is to be stored over several days or weeks, for example for seasonal energy storage.
- Storage media: Choosing the right storage medium is crucial for the efficiency and reliability of the thermal storage device. Different materials have different heat capacities and specific properties that can affect storage performance. In addition, the storage media often must be inexpensive and environmentally friendly.
- Cycle Stability: Heat accumulators are typically used in a cyclic operation where the thermal energy is stored and released again. This cycle can negatively impact memory life and performance. The materials and components of the memory must therefore be cycle-stable to ensure long-term and reliable functioning.
- Integration into energy systems: The integration of thermal storage systems into existing energy systems can pose another challenge. It requires appropriate control and regulation to match the storage and release of thermal energy to the needs of the system. In addition, the

storage tanks must harmonize with the other components of the energy system, such as heat generators and heat consumers.

3.3 Hydrogen storage technologies

Table 31: Advantages and disadvantages of hydrogen storage technologies

Technology	Advantages	Disadvantages
Hydrogen in pressure containers	Commercially available, combined with a fuel cell makes for quick electricity production	Small or medium scale storage, short to medium term storage, high pressure requirements to containers, hydrogen embrittlement of the container, hydrogen permeation, whole system efficiency 40-45 %
Liquid organic hydrogen carrier	Stored in liquid form in ambient temperature and atmospheric pressure, easy to transport, no storage losses, ideal for large scale hydrogen storage	Prototypes on market, hydrogen liberation is energy consuming, possibly toxic

Table 32: Summary of PESTLE results for hydrogen storage technologies

Political	Hydrogen is expected to play a significant role in the green transition, national hydrogen strategies are under way in some countries. Some countries have subsidies for hydrogen related investments
Economic	Electricity price has significant impact, economical aspect under consideration
Technical	Relatively new applications of technology. Electricity production, quick response to seasonal storage, peak shaving, RES integration, black start
Social	Liquid organic hydrogen carrier (LOCH) can use the same infrastructure as petrol and diesel. Wind farm related opposition might affect hydrogen
Environmental	Large leakages could speed up the destruction of the ozone layer, LOCH related flammability, toxicity etc. Low toxicity LOCH are researched
Legal	For now, hydrogen follows similar safety and health legislation as natural gas

The acceptance of hydrogen as an energy source has increased in recent years and is the subject of intense debate around the world. There are several reasons why hydrogen is considered a promising option:

- Environmental friendliness: Hydrogen can be produced and burned without harmful emissions. When hydrogen burns, only water vapor is produced, meaning it produces no greenhouse gases or air pollution. When produced with renewable energy sources, hydrogen can make an important contribution to the decarbonization of the energy system.
- Versatile applications: Hydrogen can be used in various areas, such as in the transport sector,

for power generation, in industry and in the home. It can be used as a fuel for vehicles, used to store renewable energy, and as a raw material for the chemical industry.

- Energy storage: Hydrogen can serve as energy storage, especially for renewable energy sources such as solar and wind power. Excess energy can be used to convert water into hydrogen, which can then be converted back into energy when needed.

Despite these advantages, however, there are also challenges in the acceptance of hydrogen:

- Infrastructure: The existing infrastructure for hydrogen is limited and needs to be further developed, especially regarding hydrogen filling stations, pipelines, and storage facilities. Building a comprehensive infrastructure requires significant investment and time.
- Cost: The production of hydrogen is currently still relatively expensive, especially if it is obtained from renewable energy sources. Costs need to be further reduced to make hydrogen more competitive.
- Safety: Hydrogen is a highly flammable gas, which raises safety concerns. Strict safety standards and regulations must be followed to ensure safe handling and use.

Despite these challenges, hydrogen is seen as an important part of the future energy mix and its uptake is expected to continue to grow as technology improves and infrastructure expands.

3.4 Biomethane storage technologies

Table 33: Advantages and disadvantages of biomethane storage technologies

Technology	Advantages	Disadvantages
Upgrading from biogas	Biogas production is well established, which gives opportunities for biomethane	The uptake of biogas has been relatively slow, upgrading biogas requires investments
Methanation of hydrogen	One form of utilizing hydrogen	Hydrogen production is an upcoming technology
Low pressure	Lowest costs, on-site application	Short term storage
High pressure	Longer storage periods, smaller space requirements, transportation possible	Higher costs and more safety regulations, requirements on gas purity
Cryogenic (Low temperature)	Smaller space requirements, transportation possibility	Transportation requires large enough volumes
Absorbed	Smaller space requirement, can be stored at ambient temperature and atmospheric pressure	Materials being researched

For production two possible routes were included, biomethane production via digestion from biomass and upgraded from biogas (the focus) and methanation of the hydrogen.

Table 34: Summary of PESTLE results for biomethane storage technologies

Political	Biogas and upgrading it to biomethane has a differing position between countries
Economic	Local job creation in the biomethane production chain, initial investment is often relatively high
Technical	Biogas production well established technology, biomass collection, Power-to-power total efficiency with hydrogen methanation may become low
Social	Local community engagement possibilities
Environmental	Possible methane leakages and the effect on climate change, Waste management
Legal	Biogas is often governed by national regulation for natural gas in relation to safety

The acceptability of hydrogen methanation varies depending on the context and the stakeholders involved. Here are some important aspects to consider:

- Climate change and renewable energies: Methanation of hydrogen can help to store renewable hydrogen and use it as an energy carrier. Since methane is a stable gas and existing infrastructure can be used for natural gas, methanation could be a way to better utilize and integrate renewable energy sources such as wind and solar power. In this context, methanation is often discussed as a possible solution to decarbonize the energy system.
- Efficiency and losses: However, there are losses in the methanation of hydrogen because the process requires energy. The efficiency of methanation is therefore an important factor in assessing acceptability. If the hydrogen comes from renewable sources and excess energy is used, then methanation can be considered a viable option. However, potential energy losses and the overall energy balance of the process should be considered.
- Infrastructure and Market Development: Methanation requires existing infrastructures to distribute and use methane, which is already the case in some regions. If methanation is viewed as part of a broader concept for a hydrogen economy, it could increase uptake as already established gas infrastructure can be used.
- Technology Development and Cost: Methanation technology is still in the development phase and cost plays a significant role in acceptance. Reducing the cost of hydrogen methanation, especially when compared to alternative hydrogen storage options, could increase uptake.
- Environmental Impact: The methanation of hydrogen produces methane, a potential greenhouse gas. The control and management of methane emissions is therefore of great importance to minimize the environmental impact and to ensure that methanation actually contributes to a reduction in greenhouse gas emissions. However, the biomethanation is viable option to remove CO_2 from biogas.

The methanation of hydrogen as power-to-gas can represent an element for the storage and use of excess electricity but must be integrated into other measures such as the use of waste heat from the methanation process, other uses of electricity such as power-to-heat and power-to-liquid and better use of excess electricity by building a European Supergrid.

3.5 Potential energy storage technologies

Table 35: Advantages and disadvantages of potential energy storage technologies

Technology	Advantages	Disadvantages
Pumped hydro	Pumped hydro energy storage can provide municipalities with opportunities for energy cost management. By storing electricity during off-peak hours when electricity prices are low and releasing it during peak hours when prices are high, municipalities can optimize their energy consumption and reduce their electricity costs.	Pumped hydro is not included in the calculation of RES produced (RES directive), Integration of intermittent renewable energy sources with pumped hydropower storage* (HYDROPOWER AND PUMPED HYDROPOWER STORAGE IN THE EUROPEAN UNION-2022)

Table 36: Summary of PESTLE result for potential energy storage technologies

Political	Not in favour politically, typically no subsidies offered in Baltic Sea/ EU countries
Economic	The initial investment cost high, but operational costs low. Difficulties in finding building sites, low amount of production and potential. Relatively good energy efficiency
Technical	Easily scalable, mature technology base, provide grid stability and reliability
Social	Acceptance of pumped storage plants is a complex matter due to impacts on environment, landscape, and local community
Environmental	Changes to water bodies, ecosystems, and local habitats. Impacts may include changes to water levels, water quality and biodiversity. Concerns of migration disturbance of living organisms in certain areas and the creation of additional erosion.
Legal	Difficulties with legal procedures. Planning and approval because of environmental, water laws etc.

The acceptance of pumped storage plants varies depending on the region and the associated local impact. In general, there are several factors that can influence the acceptance of pumped storage plants:

- Energy Demands and Energy Security: In regions with high energy demands and concerns about energy security, pumped storage plants are often considered an important infrastructure to meet energy demands and stabilize supplies.
- Environmental impacts: Pumped storage plants have an impact on the environment, especially in relation to the water balance and the landscape. The construction of dams and reservoirs can lead to changes in ecosystems and affect natural flow patterns. This can raise concerns about habitat loss, disruption to fish migration, and other environmental impacts.

- Landscape and tourism: pumped storage plants are often large structures that must be integrated into the landscape. In regions that rely heavily on tourism or where natural beauty plays an important role, concerns about the landscape and visitor attractiveness may arise.
- Local community and impact: The direct impact on the local community affected by a pumped storage plant also plays a role. This includes issues of land expropriation, community resettlement and the impact on local economies. Acceptance is highly dependent on the type of consultation, community involvement and possible compensatory measures.
- Renewable energies and climate protection: Pumped storage plants are considered an important part of the energy system to integrate renewable energy sources such as wind and solar energy and to increase the flexibility of the electricity grid. In regions where the expansion of renewable energies and climate protection have a high priority, pumped storage plants are often rated positively.

3.6 General results and summary on energy storage policies

The use of renewable energies has increased in all 27 countries of the European Union (EU) in recent years. On average in the EU, the share of renewable energies in **gross final energy consumption** increased from 13.9% to 21.8% between 2009 and 2021.

As reported on the occasion of the European Statistics Day the pioneers of the energy transition can be found in Northern Europe. In 2021, Sweden already covered 62.6% of its gross final energy consumption from renewable energies, which was the highest value in the EU. In addition to Sweden, Finland also recorded high shares of renewable energies in gross final energy consumption in 2021 with 43.1%, Latvia with 42.1% and Denmark with 34.7%. In Germany, according to data from the European statistical authority Eurostat, the proportion increased from 10.9% to 19.2% between 2009 and 2019.

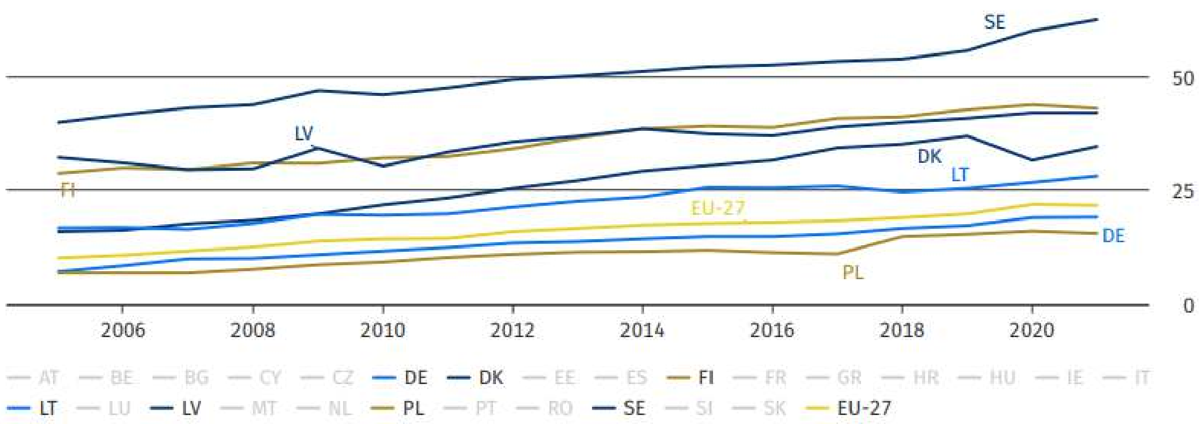


Figure 4: share of renewable energies in gross final energy consumption

On 30 March 2023, the European Council and the European Parliament negotiators reached a provisional political agreement to raise the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030 with an additional 2.5% indicative top up that would allow to reach 45%.

Between 2005 and 2020, the share of **renewable sources in electricity** consumed in the EU-27 grew from 16% to 37%, which corresponds to an average increase of 1.4 percentage points per year. It must be noted, however, that the increase in the share between 2019 and 2020 mainly resulted from an overall, pandemic-related reduction in total electricity production. In 2021, the renewable share of electricity is estimated to have been 38%.

By 2030, the EU Commission wants to quadruple the installed photovoltaic capacity across the EU to a total of 600 gigawatts. In 2021, the electricity generation capacity from photovoltaics in the EU was 162 gigawatts.

Denmark is the EU leader in terms of electricity generation from renewable sources. In 2022, the share of renewable energy in total Danish net electricity generation was around 75.9 %t.

The national objective in Sweden is 100 % renewable electricity production to 2040.

To achieve the climate protection goals and become independent of fossil energy imports, the share of renewable energies in gross electricity consumption in Germany should increase to at least 80 % by 2030 and to 100 % by 2035. In 2022 it was 46.2 %.

The Swedish Energy Agency has developed a draft **hydrogen** strategy. The objectives within in the strategy are 5 GW electrolyser capacity to 2030 and 10 GW to 2045 (ER 2021:34).

Currently, there is no specific national-level policy for hydrogen in Latvia. However, the Latvian National Energy and Climate Plan 2021-2030 (NECP) outlines several directions of action aimed at accelerating the development and deployment of hydrogen.

The Finish government adopted a resolution on hydrogen (9 Feb. 2023). The resolution describes Finland's objectives regarding hydrogen and the measures to promote them. Finland's goal is to become the European leader in the hydrogen economy in the entire value chain.

In June 2020, the German federal government decided on the national hydrogen strategy ("Nationale Wasserstoffstrategie") which is currently being updated. The strategy pursues the following goals in particular: Establish hydrogen technologies as core elements of the energy transition in order to decarbonize production processes with the help of renewable energies; to create the regulatory conditions for the market ramp-up of hydrogen technologies; strengthen German companies and their competitiveness by promoting research and development and technology export around innovative hydrogen technologies; secure and shape the future national supply of CO2-free hydrogen and its derivatives.

Hydrogen technology is very new in Lithuania. The ongoing activities after the establishment of the Hydrogen Platform are promotion, design stages, preparation of infrastructure and initiation of pilot projects.

The new EU regulation aims to promote **a circular battery** economy. By reforming the battery regulation, the Commission aims to respond to the legislative pressure that the electrification of transport will create in the coming years. For example, according to the World Economic Forum, battery production will need to increase 19-fold in the coming years. Meeting climate targets will require increased use of batteries in several sectors, including transport, renewable energy, and digitalisation.

The Finnish government's vision is that the green transition will create new technologies that will accelerate the transition away from fossil energy. Main idea of the policy is to reduce emissions and at the same time provide possible opportunities for new export businesses for Finnish operators.

Latvia has not established specific goals for the installation of electricity storage capacity by 2030. However, the National Energy and Climate Plan prioritizes the development of innovative renewable energy technologies, including energy storage, integration, and smart transmission.

Sweden does not have specific objectives for using batteries for storage of electricity. However, batteries are pinpointed by the Swedish Energy Agency as an important part of net zero emission energy system to 2045.

In Germany battery storage is seen as an important component of a storage strategy as power storage (seconds to minutes) and as displacement storage (minutes to hours), among other things because they have a high overall efficiency.

In Poland currently is no specific national-level policy concerning batteries.

On the EU level **thermal energy storage** is seen as an important aspect of the reaching climate targets in district heating & cooling and building sectors.

Infrastructure development for district heating and cooling networks should be stepped up and steered towards harnessing a wider range of renewable heat and cold sources in an efficient and flexible way in order to increase the deployment of renewable energy and deepen energy system integration.

3.7 Importance of the different factors in PESTLE analysis

In the PESTEL analysis, the importance of the different factors for each of the five selected energy storage technologies has been assessed using five different possible weights. The weightings are high, medium-high, medium, low-medium, and low.

Table 37: Importance of different factors in the PESTLE analysis for each energy storage technologies

	Factors	Batteries	Thermal Storage	Hydrogen	Biomethane	Potential Energy
POLITICAL	EU level policy	High	High	Medium	Medium-high	Medium-high
	National government policy	High	High	Medium	Medium-high	High
	Political stability	Medium	Low	Medium	High	Medium-high
	Existing political support mechanisms	High	Medium-High	Medium-high	Medium-high	Low
	Tax	Medium	Medium	Medium	Medium-high	Low-medium
	Municipal level policy	Low-medium	Medium	High	High	Low-medium
ECONOMIC	Payback time	High	High	Low-medium	High	N/A
	Energy price	High	High	Medium-high	Medium-high	High
	Energy market	Medium-High	High	Medium-high	Medium-high	High
	Opportunities for capital access to finance investments	Medium	High	Medium-high	Medium-high	High
	Funding gaps	High	High	High	Medium-high	N/A
	Initial investment	High	High	Medium-high	Medium-high	High
	Production cost	High	High	Medium-high	Medium-high	Low-medium
SOCIAL	Public acceptance	High	Low	Medium-high	Medium	Medium
	Employment opportunities	Medium	Low	Medium-high	Medium	Medium
	Adaptability of the society to innovations and new techn	Medium	Medium-High	Medium-high	Medium	Medium-high
TECHNOLOGY	Requires a large source of electricity	Medium	(High/Low)	Medium-high	Medium-high	Medium-high
	Integration to the existing grid	Medium	Low	Medium-high	High	Low
	Technical applications	Medium	High	High	Medium	Low-medium
LEGAL	Level of complexity to get necessary permits	Medium-High	Medium	Medium-high	High	High
	Time of approval for energy development project	Medium-High	Medium	Medium-high	High	High
	Land use planning	Low-medium	Medium	Low-medium	High	High
ENVIRONMENTAL	Risk of environmental damage	High	Low	Medium-high	Medium	Medium
	Risk of indirect environmental damage	High	Low	Medium-high	Medium	Medium
	Life cycle	Low-medium	Low	Low-medium	Low-medium	Low
	Risk of no reduction in carbon foot print	Low-medium	Low	Low	Low	Low

The political and economic impacts are more pronounced for battery and thermal storage. These two storage technologies are relatively mature and sophisticated and are available in several power classes. The question of their economic viability is therefore very much at stake, and it is the political support and the cost of energy and investment that is highlighted.

In contrast, the exploitation of hydrogen, biomethane and potential energy entails more regulatory requirements and licensing. For hydrogen and biomethane, technological development is still partly at an early stage. In the case of thermal storage, both the environmental impact is seen as positive and there is widespread social acceptance.

Potential energy sources are mainly early-stage technologies, particularly the potential energy of water. The potential for their construction is limited, as neither land-use planning, legislation nor policy favours their construction. However, the advantage would be that the post-construction generation costs are very low and integration into the electricity grid is easy.

4 Annex

4.1 List of sources

[1] Danish Energy Agency, "Technology Data for Energy Storage," *Energistyrelsen*, Oct. 17, 2018. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-energy-storage (accessed Mar. 30, 2023).
[2] R. Christensen, "Na-S battery. In Technology Data for Energy storage: November 2018 (pp. 129-146). [182] Danish Energy Agency." 2018. [Online]. Available: https://backend.orbit.dtu.dk/ws/portalfiles/portal/163012494/Pages_NA_S_BATTERY.pdf
[3] Sumitomo Electric, "Sumitomo Electric." https://sumitomoelectric.com/
[4] R. Christensen, "Vanadium Redox Flow Battery. In Technology Data for Energy storage: November 2018 (pp. 113-146). [181]. Danish Energy Agency." 2018. [Online]. Available: https://backend.orbit.dtu.dk/ws/portalfiles/portal/163012270/Pages_VANADIUM_REDOX_FLOW_BATTERY.pdf
[5] GSC tanks, "7 Types of Industrial Storage Tanks Explained.," 2018. https://www.gsctanks.com/industrial-storage-tanks/
[6] L. F. Cabeza, "Advances in thermal energy storage systems: methods and applications," in *Advances in Thermal Energy Storage Systems*, Elsevier, 2021, pp. 37–54. doi: 10.1016/B978-0-12-819885-8.00002-4.
[7] IEA-ETSAP and IRENA, "Thermal Energy Storage. Technology Brief." 2013. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/IRENA-ETSAP-Tech-Brief-E17-Thermal-Energy-Storage.pdf
[8] Celsius project, "Thermal Energy Storage," 2020. https://celsiuscity.eu/thermal-energy-storage/ (accessed Feb. 28, 2023).
[9] IRENA, "Innovation outlook: Thermal energy storage," 2020. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf
[10] vsiluma.lt, "Atidaryta Matuizų katilinė. UAB „Varėnos šiluma." https://vsiluma.lt/2017/11/08/antros-naujienos-antraste-antros-naujienos-antraste-antros-naujienos-antraste-antros-naujienos-antraste/
[11] Heliostorage, "Borehole Thermal Energy Storage," Mar. 03, 2023. https://heliostorage.com/borehole-thermal-energy-storage/
[12] helen.fi, "Mustikkamaan jättimäiset lämpöluolat ovat nyt täynnä vettä," 2021. https://www.helen.fi/uutiset/2021/ilmastoteko-jalkojemme-alla-mustikkamaan-j%C3%A4ttim%C3%A4iset-l%C3%A4mp%C3%B6luolat-ovat-nyt-t%C3%A4ynn%C3%A4-vett%C3%A4 (accessed Mar. 04, 2023).
[13] EPV, "Storing heat and power." Accessed: Apr. 04, 2023. [Online]. Available: https://www.epv.fi/en/project/storing-heat-and-power/
[14] Sitra, "Solar district heating, Marstal," 2019. https://www.sitra.fi/en/cases/solar-district-heating-marstal/ (accessed Apr. 04, 2023).
[15] R-ACES, "Marstal-District-Heating." 2015. [Online]. Available: https://r-aces.eu/wp-content/uploads/2021/05/Marstal-District-Heating-%E2%80%93-R-Aces.pdf
[16] Kauno Technologijos Universitetas, "Išmanaus tinklo kompetencijų centras mokslinių tyrimų, inovacijų ir švietimo gebėjimų stiprinimui energetikos transformacijai (SMAGRINET)." https://ktu.edu/projects/ismanaus-tinklo-kompetenciju-centras-mokslinių-tyrimu-inovaciju-ir-svietimo-gebejimu-stiprinimui-energetikos-transformacijai-smagrinet/
[17] Veolia, "Akumulator Ciepła w Poznaniu," 2021. https://www.veolia.pl/media/aktualnosci/akumulator-ciepla-w-poznaniu (accessed Apr. 04, 2023).

[18] Energetykacieplna, "Bezpieczniej z akumulatorem ciepła," 2009. https://www.energetykacieplna.pl/artykuly/bezpieczniej-z-akumulatorem-ciepla-37136-6#_ (accessed Mar. 04, 2023).
[19] Rondo, "Rondo Energy." https://rondo.com/ (accessed Apr. 04, 2023).
[20] swiatoze.pl, "Ceglany magazyn energii i ciepła może zastąpić inne skomplikowane technologie," 2022. https://swiatoze.pl/ceglany-magazyn-energii-i-ciepla-moze-zastapic-inne-skomplikowane-technologie/ (accessed Apr. 04, 2023).
[21] M. Reszuta, "Rewelacyjny wynalazek polskich naukowców – trzykrotne wydłużenie żywotności akumulatora do elektryków," 2022. https://top-oze.pl/rewelacyjny-wynalazek-polskich-naukowcow-trzykrotne-wydluzenie-zywotnosci-akumulatora-do-elektrykow/ (accessed Apr. 04, 2023).
[22] CleanTechnica, "Hot Sand To Store Energy. Energy Storage in Sand Offers Low-Cost Pathway for Reliable Electricity and Heat Supply in Renewable Energy Era.," 2021. https://cleantechnica.com/2021/08/31/using-hot-sand-to-store-energy/ (accessed Mar. 02, 2023).
[23] E. Bellini, "Long-duration thermal storage system based on silica sand," 2021. https://www.pv-magazine.com/2021/11/05/long-duration-thermal-storage-system-based-on-silica-sand/ (accessed Mar. 02, 2023).
[24] Polar Night Energy, "The First Commercial Sand-based Thermal Energy Storage in the World Is in Operation," 2022. https://polarnightenergy.fi/news/2022/7/5/the-first-commercial-sand-based-thermal-energy-storage-in-the-world-is-in-operation-bbc-news-visited-polar-night-energy (accessed Mar. 02, 2023).
[25] Polar Night Energy, "Store Wind and Solar Power as Heat in Sand." https://polarnightenergy.fi/technology (accessed Mar. 02, 2023).
[26] D. J. Cross, "New Thermal Energy Storage Methods Using Hot Sand," 2021. https://www.azocleantech.com/news.aspx?newsID=30291 (accessed Mar. 02, 2023).
[27] Magaldi, "Thermal Energy Storage." https://www.magaldigreenenergy.com/en/thermal-energy-storage (accessed Apr. 04, 2023).
[28] BYinnovation, "Sand thermal energy storage," 2022. https://byinnovation.eu/sand-thermal-energy-storage/ (accessed Apr. 03, 2023).
[29] J. Dodaro, "Molten Salt Storage." 2015. Accessed: Sep. 03, 2023. [Online]. Available: http://large.stanford.edu/courses/2015/ph240/dodaro2/
[30] M. Green *et al.*, "Nuclear Hybrid Energy System: Molten Salt Energy Storage," 2013. Accessed: Sep. 03, 2023. [Online]. Available: http://large.stanford.edu/courses/2015/ph240/dodaro2/docs/6339782.pdf
[31] Z. Yang and S. V. Garimella, "Cyclic operation of molten-salt thermal energy storage in thermoclines for solar power plants," *Applied Energy*, vol. 103, pp. 256–265, Mar. 2013, doi: 10.1016/j.apenergy.2012.09.043.
[32] European Commission, Directorate General for Energy., and Enerdata., "Study on energy storage: contribution to the security of the electricity supply in Europe.," Publications Office, 2020. Accessed: Jul. 27, 2023. [Online]. Available: https://data.europa.eu/doi/10.2833/077257
[33] Bioenergy International, "Vattenfall and SaltX launch novel power-to-heat storage project in Berlin," 2019. https://bioenergyinternational.com/vattenfall-launches-heat-storage-pilot-project-in-berlin/ (accessed May 05, 2023).
[34] US Kings, "WORLDKINGS – Worldkings News – Europe Records Institute (EURI) – Archimede: World's first concentrating solar power plant to use molten salts for heat transfer and storage," 2020. https://uskings.us/worldkings-worldkings-news-europe-records-institute-euri-archimede-world-s-first-concentrating-solar-power-plant-to-use-molten-salts-for-heat-transfer-and-storage/ (accessed May 04, 2023).
[35] Alchetron, "Archimede solar power plant," 2022. https://alchetron.com/Archimede-solar-power-plant (accessed May 05, 2023).
[36] NREL, "Archimede CSP Project." https://solarpaces.nrel.gov/project/archimede (accessed May 05, 2023).
[37] Gadzetomania, "Zapomnij o gazie. Akumulator ciepła może uwolnić od niego domy," 2022.

https://gadzetomania.pl/zapomnij-o-gazie-akumulator-ciepla-moze-uwolnic-od-niego-domy,6763462471142208a (accessed May 04, 2023).
[38] Y. Tian and C. Y. Zhao, "A review of solar collectors and thermal energy storage in solar thermal applications," *Applied Energy*, vol. 104, pp. 538–553, Apr. 2013, doi: 10.1016/j.apenergy.2012.11.051.
[39] A. M. Hayder, A. B. Sapit, and Q. A. Abed, "REVIEW OF SOLAR THERMAL STORAGE TECHNIQUES," vol. 12, no. 21, 2017.
[40] Axiotherm, "Energy storage solutions for water-based applications: HeatStixx® Retrofit System." https://www.axiotherm.de/en/produkte/heatstixx%C2%AE/ (accessed May 05, 2023).
[41] Wernersobek, "Futurium." https://www.wernersobek.com/projects/futurium/ (accessed May 05, 2023).
[42] J. KARWACKI, R. KWIDZINSKI, and P. LEPUTA, "Performance analysis and PCM selection for adsorption chiller aided by energy storage supplied from the district heating system," *Archives of Thermodynamics*, Jul. 2023, doi: 10.24425/ather.2022.144409.
[43] N. Connor, "What is Thermo-chemical Storage – Definition," 2019. https://www.thermal-engineering.org/what-is-thermo-chemical-storage-definition/?utm_content=cmp-true (accessed Jul. 03, 2023).
[44] T. Yan, T. X. Li, and R. Z. Wang, "Thermochemical heat storage for solar heating and cooling systems," in *Advances in Solar Heating and Cooling*, Elsevier, 2016, pp. 491–522. doi: 10.1016/B978-0-08-100301-5.00018-7.
[45] pv magazine, "Wärtsilä completes its first European energy storage project," 2018. https://www.pv-magazine.com/2018/08/23/wartsila-completes-its-first-european-energy-storage-project/ (accessed May 05, 2023).
[46] Mostostal Warszawa, "Projekt MERITS - pierwsza bateria termochemiczna na świecie." https://www.mostostal.waw.pl/media/filmy/badania-i-rozwoj/projekt-merits-pierwsza-bateria-termochemiczna-na- (accessed May 05, 2023).
[47] Top-Oze, "Archiwa magazyny energii." https://top-oze.pl/tag/magazyny-energii/ (accessed May 05, 2023).
[48] Energydome, "Energy Dome. Groundbreaking Long Duration Energy Storage." https://energydome.com/ (accessed Apr. 04, 2023).
[49] Renewable energy magazine, "First Commercial Sand-based Thermal Energy Storage Is in Operation," 2022. https://www.renewableenergymagazine.com/storage/first-commercial-sandbased-thermal-energy-storage-is-20220707 (accessed Feb. 03, 2023).
[50] Z. He, X. Wang, X. Du, C. Xu, and L. Yang, "Cyclic characteristics of water thermocline storage tank with encapsulated PCM packed bed," *International Journal of Heat and Mass Transfer*, vol. 139, pp. 1077–1086, Aug. 2019, doi: 10.1016/j.ijheatmasstransfer.2019.05.093.
[51] Y. Hu, P. K. Heiselberg, C. Drivsholm, A. S. Søvsø, P. J. C. Vogler-Finck, and K. Kronby, "Experimental and numerical study of PCM storage integrated with HVAC system for energy flexibility," *Energy and Buildings*, vol. 255, p. 111651, Jan. 2022, doi: 10.1016/j.enbuild.2021.111651.
[52] Oxera, "High time for hydrogen: establishing a hydrogen value chain in Europe (part 1)," 2021. https://www.oxera.com/insights/agenda/articles/high-time-for-hydrogen-establishing-a-hydrogen-value-chain-in-europe/ (accessed Jan. 05, 2023).
[53] SES Hydrogen, "Hydrogen and steam generation," Jan. 05, 2023. https://seshydrogen.com/en/hydrogen-boiler-house/
[54] Gramwzielone.pl, "Mieszkania w Wielkopolsce ogrzewane wodorem," 2022. https://www.gramwzielone.pl/wodor/109405/mieszkania-w-wielkopolsce-ogrzewane-wodorem (accessed Jan. 04, 2023).
[55] Metropoloa Bydgoska, "Wodorowa lokomotywa PESY jako pierwsza na świecie została dopuszczona do eksploatacji," 2023. https://metropoliabydgoska.pl/lokomotywa-wodorowa-pesa/ (accessed Oct. 06, 2023).
[56] Gicon, "Gicon group." https://www.gicon.de/en (accessed May 05, 2023).
[57] L. Tock, M. Gassner, and F. Maréchal, "Thermochemical production of liquid fuels from biomass: Thermo-economic modeling, process design and process integration analysis," *Biomass*

and Bioenergy, vol. 34, no. 12, pp. 1838–1854, Dec. 2010, doi: 10.1016/j.biombioe.2010.07.018.
[58] A. Larsson, I. Gunnarsson, and F. Tengberg, "The GoBiGas Project Demonstration of the Production of Biomethane from Biomass via Gasification," 2018, doi: 10.13140/RG.2.2.27352.55043.
[59] H. Thunman and M. Seemann, "The GoBiGas plant," in *Substitute Natural Gas from Waste*, Elsevier, 2019, pp. 455–474. doi: 10.1016/B978-0-12-815554-7.00017-9.
[60] Adnan, Ong, Nomanbhay, Chew, and Show, "Technologies for Biogas Upgrading to Biomethane: A Review," *Bioengineering*, vol. 6, no. 4, p. 92, Oct. 2019, doi: 10.3390/bioengineering6040092.
[61] M. Aresta, Ed., "Carbon Dioxide as Chemical Feedstock," in *Carbon Dioxide as Chemical Feedstock*, Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2010, pp. i–xix. doi: 10.1002/9783527629916.fmatter.
[62] M. Burkhardt, "Biochemie und Technologie der Biomethanisierung – Prozesslimitierungen und Verfahrensentwicklungen, Habilitationsschrift, BTU, Cottbus." 2017.
[63] M. Burkhardt, M. Tietze, F. Niebling, and H. Hilse, "Biological methanation by GICON®-trickle bed process – an upgrade for conventional biogas plants, GICON." 2022.
[64] B. Demirel and P. Scherer, "The roles of acetotrophic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: a review," *Rev Environ Sci Biotechnol*, vol. 7, no. 2, pp. 173–190, Jun. 2008, doi: 10.1007/s11157-008-9131-1.
[65] S. M. Hashemnejad and M. Parvari, "Deactivation and Regeneration of Nickel-Based Catalysts for Steam-Methane Reforming," *Chinese Journal of Catalysis*, vol. 32, no. 1–2, pp. 273–279, Jan. 2011, doi: 10.1016/S1872-2067(10)60175-1.
[66] L. Jürgensen, E. A. Ehimen, J. Born, and J. B. Holm-Nielsen, "Dynamic biogas upgrading based on the Sabatier process: Thermodynamic and dynamic process simulation," *Bioresource Technology*, vol. 178, pp. 323–329, Feb. 2015, doi: 10.1016/j.biortech.2014.10.069.
[67] L. Jürgensen, E. A. Ehimen, J. Born, and J. B. Holm-Nielsen, "Utilization of surplus electricity from wind power for dynamic biogas upgrading: Northern Germany case study," *Biomass and Bioenergy*, vol. 66, pp. 126–132, Jul. 2014, doi: 10.1016/j.biombioe.2014.02.032.
[68] P. G. Kougias, L. Treu, D. P. Benavente, K. Boe, S. Campanaro, and I. Angelidaki, "Ex-situ biogas upgrading and enhancement in different reactor systems," *Bioresource Technology*, vol. 225, pp. 429–437, Feb. 2017, doi: 10.1016/j.biortech.2016.11.124.
[69] H. Li, D. Mehmood, E. Thorin, and Z. Yu, "Biomethane Production Via Anaerobic Digestion and Biomass Gasification," *Energy Procedia*, vol. 105, pp. 1172–1177, May 2017, doi: 10.1016/j.egypro.2017.03.490.
[70] B. Mutz *et al.*, "Surface Oxidation of Supported Ni Particles and Its Impact on the Catalytic Performance during Dynamically Operated Methanation of CO2," *Catalysts*, vol. 7, no. 9, p. 279, Sep. 2017, doi: 10.3390/catal7090279.
[71] IEA, "Outlook for biogas and biomethane. Prospects for organic growth. World Energy Outlook Special Report." 2020. [Online]. Available: https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf
[72] G. Piechota and B. Igliński, "Biomethane in Poland—Current Status, Potential, Perspective and Development," *Energies*, vol. 14, no. 6, p. 1517, Mar. 2021, doi: 10.3390/en14061517.
[73] K. Schuchmann and V. Müller, "Autotrophy at the thermodynamic limit of life: a model for energy conservation in acetogenic bacteria," *Nat Rev Microbiol*, vol. 12, no. 12, pp. 809–821, Dec. 2014, doi: 10.1038/nrmicro3365.
[74] S. Singhal, S. Agarwal, S. Arora, P. Sharma, and N. Singhal, "Upgrading techniques for transformation of biogas to bio-CNG: a review: A review on upgradation techniques to transform biogas to bio-CNG," *Int. J. Energy Res.*, vol. 41, no. 12, pp. 1657–1669, Oct. 2017, doi: 10.1002/er.3719.
[75] A. J. M. Stams and C. M. Plugge, "Electron transfer in syntrophic communities of anaerobic bacteria and archaea," *Nat Rev Microbiol*, vol. 7, no. 8, pp. 568–577, Aug. 2009, doi: 10.1038/nrmicro2166.

[76] K. Stangeland, D. Kalai, H. Li, and Z. Yu, "CO 2 Methanation: The Effect of Catalysts and Reaction Conditions," *Energy Procedia*, vol. 105, pp. 2022–2027, May 2017, doi: 10.1016/j.egypro.2017.03.577.
[77] X. Su, J. Xu, B. Liang, H. Duan, B. Hou, and Y. Huang, "Catalytic carbon dioxide hydrogenation to methane: A review of recent studies," *Journal of Energy Chemistry*, vol. 25, no. 4, pp. 553–565, Jul. 2016, doi: 10.1016/j.jechem.2016.03.009.
[78] U.S. Energy Information Administration (EIA)., "International Energy Outlook 2017." 2017. [Online]. Available: https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf
[79] M. Williams, "The Merck Index: An Encyclopedia of Chemicals, Drugs, and Biologicals," *Drug Dev. Res.*, vol. 74, no. 5, pp. 339–339, Aug. 2013, doi: 10.1002/ddr.21085.
[80] M. Wu *et al.*, "Coupled CO 2 fixation from ethylene oxide off-gas with bio-based succinic acid production by engineered recombinant Escherichia coli," *Biochemical Engineering Journal*, vol. 117, pp. 1–6, Jan. 2017, doi: 10.1016/j.bej.2016.07.019.
[81] K. Webb, "Pumped-Hydro Energy Storage." 2018.
[82] Max Bogl, "Gaildorf als Vorreiter für Stromspeicher." 2012. [Online]. Available: https://www.mbrenewables.com/pilotprojekt-gaildorf/
[83] A. Arabkoohsar and H. Namib, "Pumped hydropower storage," in *Mechanical Energy Storage Technologies*, Elsevier, 2021, pp. 73–100. doi: 10.1016/B978-0-12-820023-0.00004-3.
[84] A. Blakers, M. Stocks, B. Lu, and C. Cheng, "A review of pumped hydro energy storage," *Prog. Energy*, vol. 3, no. 2, p. 022003, Apr. 2021, doi: 10.1088/2516-1083/abeb5b.
[85] elektroenergetyka.pl, "Elektrownia Wodna Żarnowiec – historia i dzień dzisiejszy, sierpień." 2003. [Online]. Available: https://elektroenergetyka.pl/upload/file/2003/8/elektroenergetyka_nr_03_08_1.pdf
[86] Energa, "ENERGA zwiększa sprawność elektrowni Żydowo." 2013. [Online]. Available: https://grupa.energa.pl/informacje/384105/energa-zwieksza-sprawnosc-elektrowni-zydowo
[87] M. Guittet, M. Capezzali, L. Gaudard, F. Romerio, F. Vuille, and F. Avellan, "Study of the drivers and asset management of pumped-storage power plants historical and geographical perspective," *Energy*, vol. 111, pp. 560–579, Sep. 2016, doi: 10.1016/j.energy.2016.04.052.
[88] A. Harby, J. Sauterleute, M. Korpås, Å. Killingtveit, E. Solvang, and T. Nielsen, "Pumped Storage Hydropower," in *Transition to Renewable Energy Systems*, D. Stolten and V. Scherer, Eds., Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2013, pp. 597–618. doi: 10.1002/9783527673872.ch29.
[89] Max Bogl, "Pilot project with high capacity for innovation." 2016. [Online]. Available: https://max-boegl.de/nl/prestatiegebieden/infrastructuur/bruggenbouw/pilot-project-with-high-capacity-for-innovation