DaCES
Danish Center for Energy Storage

STATUS STRENGTHS SYNERGIES

DaCES REPORT ON ENERGY STORAGE IN DENMARK 2023

STATUS, STRENGTHS, SYNERGIES
DaCES REPORT ON ENERGY STORAGE IN DENMARK 2023

With DaCES' report on energy storage in Denmark 2023, we present a number of recommendations with decision-makers, authorities and funding agencies as the primary target, and investors, technology and business leaders as secondary. The vision is to turn energy storage and conversion into a Danish position of strength.

The recommendations and the contents of the report have been prepared in close dialogue with members of DaCES' professional working groups and members of the DaCES Steering Committee. Working group meetings and a cross-disciplinary workshop have been organised, where we discussed and selected the contents. External experts have answered and approved answers to questions made by DaCES. The report includes a number of cases – selected Danish key projects that demonstrate innovation, research and development within energy storage.

DaCES has coordinated, challenged, and combined contributions by Chief Technical Consultant Niels Dyreborg Nielsen and Chief Consultant Dorthe Brander Pedersen, Communication Consultant Julie Søgaard and Director Anne Marie Damgaard.

DANISH CENTER FOR ENERGY STORAGE (DaCES)

Denmark must become a pioneering leader in research, development, application, and integration of energy storage technologies that are competitive in a global market and contribute to reducing the world's climate footprint.

DaCES is a neutral and independent forum, working to guide research, education and innovation in energy storage and conversion. We are a member driven, network based and action-oriented organisation that brings together actors in a professionally and equality-based community of interests. We work across energy storage technologies and professional disciplines such as natural and engineering sciences, mathematics, social sciences, economics and humanities, etc. The aim is to create collaborations, networks and partnerships that bring together research environments and companies to help solve major societal challenges and free us from fossil fuels. We work to ensure that strategic and cross-disciplinary research and education contribute to energy storage becoming a Danish position of strength for the benefit of climate, business, and society.

DaCES is supported by the Danish Industry Foundation.

In 2023, DaCES was established as an independent association with an attachment to Academy of Technical Sciences (ATV). DaCES is based on membership of more than 50 companies and organisations.

For membership: www.daces.dk

DaCES' working groups

DaCES leads and facilitates four technical working groups in thermal storage, batteries, PtX and system integration, as well as a working group on education. Members of the working groups are listed at the end of the report.

Disclaimer

DaCES has the sole responsibility for the report, which does not necessarily reflect the individual member organisations' own positions, but the compromises reached in the five respective working groups. Members of DaCES are not responsible for any use of the information in this report.

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FOREWORD

The world's climate challenges have become increasingly acute and visible in recent years. This summer's global warming records, wildfires, heavy precipitation, and flooding are a warning of a future in which extreme weather will occur with greater frequency. There is a broad consensus that we need to act on the crisis. Climate is also energy, business, foreign and security policy.

Denmark has adopted a climate law with an ambitious target to reduce greenhouse gas emissions by 70 percent by 2030 and reach climate neutrality by 2045 – with a pitstop already in 2025. The Danish government has adopted a large number of political agreements to make climate objectives a reality, promote the green transition and free Denmark from Russian gas.

The climate-neutral energy systems of the future will be based primarily on renewable energy production. It will benefit the climate but will also create increased vulnerability with imbalances between electricity consumption and generation. This may lead to inconvenient energy shortages or energy surpluses, varying over time, and thus vulnerability and highly volatile prices in the energy market.

Energy storage is therefore a key to a robust energy system and thus a crucial element in delivering a carbon neutral, integrated and cost-effective energy system. Our neighbouring countries have already developed comprehensive energy storage strategies and plans. And the European Commission considers energy storage one of eight key technologies to ensure Europe's green transition. The race is underway, and Denmark risks losing its position as a green pioneer as well as losing market shares abroad, if we do not quickly invest time and more resources in the area.

Denmark has the foundation to become a leader in energy storage, energy conversion and integration of renewable energy across sectors and systems. Our specialised knowledge enables us to accelerate the green transition, both nationally and internationally. The prerequisite is rapid, supportive, and sustained action by several levels, professional groups and sectors.

The Danish Center for Energy Storage (DaCES) helps to solve the challenges and make Denmark a frontrunner in the field of energy storage. We do this by initiating collaborations and ensuring knowledge sharing between Danish business and knowledge institutions. Our coordination will accelerate the efforts of stakeholders in research, development, demonstration and optimisation of energy storage and conversion technologies that can be developed into green, innovative, and competitive solutions. And by working to ensure that technologies address the needs and acceptance of citizens.

Our suggestions on how Denmark can deliver on the potential of energy storage are described in this report. The report has been prepared in close cooperation with DaCES' members and working groups – many of Denmark's leading experts in the field.

This is DaCES' first report on "Status, strengths, synergies for energy storage in Denmark". The report presents a mapping of the potential of a number of energy storage technologies: Thermal energy storage, batteries, Power-to-X and system integration into an energy system based on renewable energy. We present concrete proposals to help achieve a green and sustainable transition.

Firstly, the report presents a number of recommendations for each of the professional areas. Secondly, on a more detailed level, the opportunities, and challenges are presented in each area. The descriptions of thermal energy storage, batteries and PtX respectively, can be read individually and do not refer to each other, while the description of system integration seeks to provide an overall understanding of energy storage. In addition, there is a section on education and the need for labour to succeed the green transition.

In total, we present 17 recommendations to strengthen Denmark's role as a green pioneer in the field of energy storage. It is crucial that DaCES' recommendations are shared, discussed, and further developed in the right forums. Therefore, based on the recommendations, DaCES will initiate dialogue and cooperation with decision makers, authorities, funding agencies, and the business community to realise the potential of the Danish ecosystem of actors working with energy storage.

The transformation of our energy systems is so extensive and radical that the only way it can be carried out is in terms of interdisciplinary and intersectoral cooperations. At the same time, time is scarce and there is a need for a faster development than we have witnessed with other observed technology transitions and developments. Since 2021, DaCES has been deeply involved in developing and operating the Innovation Mission and Partnership MissionGreenFuels to develop green fuels for transport and industry by 2030 and 2045/50. It is an overwhelming task where collaboration and knowledge sharing across insights, technologies and actors are crucial.

We do not know the exact recipe for succeeding in making the transition happen, but it is beyond doubt that we as a society are on a mission and that institutions like DaCES are necessary to set the right teams and create the right framework for fulfilling the mission of a deep, comprehensive AND rapid transformation of our energy system, independent of specific interests.

Enjoy your reading!

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Danish Center for Energy Storage has 17 recommendations

DaCES promotes the development of energy storage and conversion technologies by bringing together the key players from research, business, RTOs, and authorities. The goal is to make energy storage a Danish position of on a global scale. DaCES works with five focus areas: Thermal energy storage, batteries, PtX, system integration, and education.

If we are to succeed in a sustainable and cost-effective transformation of our energy system, it requires a focus on technology development and on exploiting synergies between the different technologies and their application. This requires close cooperation between research, innovation, and policy – universities, businesses, RTOs, advisors, investors, authorities, and regulators. Equally crucial is securing the necessary workforce, including highly skilled labour. Already today, skilled employees contribute to the operation optimisation of plants with digital and sector integration solutions, material development and optimal use of resources. However, the need increases along the transition. It is therefore essential to scale up the STEM labour supply through political prioritisation of technical, research and continuing training.

Our recommendations are divided into five areas:

1. Thermal energy storage
2. Batteries
3. Power-to-X
4. System integration
5. Training & education

Our recommendations map how the different technologies and areas of energy storage and conversion contribute to reducing the climate impact from industry and providing solutions for the green transition. Energy storage and conversion are key elements in the green transition. There is no "one size fits all", the needs are diverse, which is why the solutions also are different.

We note an overall lack of investment in research and technology development in the field of energy storage – both for the individual technologies and for the solutions that optimise energy systems across. In addition, there is a need for better framework conditions and information on what energy storage and conversion really are, and how technologies are part of the overall energy system.

RECOMMENDATIONS from DaCES

1. Thermal energy storage

1.1 Conversion of industrial heat consumption: Heat storage has a large, overlooked potential

The industry's demand for heat above 100 ºC is significant and has a negative climate impact. Industrial processes have an operating pattern that is difficult to adjust to the fluctuating generation of renewable electricity and electricity prices. Industry is naturally focused on producing competitive and high-quality products. Decarbonisation of industrial process heat will be promoted through the development and optimisation of heat storage in interaction with heat production. We also propose to provide investors with better toolsto assess the economy of heat storage projects by developing standardised techno-economic calculation methods.

1.2 Optimisation of flexible heat and cold storages below 100 ºC

Heat storage can be more cost-effective than electrical storages and can work in synergy with heat pumps, solar heat, electric heat, industrial waste heat and PtX plants, depending on temperature. Thermal storage below 100 ºC has great potential to meet CO_2 reductions in areas without district heating as well as areas with cooling demand. These are already widely used but can be further developed. Realisation of the potential requires that storage technologies are developed and optimised to integrate varying renewable energy supplies flexibly, intelligently, and cost-efficiently (solar heat, heat pumps, etc.).

1.3 Remove the price cap for waste heat and except waste incineration plants from heat tax for storage.

Industry, waste incineration plants, data centers, etc. must have a greater incentive to recover their waste heat. The unused surplus heat potential is currently around 7.8 TWh/year, equivalent to 10 % of Denmark's heat consumption, and in 2045 it may amount to 19 TWh [1] [2]. Data centers and electrolysis plants for the production of PtX can significantly increase the potential of excess heat [3]. A price cap is unnecessary, as the Project Order requires that surplus heat projects are an economic advantage for consumers, companies, industry, and society. The Project Order describes how a municipal council's planning for heat supply, approval of projects for collective heat supply, and processing of cases are carried out in accordance with the law on heat supply.

2. Batteries

2.1 Develop a long-term national battery strategy with measurable initiatives and prioritization of strengths

The strategy will stimulate research, growth, and investment in the Danish battery sector. It will strengthen Denmark's competitiveness in a market where our neighbouring countries have developed comprehensive strategies and plans. The battery strategy aims to demonstrate how Denmark, by strengthening our core competences, can increase our efforts in the European battery cooperation.

2.2 Energy storage, including batteries, should be prioritised as an independent strategic theme in grants from Danish public and private stakeholders

With a national battery strategy, we can support and further develop already established Danish strength positions such as next generation ion batteries, new reusable battery types, and digital optimisation tools. This includes intelligent control, integration, and automation of battery systems. In particular, it is targeted at cars, trucks, buses, ferries and charging infrastructure, as well as local energy balancing, which reduces bottlenecks in the electricity grid and provides ancillary services.

2.3 Create supportive conditions for the use of self-produced RE electricity in energy communities

Energy communities may consist of citizens, municipalities, associations, institutions, and businesses. Energy communities can reduce local, costly electricity grid build-up, and encourage local green initiatives, resulting in CO_2 reductions. The tools are local production as well as flexible sharing, consumption, and storage of self-produced energy, especially electricity. The economy of energy communities is challenged due to electricity taxes and tariffs for both charging and discharging from a common battery. We propose changing inappropriate regulation and requirements to achieve both local and societal benefits. This must be implemented without the changes affecting consumers who do not have financial leeway to invest in renewable energy installations.

3. Power-to-X

3.1 Invest in innovation missions and long-term partnerships to reach climate goals 2030 og 2045/50

Denmark must reduce greenhouse gas emissions by 70 percent by 2030, reach climate neutrality by 2045 and thereby contribute to global climate solutions. Establishing long-term partnerships in a mission-based approach to research and innovation, bringing together actors, resources, and competences to achieve a sole objective is important. Danish knowledge institutions, companies and advisors have strong competencies in PtX technology and green fuels across the entire value chain. The MissionGreenFuels partnership focuses on developing green fuels for transport and industry by 2030 and 2045/50. Denmark can become a leader in the development of PtX solutions and green fuels, but this requires funding for the innovation missions with a longer time horizon that supports the long-term goals towards 2045/50.

3.2 Create clear framework conditions that will make Denmark a pioneer in PtX technology

Danish universities, knowledge institutions, businesses and advisors are strongly represented throughout the PtX value chain. These stakeholders work with application-oriented technology maturation of well-known, but immature technologies, and with basic research into new technologies with a 30-year perspective. Based on this strength, Denmark can accelerate research, development, and demonstration of innovative and industrial PtX solutions that have a global export potential. To realise this potential, it is essential that public authorities identify 1) regulation with a long-term perspective that encompasses new technologies and instruments, and 2) long-term framework conditions that intensify high-risk, capital-intensive investments in facilities to support demand and market development for PtX technology and green fuels.

3.3 Prioritising PtX to energy-intensive industries and long-distance air and shipping for maximum climate gain

To develop PtX will require large resources of water, electricity, materials, and labour. The development of PtX products involves energy-intensive processes with several complex process steps and associated high energy losses. Therefore, PtX must be allocated for selected purposes including fertilisers, methanol, raw material in chemical processes, hydrogen-intensive processes, steel, shipping, and transcontinental aviation. This will provide the highest climate impact for the money, resources, raw materials, and working hours spent

4. System integration

4.1 Development of system integration solutions is crucial for the efficient energy system of the future

It will be complex with large-scale electrification and more renewable energy. System solutions are key to integrating renewable energy in an economically and societal useful way. There are great opportunities for harnessing synergies in terms of flexibility, switching between energy sources, and recovery of otherwise unutilized energy. But this requires strategic energy planning and a better system understanding, modelling and management of the components of various energy systems. To succeed in developing energy-efficient system solutions, research and industry must work closely together. Key tools are industrial demonstration based on research and development in AI and data-driven digital twins, algorithms, and software.

4.2 Establish strategic energy planning and coordination between actors at all levels

A strong, market-driven implementation requires coordinated, strategic energy planning across municipalities as well as between municipalities and governments. The coordination will enable accelerated and intelligent implementation of wind turbines, solar cells, biogas plants, PtX technologies, district heating, energy efficiency, geothermal and energy storage. The construction of transmission power lines is extensive and costly. By coordinating and co-locating new large renewable energy plants close to large electricity consumers, the construction of power lines for transmission grids can be significantly reduced and the cost for the green transition significantly reduced. It is crucial that planning is being made across the energy actors involved at municipal, regional, and national levels to increase the use of existing and new energy infrastructure.

4.3 Create simple and transparent framework conditions promoting efficient integration of renewable energy, locally, nationally and internationally

Variable electricity prices and grid tariffs, as well as the possibility to establish direct power lines, encourages that energy storage should play a greater societal beneficial role in developing more dynamic tariffs and new, digital and automatic solutions. The establishment of PtX production and large electrolysis plants is energy-intensive, which is why renewable energy sources must supply them with energy. Legislators must ensure framework conditions for the establishment of flexible operation of electrolysis plants, the appropriate location of the plants concerned, and a foundation for the marketing of PtX products.

Continuous alignment of legislation and regulation is essential to ensure constructive support for, and active involvement in, the green transition from municipalities, utilities, businesses, citizens, and communities. The adaptation of framework conditions should also take place internationally, which implies coordinated European energy cooperation. The integration and exchange of electricity and gas can reduce the path to climate neutrality by strengthening the common economy, security and renewable energy supply.

4.4 Allocate resources to update the Danish Energy Agency's Technology Data for energy storage in dialogue with researchers, business, and consultants

The development of energy storage technologies is very fast. Therefore, the Danish Energy Agency's Technology Data risk to contain outdated estimates. A process for continuous updating must be ensured in close dialogue with relevant stakeholders. The catalogue is subjected to professional quality assurance and central to energy planning in Denmark and abroad. It is used in profitability analyses of energy storage projects on which investors, industry and consultants base their work. Continuous updating is essential for the catalogue's data to be accurate and usable for the entire group of stakeholders who work with energy systems and the green transition.

5. Education

5.1 Upscale the labour supply of STEM candidates

Energy storage technologies play a key role in the future energy system and have a global growth potential that requires STEM experts. Denmark has a highly trained workforce that already contributes to the operational optimisation of plants with digital and sector-integrated solutions, material development, and optimal resource utilisation. It is crucial to scale up the STEM labour supply through political prioritisation of technical education, research, and training, including a focus on young people's and especially women's educational choices.

5.2 Strengthen continuing education – green mindset, digitalisation, economics and law

Continuing education and training of adults must ensure that businesses have the necessary skills for the green transition. The adult further education systems should be made more flexible and manageable, and the quality of teaching should be strengthened. Digitalisation is an essential part of the green transition. Efforts should be made to strengthen the digital competences of the Danish workforce, where 25% lack basic skills [4]. Competences related to the economic and legal framework conditions for the green transition are also crucial and should be strengthened.

5.3 Increase recruitment and retention of foreign labour

The green transition increases the need for recruitment of foreign labour. Foreign students staying in Denmark after graduation are a major gain for the Danish labour market and economy [5]. Denmark, on the other hand, is not good at attracting foreign skilled labour [6]. A targeted effort should be implemented to increase the recruitment and retention of foreign labour – both vocationally and academically trained.

5.4 Prioritise labour for the green transition

There is a need for a political prioritisation of labour for the green transition. The ecosystem of Danish energy storage supports Think Tanks CONCITO's and Mandag Morgen's (Monday Morning) recommendation that there should be closer cooperation between the Ministry of Climate, Energy and Utilities and the Ministry of Employment, so that climate and environmental legislation and policies can be assessed in relation to labour requirements [7].

THERMAL ENERGY STORAGE IS ESSENTIAL TO REALISE A GREEN ENERGY SYSTEM

Both in Denmark and abroad, there is an increasing interest in thermal storage. The drivers in Denmark include the increase in carbon emissions, carbon tax and gas independence, increased electrification, and reduced climate footprint [8] [9]. More uncontrollable solar and wind energy in the energy system leads to more mismatch between energy consumption and production. Already in 2021, the amount of unused wind power corresponded to 7% (1,2 TWh) of Danish wind turbine production or the annual electricity consumption of 750.000 Danes [10] [11]. In addition, several thermal CHP plants will shut down, which today, for a fee, keeps the grid stable by regulating the power generation of the plants [12]. Security of supply is therefore challenged due to a higher share of renewable energy in the electricity grid, combined with the shutdown of CHP plants.

Wind turbines in Denmark supply the largest amount of renewable electricity that large-scale batteries can technically store. Current commercial batteries are generally unprofitable as large-scale energy storage for short periods (hourly basis). Thus, solutions that store electricity such as heat and cold (thermal energy) over long periods of time (hour, day, and month) are more cost-effective [13] [14] [15] [16].

Thermal energy storage can help address the challenges of a climate-neutral energy system as it offers cost-efficient, resource-optimising, and balancing energy storage that supports integration across energy systems and technologies. Industrial heat pumps and refrigeration systems are typically more cost efficient in combination with energy storage due to greater utilisation of electricity price variations. Specifically, heat storage can recover expected increasing amounts of excess heat from electrolysis plants and data infrastructure in flexible interactions with the rest of the energy system [17] [18].

This chapter reviews the concept of thermal energy storage and related principles, which form the basis for explaining the societal value of thermal energy and its indispensable role in the green transition.

Tabel 1: Overview of selected storage media associated with principles and related uses.

Temperature (°C)	Selected storage media and principle [22]	Applications [23]
Room temperature and cooling	Sensitive: water (tanks, pond heat storage, aquifer), soil (drillholes), ceramics Latent: water, paraffin, fatty acid, polyethylene, glycol, salt hydrates	Domestic heating and domestic water individually and collectively (district heating) Cooling individually and collectively (district cooling)
<100°C	Sensitive: water (tanks, pond heat storage, aquifer), soil (drillholes), ceramics Latent: paraffin, salt hydrates Sorption: water in silica, zeolite and NaOH	Low temperature process heat (direct and indirect) used in e.g. dairies, fish processing and beverage industries, paper industry
100–150°C	Sensitive: stone, molten salt, ceramic, sand, concrete, steam, oil Latent: sugar alcohol, paraffin Sorption: water in silica and zeolite	Process heat in bakeries, textile, and pharmaceutical industries
>150°C	Sensible: stone, molten salt, ceramic, sand, concrete, steam, oil Latent: sugar, alcohol, nitrate, hydroxide Sorption: water in zeolite (max 200 °C) Thermochemical: reversible thermochemical processes	Process heat in the wood, tile, plastics, cement, glass, and iron industries as well as refineries Electricity generation in e.g. CHP plants using steam turbines

Pit thermal energy storage of 70,000m³ in Høje Taastrup during establishment.

What is thermal energy storage?

Thermal energy can be stored either by heating or cooling storage media such as water, rocks, salts, oils, and metals, etc. With limited losses, the media may store the added heat or cold for later use. The choice of storage medium and principle depends on parameters such as storage temperature, speed and power during charge and discharge, storage time, energy stored, etc.

Heat energy is widely used, which in Denmark primarily includes district and process heat for households, buildings, businesses, and industries. Refrigeration is applicable, especially in retail, food, and pharmaceutical industries. Some district cooling networks exist in Denmark, including in Høje Taastrup and Copenhagen.

Principles of thermal energy storage

Thermal energy storage includes storage from cold temperatures to more than 1000 ºC, divided into principles based on how the storage medium changes state by heating or cooling. Substances are usually in solid, liquid, or gaseous state. Solids become liquid and later gases by heating, whilst cooling has the opposite effect.

- Sensitive. The storage medium's ability to store heat (heat capacity) is utilised at changing temperature, but the medium does not change phase, i.e. water remains water and does not evaporate into gas.
- Latent. The storage medium changes phase during heating from solid state (e.g. ice) to liquid (water) or from liquid (e.g. liquid/molten salt) to solid state (salt).
- Sorption. Heat is stored through heat-absorbing processes, where gas desorbs from a solid or liquid substance. Heat is released when the gas binds on a solid (adsorption) or in a liquid (absorption). Adsorption is suitable for storing small amounts of energy with rapid discharge, while absorption is suitable for storing larger amounts of energy over a long period of time.
- Thermochemical. Chemical reactions between substances can store heat. The supply of heat can split substances into smaller, separate components that store the heat. The heat is released when the constituents are brought together and react, which restores the original substance.

The four principles have different advantages, disadvantages, and scopes of application, so the optimal solution depends on technical, economic, and environmental parameters. Sensitive heat storage is well developed, while the other principles are mostly in the stage of development, with more challenges and greater cost and space reduction potentials for sensitive storage technologies [19]. Table 1 shows examples of different storage solutions broken down by temperature interval. The table shows that different thermal storage technologies can satisfy the temperature demands [20] [21].

Applications of thermal storage in Denmark

Commercial cold storages are used by LEGO and plastic moulding machines (12-18ºC) of other process industries as well as by supermarkets (around 0ºC) to even out the load on refrigeration systems and operate them more energy-efficiently. Cold storage can also be used together with data infrastructure, which will be shown later in this section as *Case 1 – DTU optimises the high energy density of phase changing materials for compact and decentralised energy storage.*

Heat storage technologies are especially suitable for daily and monthly storage with charging and discharging effects of kW to hundreds of MW and energy storage capacities of kWh to several GWh. The technologies have significant advantages of scale. That means that the storage price per kWh is lower the larger the plant. Technology development can lower the energy price for immature and expensive technologies at a low technology readiness level (TRL) as shown in Figure 1, where the energy production price dropped for solar panels by 90% in approximately ten years.
Immature heat storage technologies have similar price reduction potentials which, if realized, could become competitive export goods [27]. Heat storage, on the other hand, is not suitable for fast charging and discharging from sub second to hourly level and in scenarios with low energy storage quantities, where batteries, supercapacitors and flywheels are more suitable.

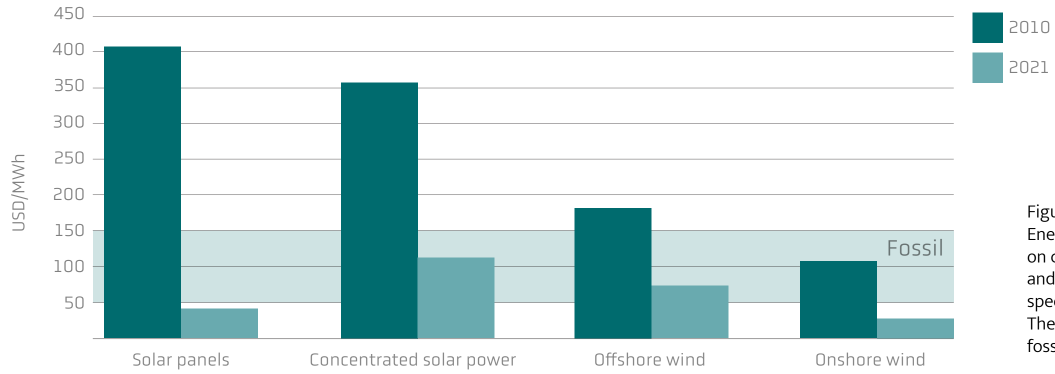


Figure 1: Evolution of Levelized Cost of Energy (LCOE) of green technologies based on commissioned installations in 2010 and 2021 as well as the techno-economic specifications of the projects [24].
The grey area shows the price spread of fossil-based electricity.

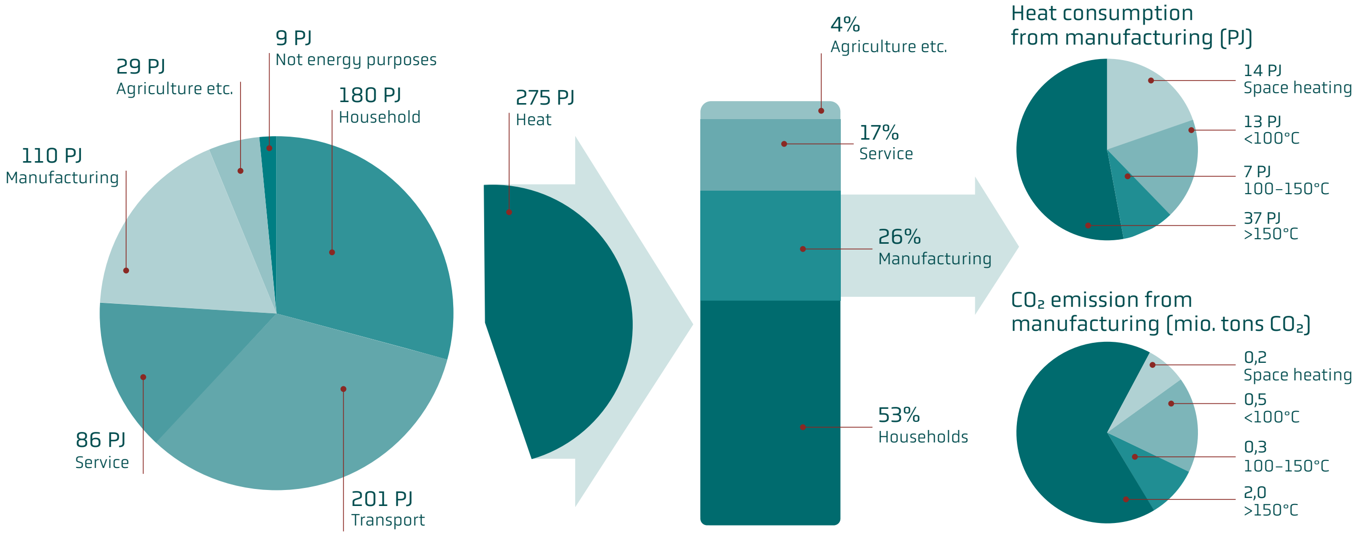
Energy storage can reduce CO_2 emissions from heat production

The heat demand represents 97% of the thermal demand in Denmark [25]. In the future, cooling needs will increase significantly due to data infrastructure cooling (seven doubling energy needs from 2021 to 2030 [26]) and climate change [27]. Thermal energy storage is divided into temperature ranges to distinguish between applications (see Table 1) and show the energy and emission distribution at different temperatures.

Households and the service sector primarily demand heat below 100ºC, where commercial solutions exist as pit thermal energy storage and heat pumps e.g. in integration with district heating [28] [29]. The climate footprint from heat supply below 100ºC will decrease with the electrification of both district heating and the service sector, as well as an increasing share of renewable electricity, but there is a great potential to boost electrification [26]. This can be achieved through the development and optimisation of flexible integration between heat stores (e.g. pit thermal energy storage and Phase Changing Material (PCM) storages) and heat from renewable energy such as solar collectors and electric heat pumps. Optimisation can accelerate both the phase out of oil and gas boilers (65,800 and 336,000 pieces in 2022, respectively) and fossil energy in district heating [26]. The potential is significant as one third of the building area is heated with gas, oil, firewood, and wood pellets [30].

The heat consumption of the manufacturing industry covers a larger temperature range distributed approximately evenly above and below 150ºC, cf. the upper pie diagram to the far right in Figure 2. The climate challenge is that fossil fuels meet the heat demand, especially at high temperatures that require a lot of energy to achieve. Heat above 150ºC therefore accounts for 2/3 of the emissions, cf. the lower diagram to the right in Figure 2. Higher temperature places extra demands on the durability, insulation capacity, etc. of storage materials. High temperature heat storage and supply technologies are underway, but there are currently few commercially developed green technologies. Time-consuming and difficult market maturation of the technologies means that the climate footprint of high temperature processes will remain high in the future unless technology development and market maturation are promoted.

Biomass burning can partly replace fossil fuels, but biomass is a scarce resource and should be reserved for sectors without techno-economically greener alternatives. High temperature heat pumps can address heat demand between 100ºC and 250ºC [31], while e.g. solar, electric, industrial waste heat incl. PtX, etc. can also meet heat demands above 250ºC, where the efficiency of heat pumps makes them less attractive.



Figur 2: Denmark's final energy and heat consumption by sector in 2022 as well as temperature and emission distribution for manufacturing industries (excluding refineries) based on data from the Danish Energy Agency..

Overall, it is imperative to develop, scale up and optimise thermal energy storage and conversion technologies for applications above and below 100ºC to reduce the climate footprint faster through optimised exploitation and accelerated integration of solar and wind energy.

Danish positions of strength

Denmark is a leader in several thermal storage technologies and has well-functioning solutions for storing heat below 100ºC, but optimisation of the technologies is necessary to deliver heat and cold in intelligent and flexible interaction with weather-dependent renewable energy.

Heat storage solutions above 100ºC for high-temperature industrial processes and steam-based electricity generation are generally absent and represent an unresolved potential that Denmark can utilise. In particular, industry calls for cost-effective heat storage solutions, on which several Danish actors are working hard, as shown by specific examples at the end of this chapter.

Denmark is an active contributor to international cooperation, including the International Energy Agency (IEA) expert panel, technical and economic working groups within the IEA Energy Storage Platform (Energy Storage Tasks 32, 35, 36, 37, 39, 40, 41, 43) [32]. In addition, Danish universities and companies are driving forces in international research and development projects in the field of thermal storage.

There are competent Danish solutions, but there is a need for upscaling and market maturation. Mutual collaborations between knowledge institutions an industry can through development and demonstration projects generate practical experience and knowledge that can make modelling tools more realistic. The industry demands a techno-economic overview, which freely available modelling tools can fulfil.

We have selected four Danish thermal solutions presented in the order of low to high storage temperature, which is important for the application. Higher temperature increases price, operational complexity, and the risk of corrosion, which puts higher demands on materials, pump equipment and technology development. To support the development of high-temperature heat storage and related solutions, more funding is needed for risk-taking collaborations.

The technologies are at different stages of development and thus varying distance from the market (TRL). From a Danish perspective, they are divided as follows:

- Low (1 -3): Thermochemical processes such as hydration and dehydration of salt in water
- Middle (4 -6): Molten salt, hot stones, latent/phase-changing materials
- High (7-9): Pit thermal energy storages are a Danish strength position and have great export opportunities.

Case 1

DTU optimises phase-changing materials' high energy density for compact and decentralised energy storage

DTU Construct works within thermal storage and has extensive knowledge of phase-changing materials that are part of building-integrated storage of heat or cold. The department collaborates closely with DTU Compute and DTU Management and develops intelligent control that increases reliability and adapts electricity consumption to low electricity prices and periods with high renewable energy share.

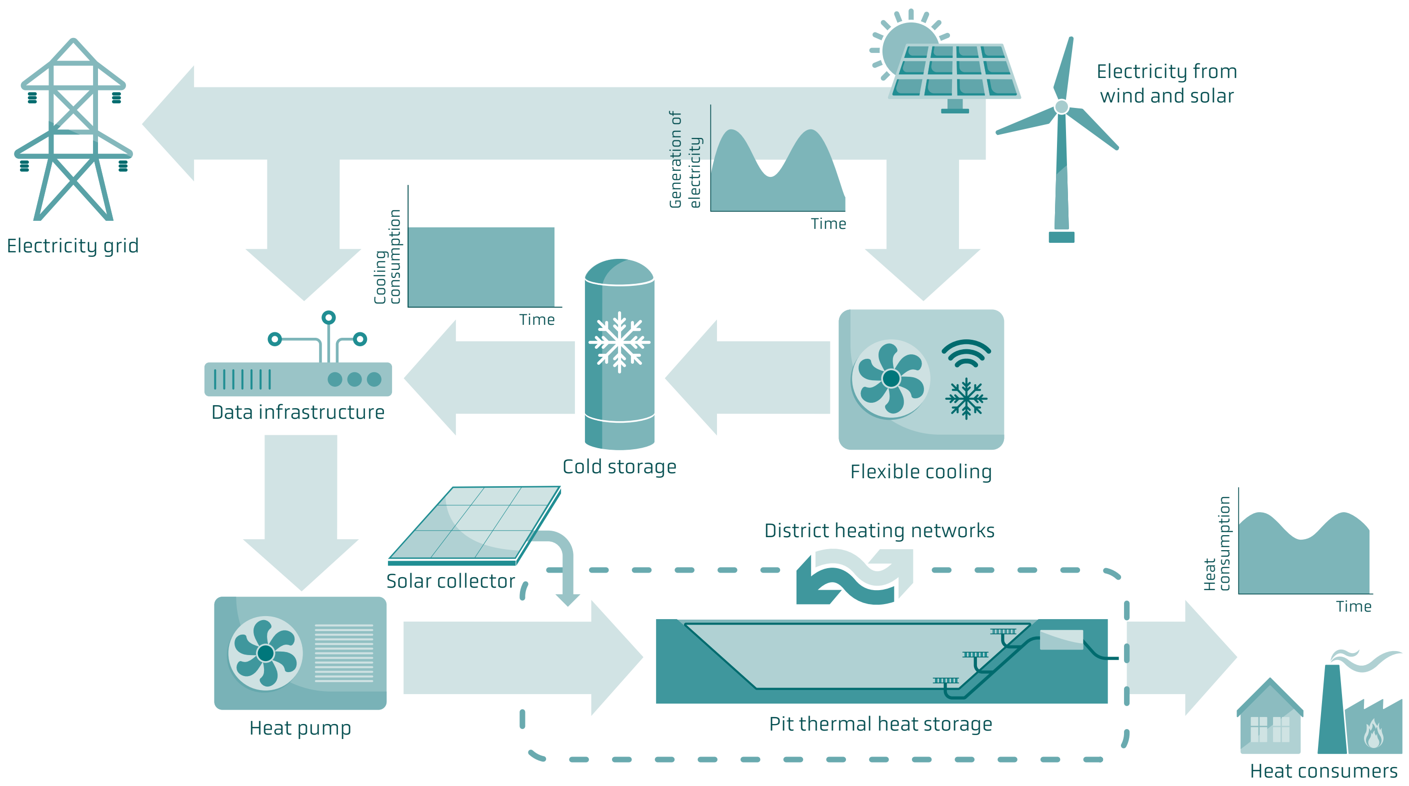


Figure 3: Electricity generation from wind and solar varies, but a flexible cold storage can smooth out the variation and deliver demanded constant cooling to data infrastructure that emits surplus heat. Heat pumps can recover the surplus heat and send it to the district heating network. However, heat consumption varies, and therefore it may be advantageous to store heat from heat pumps and solar collectors in a pit thermal energy storage (or accumulation tanks) connected to the district heating network.

CHALLENGE

The Danish Energy Agency expects that buildings without connection to district heating and cooling networks together with the consumption from data infrastructure account for 13% of Denmark's electricity consumption in 2030 [26]. Electric heat pumps and refrigeration systems can supply buildings and related data infrastructure with green heat and cold, respectively, by consuming renewable electricity. The disadvantages of electricity-based heat supply and storage are that the technologies are currently not sufficiently developed for efficient, intelligent, and flexible operation in buildings, while the energy storages are challenged by narrow temperature range and limited space.

SOLUTION

In the "Cool-Data" project, salt hydrate and organic materials are tested separately in cold storage prototypes (developed by Cool Energy Aps), which enable flexible cooling of technical and server rooms by the use of AI. [33] [34]. The project is supported by Innovation Fund Denmark. The PCM materials used melt at 15ºC, while the operating temperature of the storage varies between 10ºC and 20ºC, as melting involves high energy transfer. The tested cold stores can store five times more energy per volume (energy density) than water tanks between 10ºC and 20ºC. Integration of the cold storage with electricity supply from renewable sources, cooling unit, and data infrastructure is shown in Figure 3.

Another salt hydrate can store heat from heat pumps and solar collectors in tanks of 100-200 litres tanks, where the heat melts the salt hydrate at 58ºC [35]. The salt hydrate has lower heat loss and higher energy density than hot water tanks.

POTENTIAL

The PCM solution is at the prototype stage (TRL 4-5) with larger scale demonstrations as the next step. The Achilles heel of phase-changing materials is limited thermal conductivity and a high price in relation to sensitive heat storage technologies. Research therefore focuses on optimising heat transfer and system integration. The intention is to increase the value of the storage, including reducing space consumption and ensuring heat supply at almost constant temperature.

PCM can get closer to the market through product development, high and varying electricity prices, increased valuation of security of supply, and demand for green heating.

More information:
www.construct.dtu.dk and cool-data.dtu.dk
Gerald Englmair, Assistant Professor, DTU Construct

Case 2

Flexible and innovative pit thermal energy storage provides cheaper and greener heat for district heating customers

In Taastrup, a large pit thermal energy storage has been established, which was commercially put into operation in February 2023. The district heating companies VEKS and Høje Taastrup district heating finance the project. PlanEnergi is the primary advisor and has more than 30 years of experience with developing pit thermal energy storage in intelligent integration with district heating. Aalborg CSP has designed and delivered the pit thermal energy storage's innovative lid, while DTU Construct is involved in scientific studies on water temperature distribution, heat loss and material development over time. The project is supported by EUDP with a grant for 2025.

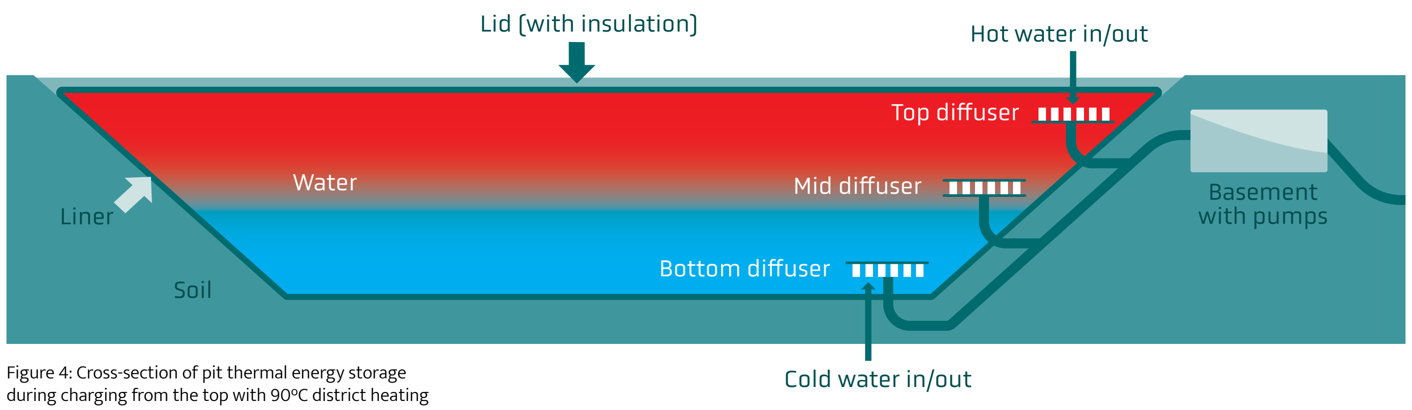


Figure 4: Cross-section of pit thermal energy storage during charging from the top with 90ºC district heating water. Discharge of 70-75ºC district heating water takes place to Høje Taastrup district heating. The pit is isolated from the surrounding soil by a lining at the bottom and sides as well as a lid at the top. Hot water is lighter than cold and ensures a temperature difference down through the water column. The lid is designed to remove air, water, and moisture accumulations.

CHALLENGE

The challenges of the project have been to prevent corrosion of inlet and outlets, temperature restriction for membranes and their durability at the high operating temperature (90ºC year-round), as well as developing cost-effective and durable solutions. Alternative containers for the project's pit thermal energy storage are steel tanks, which are more expensive on the same scale.

SOLUTION

The flexible pit thermal energy storage, shown in Figure 4 holds 70,000 m^3, offers cost-efficient storage of surplus heat and excess renewable energy for use in periods of heat deficit.
The storage pond can remove up to 15.000 tonnes of CO_2 per year [36]. The storage capacity is 3.300 MWh of hot water and can charge and discharge up to 30 MW from the VEKS transmission network and Høje Taastrup's district heating network, respectively. The success of the project is partly due to a newly developed lid solution with efficient dewatering and steam diffusion, and partly to research collaboration between polymer producers and research institutions, which has led to durable, heat-tolerant, and bespoke development of membranes made from polypropylene.
The solutions result in long lifespan (> 30 years), low energy loss (< 5% per year) and electricity price-flexible operation with 25-30 annual discharges and annual revenues of DKK 6-7 million.

POTENTIAL

The pit thermal energy storage in Taastrup consists of components that are commercially available and proven. What's new is weekly charge and discharge in flexible interaction with electric heat production and consumption, as well as a newly designed, durable and heat insulating lid. The project consists of commercial components composed in a new way, resulting in TRL level 8. Estimates indicate the project's commercial potential to be DKK 1 billion in Denmark and DKK 10-15 billion in Europe, especially in Germany, Sweden, Finland, and Eastern Europe, where district heating is most widespread in Europe. [37] .

More information:
www.planenergi.dk and www.aalborgcsp.dk
Geoffroy Gauthier, Project Leader, PlanEnergi
Per Alex Sørensen, Team Leader, PlanEnergi
Jonas I. Sørensen, Product Manager, Aalborg CSP

Case 3

Heliac delivers cost-efficient, CO_2-free and flexible storage of renewable and excess heat in stone storage

Heliac was established in 2014. The company develops and patents solutions for innovative, cost-efficient and adjustable solar collectors, which are now combined with energy storage in stone (RockStore) and intelligent integration solutions that optimise the operation of solar collectors in terms of energy consumption and storage.

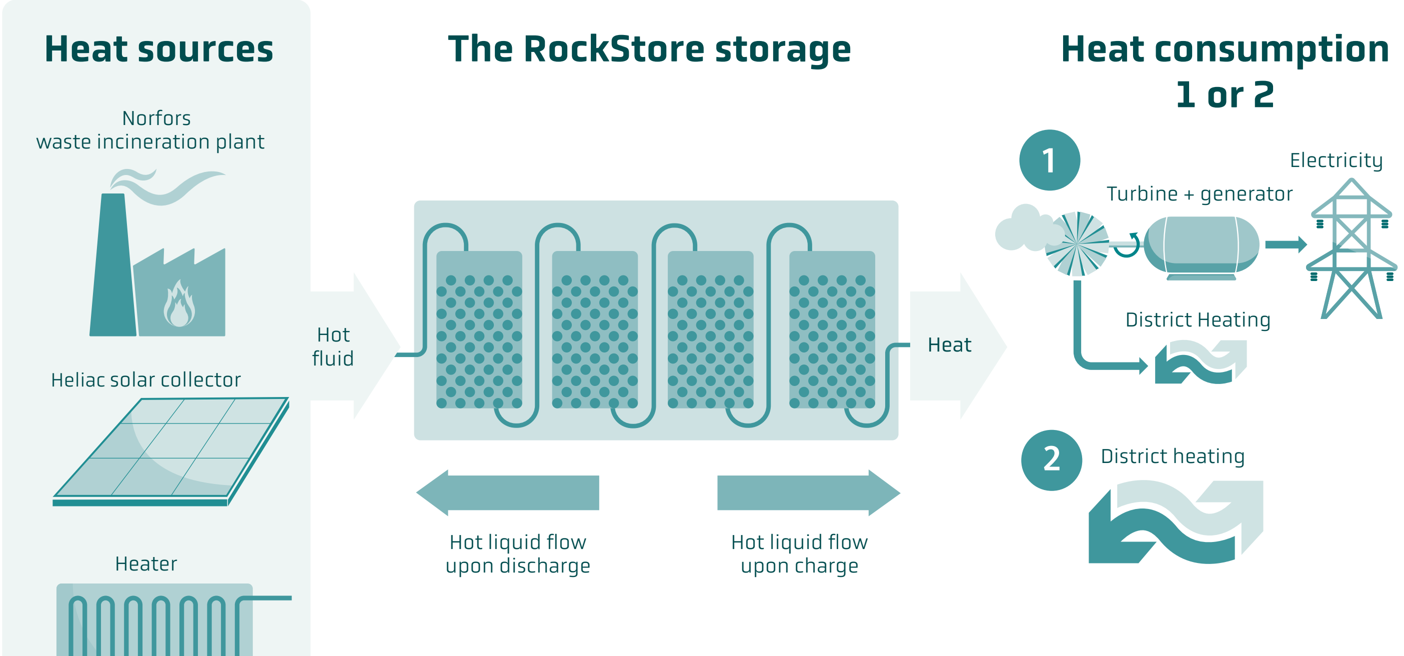


Figure 5: Potential heat sources are the cogeneration plant Norfors, Heliac's solar collector or electric heaters, which via hot oil transfers the heat (up to 3 MW) to four separate stone storages with a total of 10 MWh of storage capacity between 90ºC (right tank) and 275ºC (left tank). The high temperature makes it possible to produce electricity and heat at the same time (150 kW of electricity and 1200 kW of heat) or only heat (3000 kW of heat).

CHALLENGE

Plants handling waste incineration and high-temperature industrial processes today emit surplus heat at high temperatures to the atmosphere without recovery, due to very few commercial and efficient high-temperature heat storages.

The profitability of renewable energy plants is strained by their weather-dependent energy production. Heat storage can even out mismatches between uncontrollable renewable energy production and energy consumption, but a condition for this is intelligent operation of the storage if it is to take part in flexible and profitable interaction with variable heat supply from solar collectors, electric heat, and industrial excess heat.
In addition, the use of high temperature residual heat places additional demands on insulation, corrosion resistance and heat tolerance of equipment and materials

SOLUTION

Heliac has developed a flexible and scalable stone storage, RockStore, with expected start-up in 2024, which builds on previously created similar heat stores on a smaller scale. The heating source is renewable or excess energy which, via a heat carrying oil, transfers the heat to stone storage tanks as shown in Figure 5. The stone storage is unique as it consists of easily accessible, environmentally friendly, durable, and cost-effective materials with an annual loss of 7-10% of stored energy and an estimated lifetime of 15-20 years.
The heat produced can be used as process heat for industry, steam for power generation and district heating.
RockStore can increase the utilisation of wind and solar installations and is therefore well suited to becoming integrated with renewable energy systems. Industries and CHP plants can use the storage to store surplus heat for electricity and heat generation for later use, either for self-consumption or for the market.

POTENTIAL

In an EUDP project, Heliac explores how Norfors' annual excess heat of 10-30 GWh can be stored in RockStore for later use. The energy storage will form the basis for later upscaling to GWh size. In addition to Norfors, a large number of industrial partners and knowledge partners are involved in the project. High temperature storage requires robust and durable materials, which Heliac is constantly working to improve and optimise. Scaling up and further developing RockStore from the demonstration phase and TRL level 6 is the next step. But it requires more funds, partnerships, and regulatory freedom. Heliac has partnered with Forsyning Danmark to support the next stage of development, which includes more than 30 times larger storage than shown in Figure 5.

More information:
www.heliac.dk
www.energiteknologi.dk/projekter/rockstore
Elle Najim, Technical Project Manager, Heliac
Dan Kofoed, Project Manager, Heliac

Case 4

Hyme stores renewable electricity in molten salt for power supply and industrial process heat

Hyme was established in 2021 and has almost 40 employees. The company develops and commercialises a new type of energy storage based on hydroxide salts. Hyme originates from Seaborg Technologies, which for seven years has researched in hydroxide salts and developed a new method that makes it possible to control the corrosive nature of the salt. The result is a more scalable and cost-efficient thermal energy storage. Hyme's storage concept combines mature molten salt technology and a new type of salt with improved thermal properties. The vision is to build a large-scale plant with storage capacity of up to 1-2 GWh to ensure stable supply of electricity and heat to cities and industry in collaboration with other operators such as Alfa Laval Aalborg Header-Coil A/S.

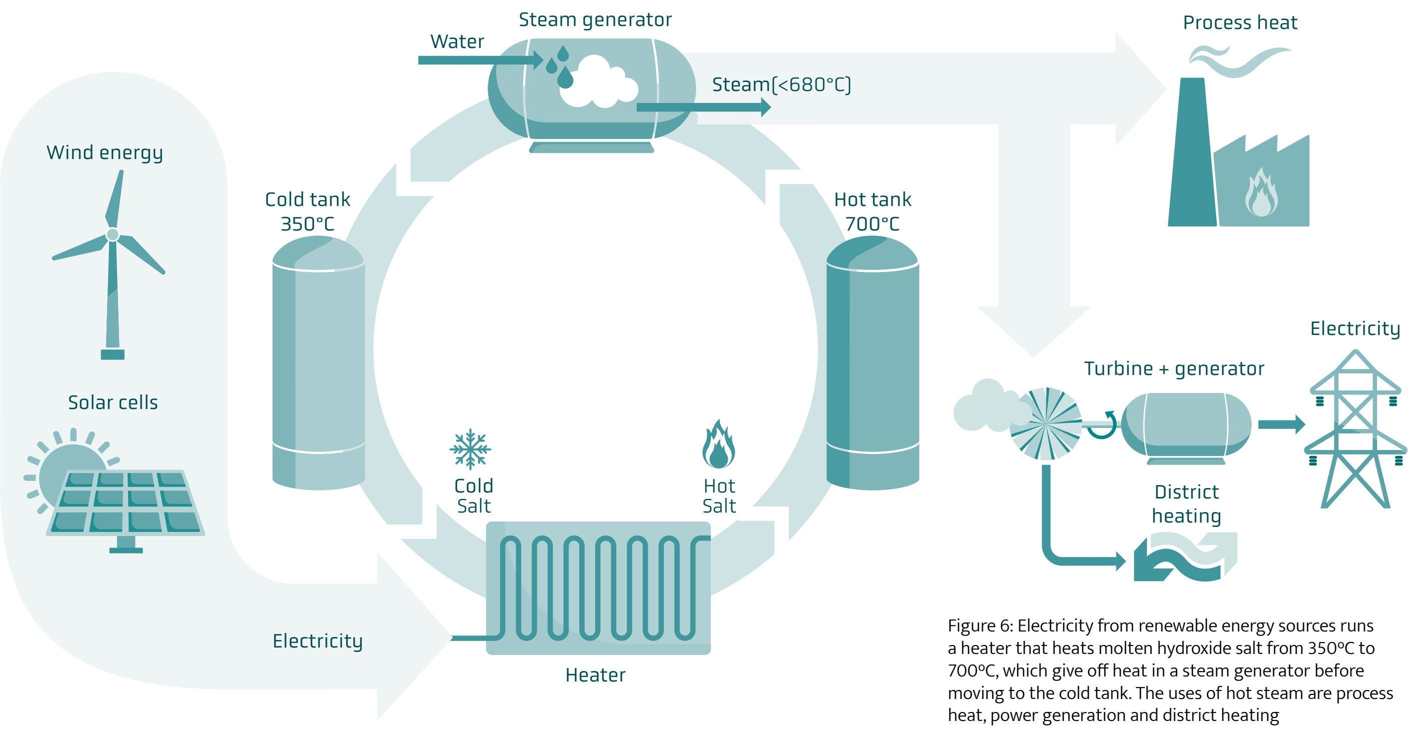


Figure 6: Electricity from renewable energy sources runs a heater that heats molten hydroxide salt from 350ºC to 700ºC, which give off heat in a steam generator before moving to the cold tank. The uses of hot steam are process heat, power generation and district heating

CHALLENGE

The industrial sector demands solutions for their high-temperature processes (over 200ºC), which are difficult to electrify profitably today. Therefore, the industry's need for high-temperature heat and steam is largely met by burning of fossil energy sources, which is harmful to the climate.

LØSNING

Hyme uses hydroxide salts (drain cleaner) to store renewable electricity as heat supplied by electric heaters heating molten salt from 350ºC to 700ºC, as shown in Figure 6. Discharging takes place by pumping 700ºC molten salt through a heat exchanger that heats water to a maximum of 680ºC steam. Industries can use steam to produce process heat. The steam can also be converted into electricity and heat via a steam turbine with a connected generator. Electricity production accounts for a maximum of 40% of energy production, while heat constitutes the rest as shown in Figure 6.
The benefits of the salt are that it is safe, easily available, inexpensive, energy-dense, and energy efficient in terms of storage and heat transfer. The storage is scalable from 0.1-2 GWh and can operate with daily charging and discharging with 1% storage loss.
The area requirement for the salt storage is one tenth and one thirtieth of lithium-ion batteries and hydropower, respectively, for the same amount of energy stored. Large-scale thermal energy storage can deliver green heat and steam at high temperatures by flexibly storing heat and steam, generated when the electricity price is low.

POTENTIAL

Hyme is demonstrating two pilot projects, which are 1 MWh of molten salt store in Esbjerg (MOSS EUDP project) and 25 MWh of molten salt store in Rønne (2LIPP EU-Horizon project). It is expected that MOSS will be operational in 2023, while 2LIPP will be operational in 2024. After 2025, the ambition is to establish commercial storages in the GWh scale.
MOSS and 2LIPP should demonstrate the concept of MWh scale over time and raise the previously tested operating temperature from 600ºC to 700ºC. The storage technology is at TRL level 6. Successful tests can form the basis for the deployment of large-scale thermal energy storage in Denmark for the benefit of security of supply, the green transition of the high-temperature industry, and the utilisation of renewable energy plants.

More information:
https://:www.hyme.energy/
Katrine Blandel, Senior Business Developer, Hyme

Recap of thermal cases

The four storage technologies are summarised in Table 2 by six categories and cover a wide temperature and scope. The storage capacities are market-relevant and show that Danish energy storage technologies have promising potential, but they need to overcome difficult challenges before commercialisation is a reality.

Tabel 2: Characterisation of four Danish thermal energy storage technologies

Case	Temperature (°C)	TRL	Input	Output	Use	Storage Capacity
Cold storage with PCM salt	Min: 10 Max: 20	4,5	Cold from electric refrigeration unit	Cold	Data infrastructure Buildings, service, and industrial businesses	15 / 50–100 kWh per module
Pit thermal energy storage	Min: 45 Max: 90	8	District heating	District heating	District heating networks	3300 MWh
Hot stones	Min: 40 Max: 300	6	Excess heat Solar heat Renewable heat from heater	Process heat District heating	Electricity generation and ancillary services Industrial District heating networks	10 MWh/ +350 MWh
Molten salt (NaOH)	Min: 350 Max: 700	6	Renewable heat from heater	Process heat District heating Electricity	Electricity generation and ancillary services Industrial District heating networks	1 / 400–1200 MWh per module

BATTERIES – A CORNERSTONE OF THE GREEN TRANSITION

Batteries can accelerate the path towards an energy supply secure and climate neutral energy system with a high share of variable renewable energy by promoting electrification of the transport sector, reducing short-term, local, grid imbalances and short-term storage of excess renewable electricity. It reduces the climate footprint, improves the utilisation of energy resources and provides high security of supply despite a high share of renewable energy. The realisation requires development of sustainable batteries and efficient upscaling of battery production, which is already in full swing at global level. .

Batteries can be included in many applications, the most important of which are listed below:

1. Energy storage for electric transport such as passenger cars, buses, trucks, ferries, etc., with intelligent connection to the power grid (Vehicle-to-Grid)
2. Ancillary services by balancing voltage and frequency of the power grid at second to hourly basis
3. Backup electricity supply for power outages instead of fossil fuelled installations
4. Local electricity storage of wind and solar energy for periods of higher electricity demand can support system integration solutions, roll-out of fast chargers and reduce both cost-intensive power grid deployment and local bottlenecks
5. Strengthen the economy of energy communities by maximising self-generation and consumption of renewable energy as well as applications behind the meter such as companies' virtual power plants, etc.

Batteries have much lower energy density compared to fossil fuels, which is why they are suitable for light transport over shorter distances. The EU requires new light-duty vehicles sold from 2035 to be emission-free [38], while Danish trucks will be subject to a kilometre-based toll from 2025 [39]. Support pools have been allocated for charging infrastructure for light and heavy transport;[40] and support pools have been set up for domestic electric shipping, etc. [41]. The actions encourage emission-free transport funds and, in 2022, for the first time contributed to the sale of more than 30,000 electric cars, while ferry services to Samsø and Als will be electric in a few years [42].

Charging infrastructure is essential to electrify the transport sector, as electric transport modes have shorter reach than fossil fuelled. Projections clearly show that the battery demand for mobile propulsion accounts for most of the rapidly increasing demand (around 90% in 2030), followed by energy storage, and finally consumer electronics [48].

The consequence is that the need for battery raw materials such as cobalt and lithium very soon will exceed the production capacity [43]. The solution is to develop new battery technologies based on more easily accessible and non-critical raw materials

The expectation is that the European battery production capacity will be twenty times higher in 2030 compared to 2020, as there is also a large increasing need for batteries, cf. Figure 7. The battery demand entails both a large growth potential in the form of a doubling of turnover from 2020 to 2030, cf. Chart 8, and high job creation within the EU sector, cf. Chart 9. Investors pays attention to the projections, as energy storage represents the largest share (26%) of global investments in green technologies. In the energy storage category, batteries account for more than half (56%) of the investments [44].

In collaboration with the University of Southern Denmark and the Danish Battery Company, DaCES attracted representatives from all parts of the value chain at the Danish Battery Summit in Sønderborg, on March 2nd 2023.

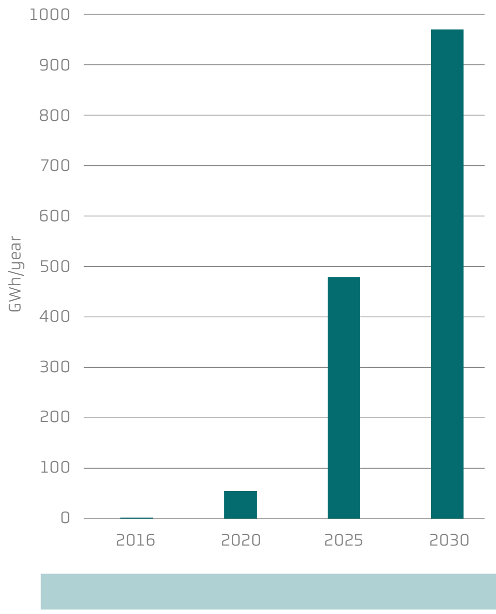


Figure 7: Projection of battery production capacity in the EU 27 countries [45].

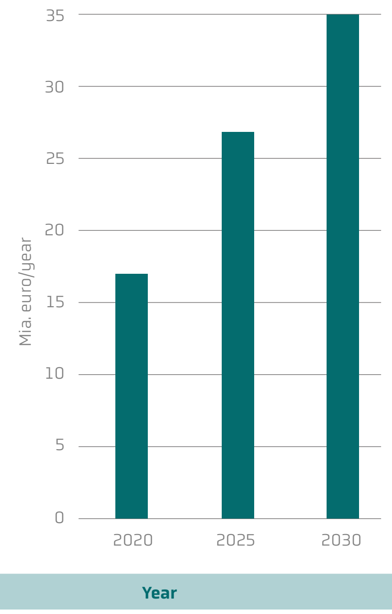


Figure 8: Projection of the turnover of the battery sector in the EU, UK, Iceland, Liechtenstein, Norway, and Switzerland [46].

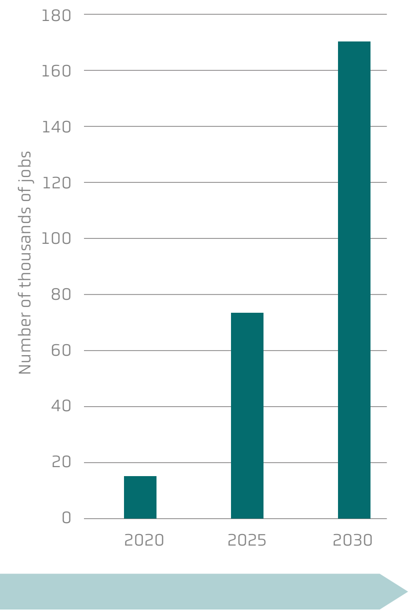


Figure 9: Projection of job creation across the total battery value chain for the 27 countries of the EU [47].

The Danish battery value chain

Danish battery actors are active in a wide range of rechargeable battery technologies, where lithium-ion (Li-ion) battery types are the most widely used and dominant in primarily electric vehicles, and secondary in stationary electrical storage and electronics [48]. Li-ion batteries have a relatively high energy density, high efficiency, long service life, and low self-discharge (low loss over time) compared to other battery types. However, raw materials for today's Li-ion battery technology are cost-intensive and have a large environmental impact, which an exponentially increasing demand is aggravating (see Figure 7). Stationary batteries are less prevalent than batteries for mobile applications and have different requirements, which generate market potential for new battery types.

Danish companies and knowledge institutions are working intensively to develop next generation batteries with a focus on sustainability, price, easily accessible materials, lifetime, energy density, as well as control and integration with power generators and consumer devices. This includes digital and data-driven optimisation tools for accelerated discovery, modelling and development of sustainable and safe battery materials.

The work also includes the development of more sustainable ion batteries such as cobalt-free Li-ion batteries and sodium-ion batteries, as well as flow batteries for especially stationary storage due to long lifetime and the use of safe and easily accessible raw materials.

Danish battery players are also competitive in automating, testing and intelligently managing battery energy management systems (BESS) in integration with e.g. the electricity grid, self-generation, and consumption (companies, housing associations, etc.). BESS can increase the utilisation of self-generated power, reduce differences in electricity prices by buying electricity cheap and sell expensive, etc.

Together with research and knowledge institutions, battery companies in the Danish Commonwealth community cover large parts of the classic battery value chain as shown with the battery value chain in Figure 10. The value chain includes raw material extraction, the development of the inner components of the batteries (functional materials) and the construction of total battery solutions (battery cell and package) that can interact with small and large RES plants (application). The 'integration' category shows companies in related technologies, such as the development and production of charging stations and software for controlling and monitoring battery packs.

The battery sector also includes esteemed researchers from the Technical University of Denmark, Aalborg University, Aarhus University, University of Southern Denmark, and specialists from the Danish Technological Institute. In addition, Danish consultancy companies contribute with qualification in relation to the design, optimisation, and realisation of battery projects. Researchers, consultants, and specialists cooperate closely with the companies shown in Figure 10, which strengthens the overall Danish battery sector.

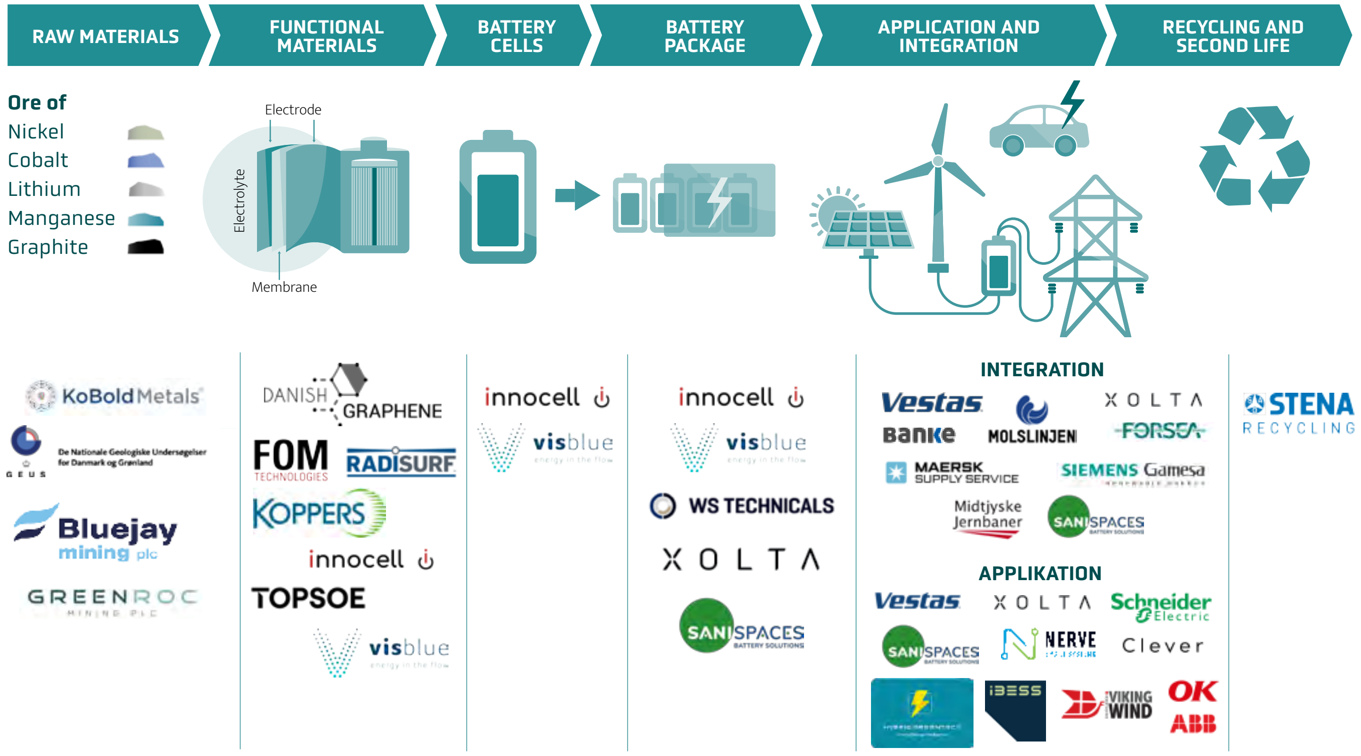


Figure 10: Examples of leading battery companies in the Danish Commonwealth and their location in the battery value chain.

Materials

Denmark has a long-standing tradition of research and development in material chemistry, which is also used in development and studies of materials for batteries, including electrochemically active materials (electrode and electrolyte materials) and other components that are the basis for optimising and improving batteries.
Denmark has an international position of strength in both theoretical and experimental characterisation of the atomic structures of battery materials as well as computer calculations coupled with artificial intelligence, which is essential for investigating and improving important battery properties such as energy density and lifetime. A consequence of these strengths is that Denmark, specifically DTU Energy, now oversees the major EU research project BIG-MAP.

Companies have specific competencies in material development and often collaborate with universities on research and development of battery materials.

Cells

Manufacturing and testing of cells are central to the development of battery materials. VisBlue and Innocell are the only Danish companies with market-related activities within flow batteries and supercapacitors. Li-ion production does not take place in Denmark, as public funding is negligible compared to neighbouring countries.

Due to a rapidly growing need to secure the supply of batteries for European production of electric cars, the establishment and scaling of Li-ion cell production in Europe is under way. Other countries are looking with interest towards Denmark to establish Li-ion cell production, as cell production is energy-intensive, and electricity in Denmark has a low carbon footprint.

Battery Management System (BMS)

Battery packs cannot work without a Battery Management System (BMS) consisting of hardware and software components. BMS monitors the voltage, current, temperature, and state of charge of the cells to avoid overload and extend lifetime.
The cells and BMS are therefore the essential components of a battery pack. European Battery Regulation requires BMS in all batteries above 2 kWh from mid-2024 [49].

BMS can contribute to intelligent disconnection of damaged battery cells, thereby avoiding downtime, which can cause irreparable damage if the batteries provide cooling for transport where continuous operation is paramount. In addition, BMS can accelerate the roll-out of fast chargers in Denmark that supply green power to the electric cars [50].

Energy Management Systems (EMS)

Danish battery companies and operators use specially developed software such as energy management system (EMS) to achieve safe, reliable, and profitable operation of batteries. EMS communicates to the complex hardware of the battery system through an application-programmed interface (API), through which the measurement and control of the hardware takes place. Some EMS can optimise the operation of the battery system by bringing digital tools like machine learning and algorithms into play. For example, EMS can regulate the temperature of households by controlling thermostats.

Reuse and recycling of batteries

Reuse (second life) is preferable to recycling. Recycling involves giving battery packs "new life" by, for example, using used electric car batteries for stationary storage. Recycling includes crushing the batteries to raw materials that are separated and recycled.

The EU's ambitions for increased self-sufficiency of battery materials and expansion of battery production necessitate significant scaling of both reuse and recycling from today's few percent to 70% lithium by 2030 [51].

Strength positions in the Danish battery sector

Denmark is in fierce international competition for development of the battery market. We need to prioritise resources wisely and strategically if we are to be among the leaders. A number of leading Danish battery players have identified niche areas and are competitive in the following areas, of which tree cases subsequently goes into detail with selected companies:

- Development of new cobalt-free battery materials and electrolytes for lithium and sodium ion batteries (Topsoe, AU, DTU)
- Production of functional carbon nanomaterials and organic materials for innovative design and coating of active battery materials (Danish Graphene, FOM, Koppers, AU)
- Development of new, safe and green battery types such as flow and solid-state batteries (VisBlue, AU, DTU, SDU) as well as energy-dense, water-based supercapacitors (Innocell, SDU)
- Integration, control, and automation of battery packs with RE-systems as virtual power plants (Vestas, XOLTA, Sanispaces, AAU) or with refrigerated trailers (Bitzer)
- Direct and complete electrification of light-duty trucks (Banke)
- Intelligent energy management, digitalisation, and automation to optimize customer's energy consumption (Schneider Electric, AAU)
- Consulting and testing facilities for characterisation, safety evaluation and development of battery-powered solutions from low power Internet of Things (IOT) devices to high performing batteries in grid-connected energy storages or electrical mobility (Department of Technology, AAU, DTU)
- Technology neutral tools such as multiscale computer models, machine learning, autonomous laboratories and test facilities that accelerate the discovery and design of new batteries (DTU, SDU, AAU)

Case 1

Topsoe develops cobalt-free cathodes with high lithium utilisation

The company's ambition is to accelerate the green transition by contributing with its in-depth experience on catalytic processes, materials, and the development of green fuels. One of the areas that Topsoe has been working on over a number of years is to develop and scale up production of next generation battery materials for lithium-ion and sodium-ion batteries.

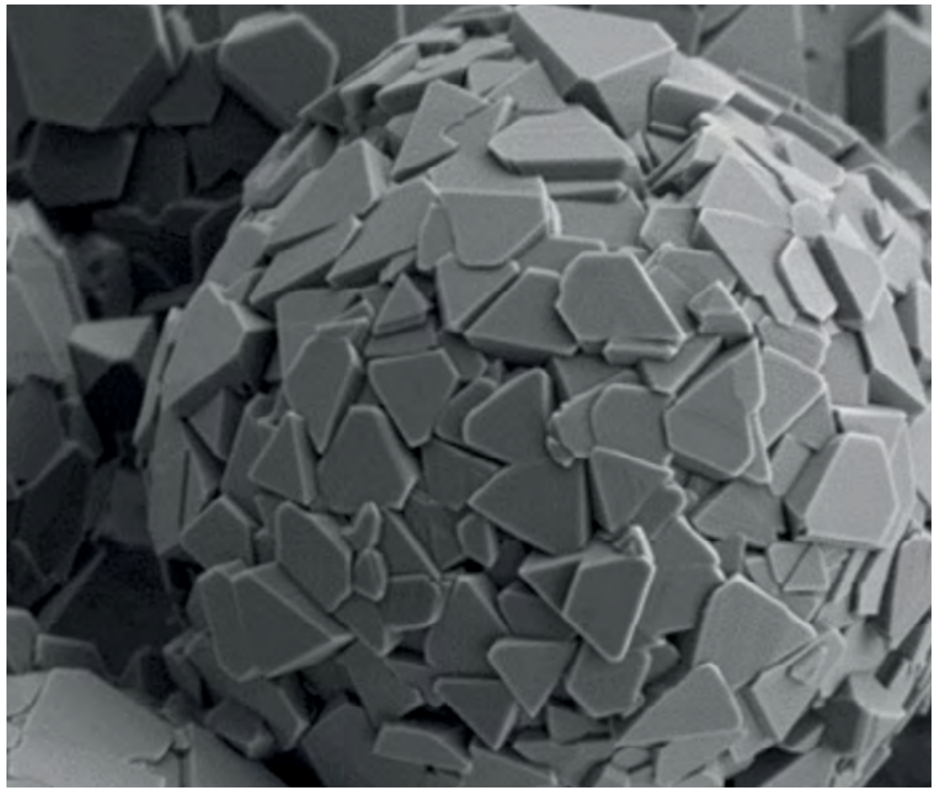


Figure 11: Visualisation of LMNO particles using scanning electron microscopy. The dense round particles have been developed to achieve high energy density in the LNMO batteries.

CHALLENGE

Exponentially increasing demand for batteries especially for electric cars is already creating problems with shortages and rising prices of critical metals for lithium-ion batteries. Among others, these include cobalt and lithium [52].

SOLUTION

Topsoe's lithium-nickel-manganese oxide (LNMO) material for lithium-ion batteries is cobalt-free with a relatively low nickel content and additionally utilises lithium very efficiently.
This makes LNMO a highly competitive and sustainable alternative to conventional battery materials currently used in lithium-ion batteries. The production of LMNO batteries from the battery material is also more sustainable because solvents that are difficult to process can be replaced with water.

Topsoe's LMNO battery enjoys great interest due to a sustained effort towards improving and promoting. In Frederikssund, a pilot plant under construction will have a capacity of more than 100 tonnes LMNO per year with expected production start in 2023. The plant provides the possibility to supply material for demonstration batteries and production mature technologies to build production on an industrial scale. It is expected that the plant on an industrial scale will be located in Northern Europe and produce 50,000 tonnes per year when fully developed.

POTENTIAL

LMNO batteries will be able to be designed for use in various applications. This applies to electric cars, where competitive price and high energy density are crucial. In addition, there are obvious uses for e.g. ferries and trains in need of very fast charging.

More information:
www.topsoe.com
Søren Dahl, lead scientist, Topsoe

Case 2

Visblue produces sustainable battery solutions for storing green power

The company is based on a collaboration between the universities in Aarhus and Porto in 2014 and has received support from both Danish and European funding programmes. Today, VisBlue has more than 20 employees and is a global partner in energy storage solutions with more than 150 installed battery systems in Denmark, Portugal, Germany, and the Czech Republic.

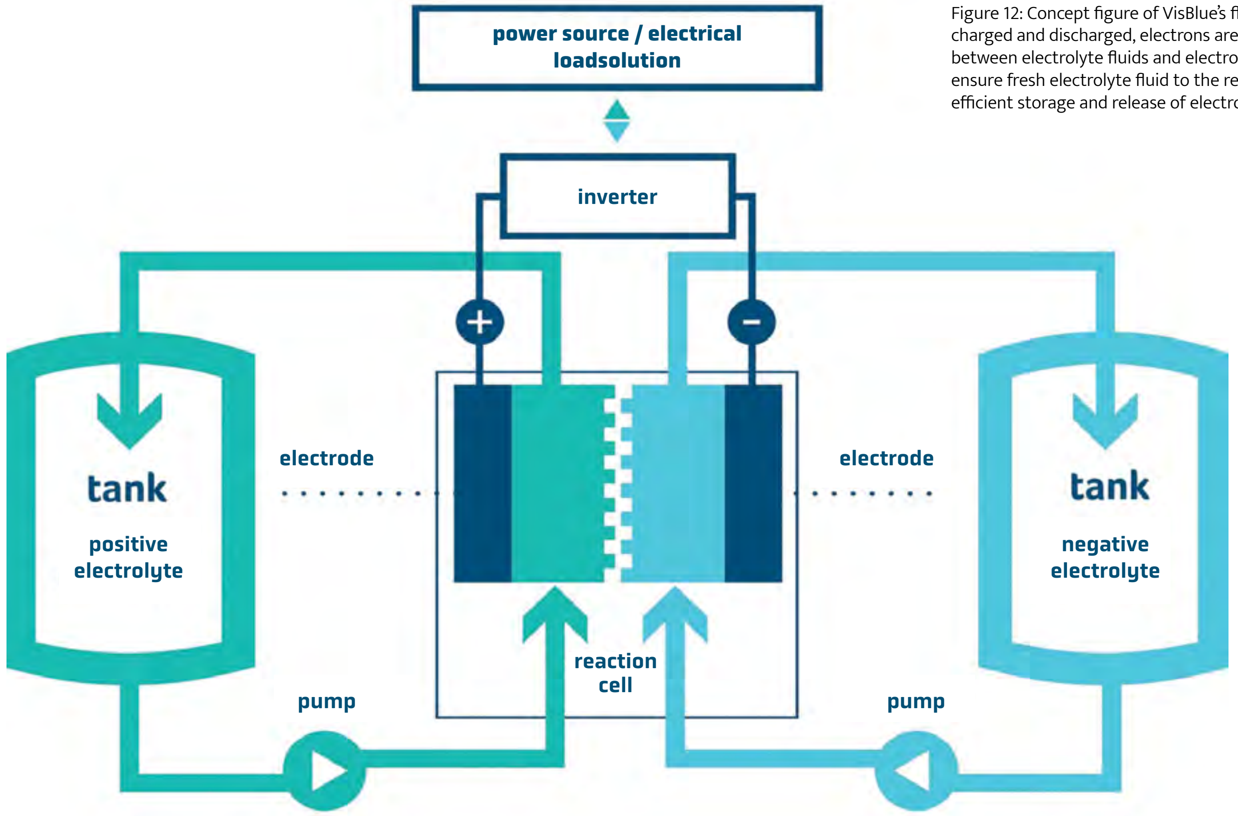


Figure 12: Concept figure of VisBlue's flow batteries. When charged and discharged, electrons are added and released between electrolyte fluids and electrodes. The pumps ensure fresh electrolyte fluid to the reaction cell for efficient storage and release of electrons in the tanks..

CHALLENGE

If we are to ensure maximum value creation of Denmark's massive expansion of wind and solar energy, we need batteries for, among other things, municipalities, industry, housing associations, and self-governing institutions. The batteries must be sustainable both economically and climate-wise.

SOLUTION

VisBlue uses proven vanadium redox flow technology to store electricity in a water-based solution characterised by its non-degradable, non-flammable and low-risk benefits. With a recycling rate of 99% and a lifetime of more than 20 years (20,000 discharges), VisBlue's scalable 40 and 250 kWh flow batteries are a sustainable, safe and long-lasting alternative to standard battery types on the market.

POTENTIAL

With VisBlue's flow batteries, customers can efficiently store electricity generated from renewable sources, such as solar and wind, for calm and cloudy days. The solution is attractive to municipalities, housing associations, self-governing institutions and industrial companies that use flow battery solutions for balancing their power consumption in a sustainable direction, both economically and climate-wise.

More information:
www.visblue.dk
Søren Bødker, CEO and Founder, VisBlue
Mia Voldum, Head of Communications & Culture, VisBlue

Case 3

XOLTA enables businesses and private individuals to optimise renewable energy systems with intelligent control

XOLTA is a Danish-owned company specialising in battery systems for storing energy. The batteries are controlled by a cloud-based intelligent software that optimises the use of the battery for both individuals, businesses, and the common electricity grid. XOLTA has installed more than 15 MWh of battery capacity across more than 1300 plants for both companies and individuals, see Figure 13.

Figure 13: Haarup's machinery factory at Silkeborg has installed 12 XOLTA batteries that store electricity from the factory's solar cells and make the factory self-sufficient with electricity from March to November [53].

CHALLENGE

The growing electricity consumption creates the need for more companies, private individuals, and housing associations etc., to establish renewable and efficient energy systems. In order to limit the load on the electricity grid it is important that more people become self-sufficient with renewable energy.

SOLUTION

The optimum use of renewable energy systems requires that the battery solution can control when batteries charge and discharge from the power grid. All XOLTA batteries are connected to a sophisticated energy management system (EMS). The system's computer-controlled optimisation tools are cloud-based and are connected to each battery. The cloud-based optimisation algorithm automatically keeps the battery's function under control whereby it always performs optimally, taking into account weather conditions, electricity prices and expected future consumption.

POTENTIAL

XOLTA batteries make it possible to optimize energy storage and thus optimize self-produced renewable energy while at the same time helping to keep the grid in balance and delaying the use of the grid to periods of low load. This provides an economic benefit for the individual company as well as the private homeowner and reduces the load on the electricity grid. At the same time, it makes the integration of renewable energy in the electricity grid simpler and cheaper, which supports Denmark's goal of a cost-efficient and green transition.

More information:
www.xolta.com
Dennis Vester, Head of Marketing, XOLTA

POWER-TO-X

The 2020 Danish Climate Law, the Power-to-X Agreement (2022) and a number of policy strategies and support programmes, clearly show that PtX is high on the political agenda and is intended to play a key role in achieving an integrated, flexible and climate-neutral energy system [54]. PtX includes technologies that are characterised by using renewable energy rather than fossil energy to produce the society's vital building blocks such as fuels, chemicals, plastics and more. The technologies encompass many processes and sectors, the area is complex, has many challenges but also great potential for climate, knowledge, and growth.

PtX can help reduce the climate footprint of sectors where alternative solutions, such as energy efficiency and direct electrification, are technically and/or economically difficult to implement or have already been fully exploited.
The corporate commitment to PtX is high as shown in Figure 14 with announced electrolysis plants and the placement of five PtX projects, which will be described in detail later.

Electrolysis capacity in 2030 (MW electricity)

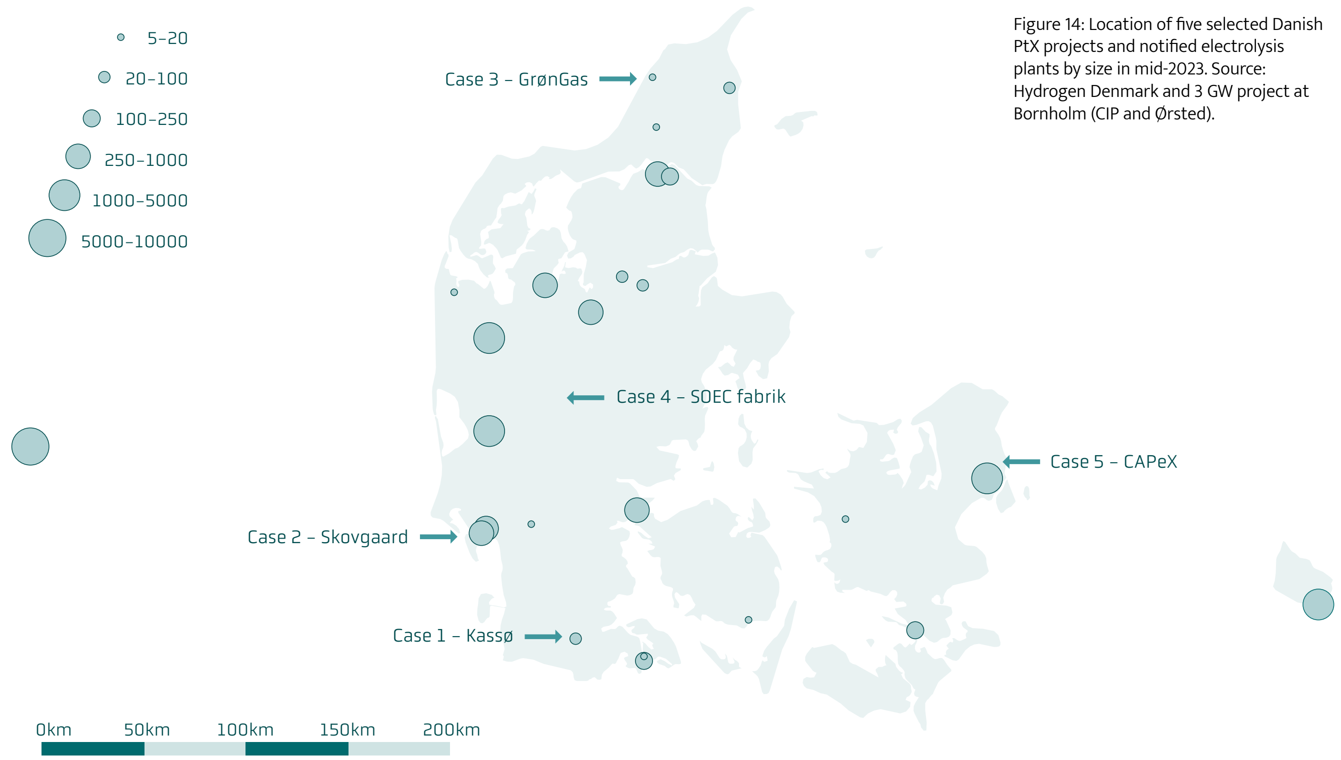


Figure 14: Location of five selected Danish PtX projects and notified electrolysis plants by size in mid-2023. Source: Hydrogen Denmark and 3 GW project at Bornholm (CIP and Ørsted).

The Danish climate policy, together with business and knowledge institutions, have created a common platform with strong competencies, partnerships, and energy infrastructure that make Denmark an obvious place for development and practice-oriented "sandbox" for research, development, and testing of internationally competitive PtX technologies. But there is great international competition for being among the first and leading countries, who develop, scale up and industrialise PtX technologies to export technologies and know-how in the field.

It is crucial that Danish actors quickly acquire and share practical experiences from operating PtX plants in cross-sectoral partnerships, which form the foundation for Denmark to become internationally recognised supplier of innovative PtX solutions. MissionGreenFuels' mission-driven research and innovation partnership supports this objective by developing green fuels for transport and industry by 2030 and 2050. Launched in 2022, the partnership brings together around 90 stakeholders from industry and research. The mission is supported by Innovation Fund Denmark with DKK 200 million and further co-financing from the participating companies.

Denmark's strong qualifications and concurrent interests make it realistic that PtX can contribute to climate goals, ensure profitable market shares and generate knowledge-based jobs, thus creating societal value.

From renewable electricity to socially important molecules

PtX is the conversion of renewable electricity (power) into chemical molecules (X) via chemical processes involving sustainable raw materials as shown in Figure 15. Renewable energy supplies electricity that can split water into hydrogen and oxygen in electrolysis plants.
Hydrogen is an essential building block in the production of chemicals, fuels, medicine, etc., where hydrogen forms molecules through reaction with nitrogen and carbon, both of which can be captured from the air. Carbon can also come from biomass or as residue from biomass-based processes such as CO_2 from biogas production, which is often not exploited. Fossil-emitted CO_2 is not included as it is not designated sustainable.

Hydrogen can react with nitrogen and/or carbon in conventional chemical plants and form respectively ammonia or molecules containing carbon and hydrogen such as methanol, methane, kerosene, and diesel.
Ammonia is the world's second most produced chemical, resulting in large amounts of CO_2 emissions [55]. The climate impact increases due to anticipation of triple production volumes by 2050, unless ammonia production becomes less detrimental to the climate.

Ammonia is mainly used for chemical fertilisers and can potentially be used as marine fuel. Shipping emits a few percent of the world's CO_2, but direct electrification cannot decarbonise shipping, which therefore looks towards potentially greener fuels such as ammonia based on renewable energy.
Hydrogen can be used directly in chemical, steel, and transport industries. Hydrocarbons contain only carbon and hydrogen and are raw materials for the production of chemicals, fuels, plastics, etc. Methanol has the same uses but contains also oxygen. Green methanol can, among other things, be used in the production of aviation fuel.

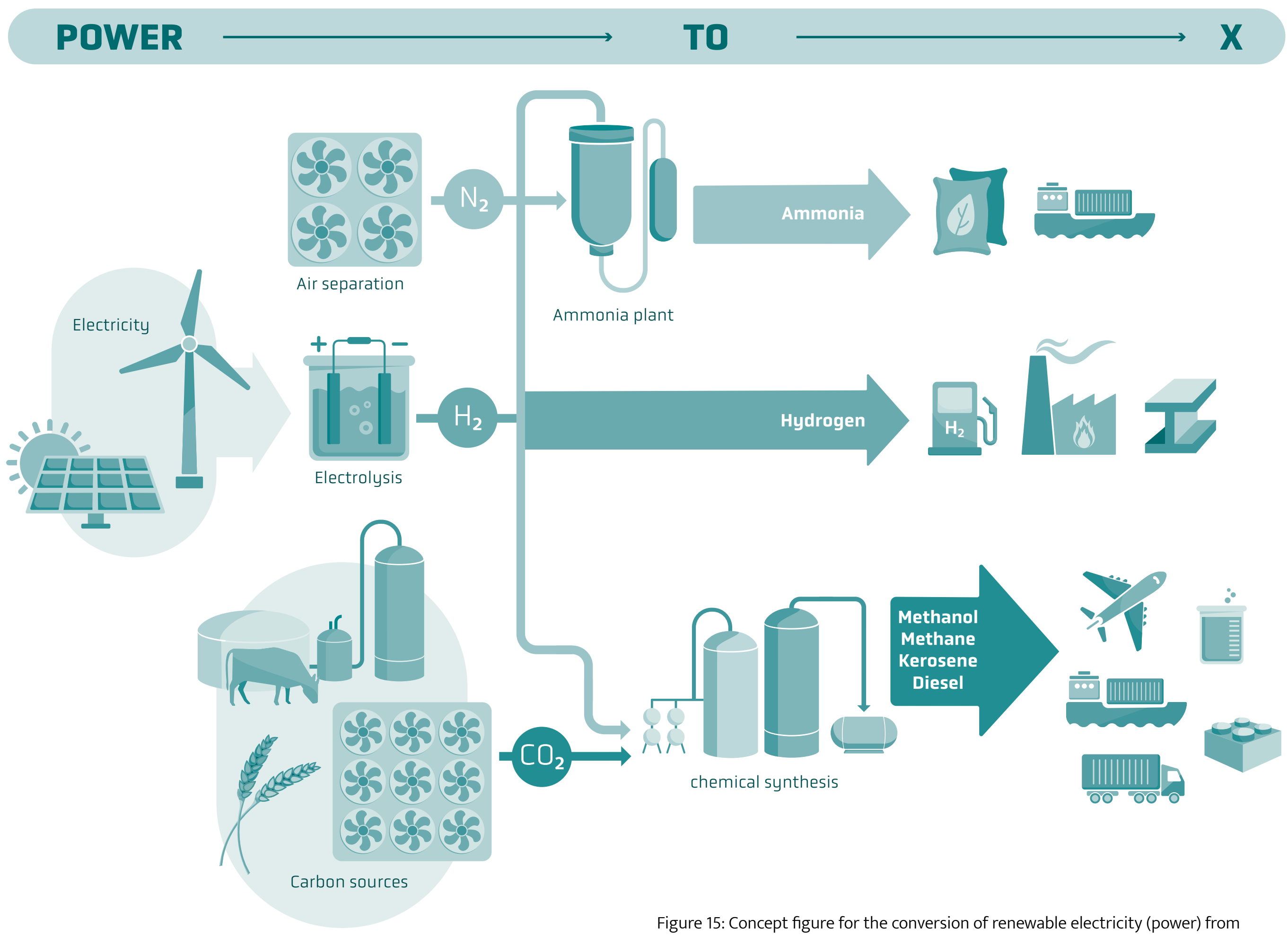


Figure 15: Concept figure for the conversion of renewable electricity (power) from primarily solar and wind in Denmark to energy bound in chemical compounds (X) in Danish context.

Development of the Danish PtX Eosystem

Danish business and knowledge institutions are ready with capital, skills, technologies, and willingness to collaborate within PtX. The advertised electrolysis capacity of the business sector exceeds the Danish Energy Agency's projections as shown in Figure 16.

The Danish Energy Agency expects 0.9 GW electrolysis capacity by 2030 with current policy agreements and 4.9 GW by the beginning of 2030 by meeting climate targets [26] [8]. With the PtX Strategy (2022), a broad political majority adopted a target of 4-6 GW electrolyte capacity by 2030 to reduce 2.5-4.0 million tonnes of CO_2 by 2030, of which Denmark accounts for 2 million tonnes in 2030 [62]. In 2020, the EU adopted a hydrogen strategy with a target of 40 GW electrolysis in the EU by 2030 [58]. Danish PtX players, on the other hand, have announced 25 GW electrolysis capacity by 2030, but only a few, smaller PtX projects are finalised in terms of investment at the time of writing. Not all projects are expected to be carried out by 2030.

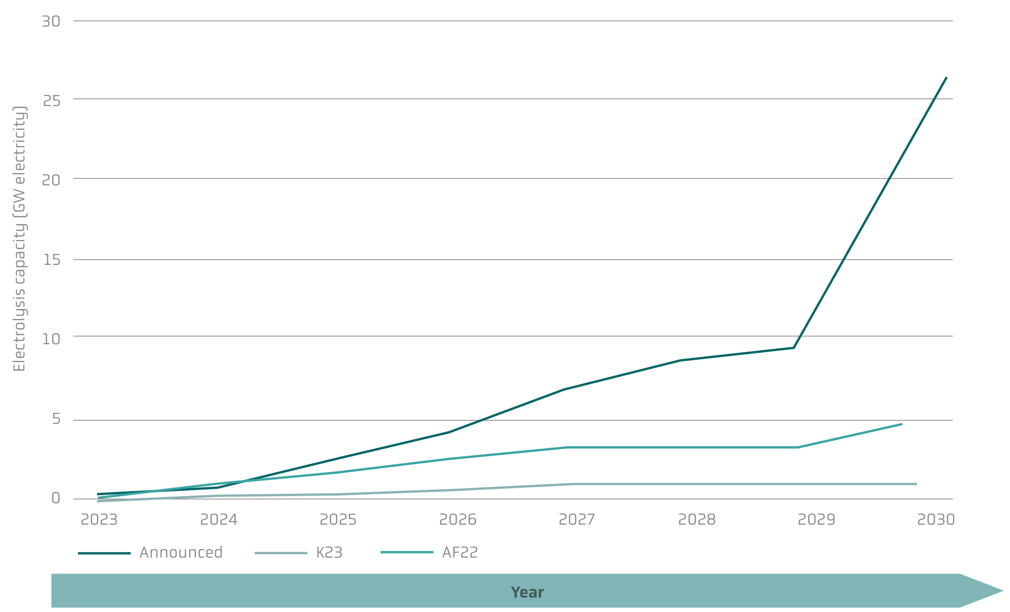


Figure 16: Projections of electrolysis capacity in Denmark to 2030 cf. PtX actors ("announced"), the Danish Energy Agency's Denmark's Climate Status and Outlook 2023 (KF23) and the Danish Energy Agency's Analysis Conditions for Energinet 2022 (AF22). Updated July 2023 with 3 GW project at Bornholm (CIP and Ørsted) and figures from Hydrogen Denmark [56].

In 2023, hydrogen consumption is 0.02 and 1.7 million tonnes per year in Denmark and Germany respectively, which is why Germany is expected to become a major purchaser of Danish hydrogen if large-scale hydrogen production is realised in Denmark [59]. Biogas plants and new hydrogen processing plants can increase Denmark's hydrogen consumption, while existing and future large hydrogen consumers in Germany also can buy hydrogen produced in Denmark. Germany expects a doubling in hydrogen consumption between 2020 and 2030, of which imports will cover 50-70% of the demand [60].

Denmark has strong skills, technical knowledge, and solid experience in electrolysis technology, synthesis, energy efficiency and digitally integrated energy systems (gas, heat, and electricity), which at the same time have high security of supply. The strengths are widely represented throughout the PtX value chain, as shown in Figure 17.

Denmark has a strong tradition of cooperating across professional sectors and authorities, knowledge institutions and industry. Companies have access to highly specialised and innovative labour, biogenic CO_2 from both biogas plants and biomass incineration plants and can consume electricity with a high share of renewable electricity. This also means that Danish companies have the opportunity to comply with EU requirements for green fuel production [61]. Based on an overall assessment, Denmark must be considered an attractive center for strong research and development of innovative PtX solutions.

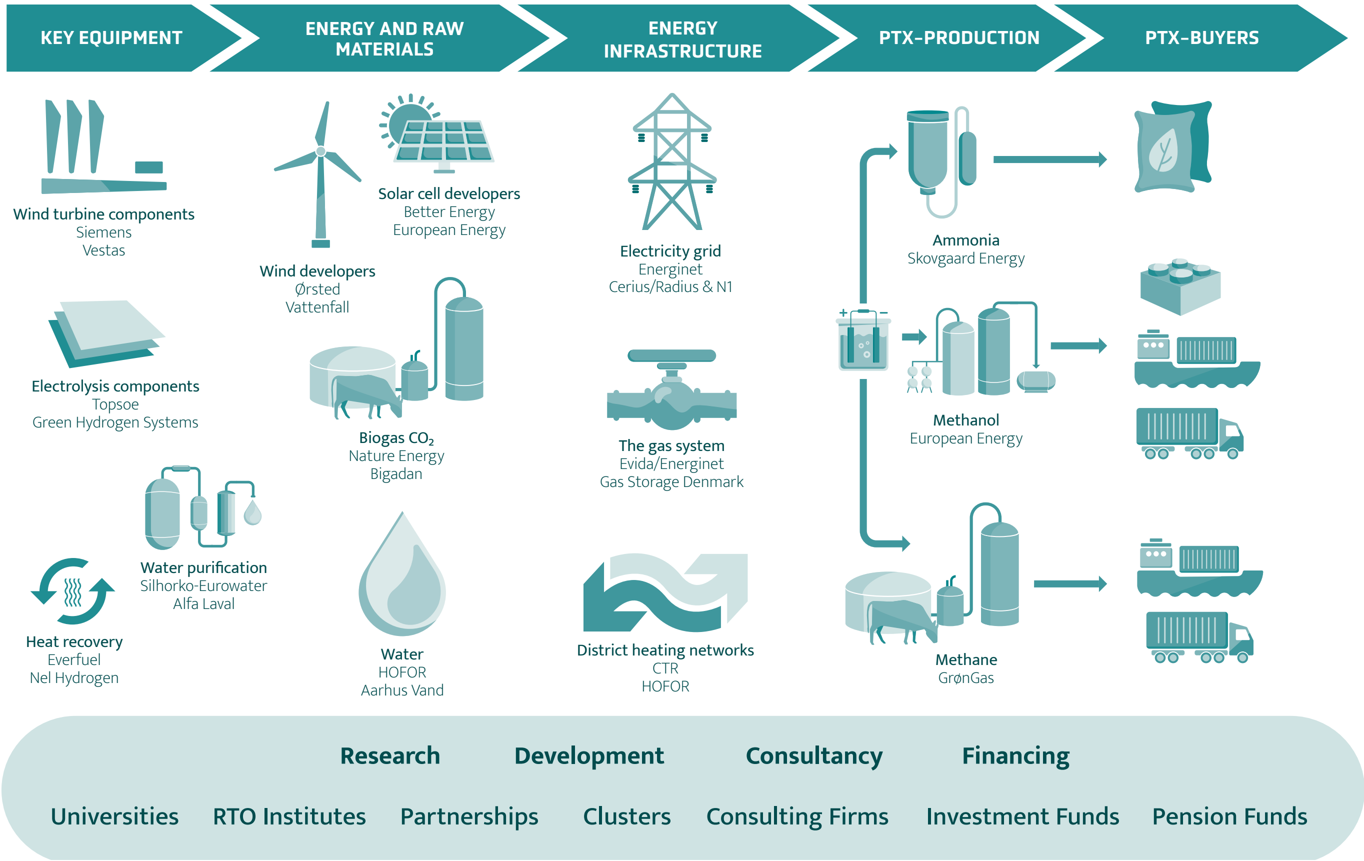


Figure 17: PtX value chain with two key companies in each category. At the bottom are stakeholders that work across and support the value chain. The list is not exhaustive.

Senior manager Anne Hauch shows around Topsoe's state-of-the-art facilities that help develop SOEC technology.

Crucial and selected PtX challenges

In the green transition there is a need for energy efficient and durable electrolysis plants, which at the same time are competitive globally. Research projects can improve electrolysis technologies and their operation, but only to a certain level. The next step is realistic testing and testing of electrolysis plants on a smaller and larger scale in integration with renewable energy plants, biogas, and processing plants to make PtX competitive compared to fossil and other alternatives. Practical experiences raise new questions and create instructive insights for industry, which together with researchers can develop innovative and optimised solutions that improve resource utilisation, efficiency, climate footprint and more.

Maturation of electrolysis technologies

The three best known electrolysis technologies are AEC (alkaline electrolysis cell), PEMEC (proton electrode membrane electrolysis cell) and SOEC (solid oxide electrolysis cell), which over the years have been matured. The technologies continue to have great development and optimisation potential, which can be realised through research, development, and demonstration projects across the value chain. Commissioning of major electrolysis plants and obtaining experience are key to mature technologies, which includes the identification, coordination, and addressing of necessary focus areas. Focus areas are industrialisation, digitalisation, automation, flexible operation, sources of water, as well as integration with electricity grids, gas systems, and district heating networks.

In parallel, research into new materials for electrolysis cells, stacks, and systems, should pave the way for more efficient electrolysis cells and new PtX technologies based on high performance, sustainable, and easily accessible materials. Higher electrical efficiency of the electrolysis process is central to reducing the use of resources such as raw materials, energy resources, labour, and land. Due to resource scarcity, it is particularly important to support research in this field.

In addition comes the purity requirement for water, as ultra-pure water is a fundamental resource for electrolysis plants. A plant of 1 GW with 50% uptime consumes 0.9 billion litres of ultra-pure water or 1.2 billion litres of groundwater annually, corresponding to the annual water consumption of 23.000 persons [63] [64]

Market mechanisms can create competitive demonstration plants

For a number of years, the Danish authorities have given selected projects the status of test zones with fewer regulatory requirements in order to promote testing of innovative solutions. The measures have accelerated technology development but only in the selected areas.
Without capital and businesses to take on the task, we will not see PtX plants on a GW scale, as the propensity to invest is closely linked to how the technologies perform in practice. The key to large-scale PtX is to create clear conditions for competitive demonstration plants. This requires clear, long-term, and market-supporting framework conditions such as tax credits, infrastructure investments, favourable charges and tariffs, as well as rapid, assisting, and efficient regulatory work together with the necessary approvals. Supporting market conditions are a necessary tool to accelerate technology development of integrated and innovative PtX solutions in Denmark.

Involvement of the local community in the construction of new plants

The local community's acceptance or lack thereof is an important aspect in the construction of large energy plants like solar cell plants and wind turbine farms. Projects risk to be delayed or cancelled by citizen groups who are worried about local environmental consequences. The examples are many both in Denmark and in our neighbouring countries. Involvement of citizen groups early in project development is central, which several Danish municipalities and private organizations increasingly practice. Democratic and cost-effective tools are continued dialogue and presence in the local community, establishment of civilian focus groups or citizen groups. It can be in the form of development of recreational areas, consideration of biodiversity and climate as well as different forms of co-ownership. Use of the mentioned tools contributes to local value creation and causes the citizens to grad take an active part in development of the projects to greater extent for the benefit of the local community the project owners and the green transition.

Case 1

The Pioneer Center CAPeX accelerates the development and discovery of sustainable and scalable PtX materials

The Pioneer Center for Accelerating P2X Materials Discovery (CAPeX) is a strategic and transformative research center that works with low TRL levels. The centre focuses on rapid scaling up of newly developed materials, discoveries, and techniques to create value for society and climate. CAPeX is interdisciplinary and transdisciplinary in its methodology approach with a 13-year time horizon to 2036 based on support from a number of Danish public and private foundations. The centre brings together leading experts from five Danish universities (DTU, AAU, SDU, AU and UCPH) in collaboration with three foreign universities and consortia (University of Toronto and Acceleration Consortium, Utrecht University and SUNERGY, and SUNCAT from Stanford University). The centre includes an academy (CAPeX Academy) targeting younger researchers with the participation of leading Danish companies in PtX and other green technologies.

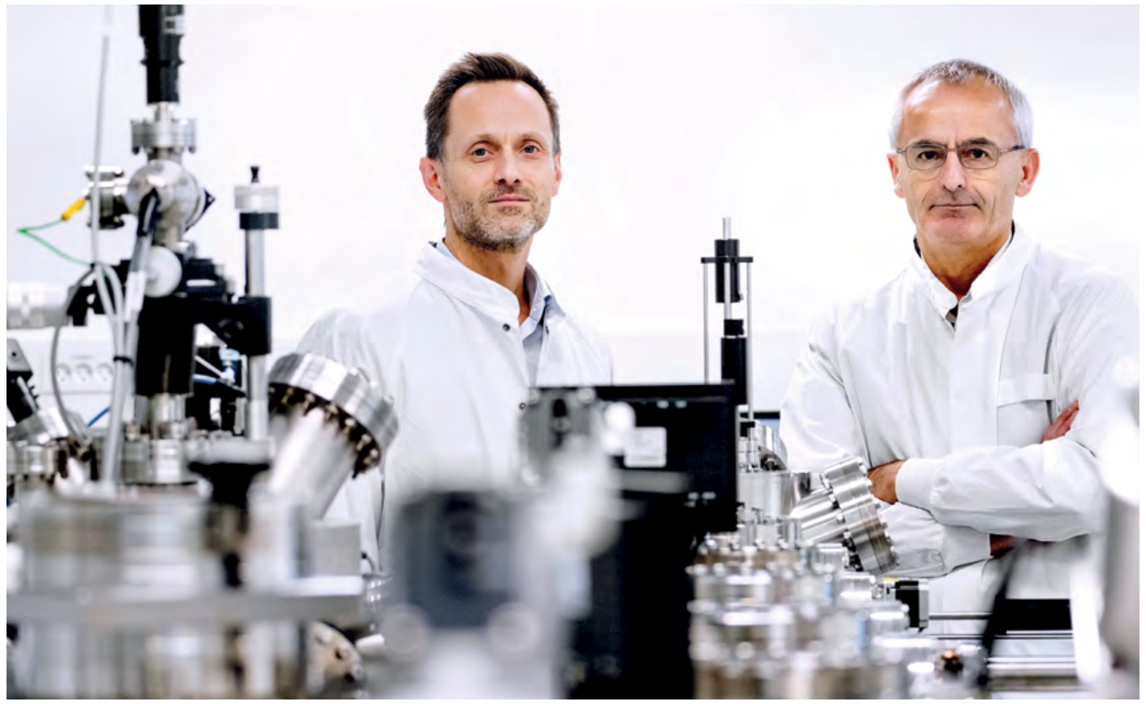


Figure 18: Professor Tejs Vegge, DTU and Professor Frede Blaabjerg, AAU, leads CAPeX.

CHALLENGE

A key challenge for the deployment of electrolysis technologies is to scale up technologies quickly without harming the world's raw materials, economy, and climate. Therefore, it is necessary to collaborate across professional groups and sectors that explore and develop new absolutely sustainable material combinations and sector couplings. In this way, the synergy potential of complex and cross-sectoral PtX solutions can become a reality. Key challenges are speed, complexity, and to succeed with open and cross-cutting cooperation

SOLUTION

CAPeX accelerates the development of PtX materials using AI, computer simulations, experiments, synthesis and fabrication, as well as open and autonomous sharing of data and materials both physically and digitally across disciplines, professional groups, and countries under the leadership of Tejs Vegge and Frede Blaabjerg as shown in Figure 18.

The research project will educate more than 100 PhDs and Postdocs ("Power2Xperts") with international vision and transdisciplinary competencies in the development and composition of materials that can contribute to the transformation of the global energy system by representing nationalities and competencies from around the world.

POTENTIAL

CAPeX's ambition is to develop new methods and autonomous laboratories for the discovery and manufacture of new, sustainable energy materials for PtX purposes. The intention is to improve the efficiency of manufacturing e.g. hydrogen, marine, and aviation fuel with high energy density, as well as sustainable chemicals and bio-electrocatalytic manufacturing of chemicals, fuels, and proteins.

The ambition is to discover new materials up to ten times faster than today, thus accelerating the transformation of the energy system towards carbon neutrality using sustainable materials.

More information:
https://capex.dtu.dk
Tejs Vegge, professor, DTU Energy
Frede Blaabjerg, professor, AAU Energy

Case 2

Topsoe's development of electrolysis cells for highly efficient SOEC electrolysis

Topsoe has 30 years of experience in the development of solid oxide cells (SOC), which has been focused on electrolysis applications, i.e. as SOEC since 2014. The development of SOEC is based on project collaborations across Danish knowledge institutions and industry partners and has been crucial for accelerating the development and commercialisation of the technology. In-house and through collaborations, Topsoe has gained access to cutting-edge research, skills, and methods that promote technology development, innovation and reduce the company's investment risk on the way to market.

Figure 19: Visualisation of Topsoe's SOEC production plant, designed to produce SOEC annually equivalent to 500 MW electrolysis from expected 2025 with options to expand to 5 GW.

CHALLENGE

Technology matured PEMEC and AEC have lower efficiency than SOEC and therefore have an increased need for renewable energy to produce the same amount of fuel e.g. hydrogen [65]. Higher operating temperature opens for using heat rather than expensive electricity to split water into hydrogen but since PEMEC and AEC today typically operate below 100 ºC they can only to a limited extent utilise industrial excess heat to increase efficiency. SOEC consists of easily accessible, recyclable, and cost-effective ceramic materials without the use of precious metals such as platinum. Results are lower supply risk and more circular materials compared to materials used by PEMEC and AEC. SOEC has a high operating temperature above 700 ºC, which results in higher efficiency, which can increase further by using heat from e.g. industries.

SOLUTION

Topsoe expects to deliver Danish-produced SOEC and associated SOEC stacks in 2025 from the factory in Herning, visualised in Figure 19 and scheduled to be completed in 2024. The first 5 GW SOEC cells are already reserved by the American partner and ammonia developer First Ammonia [66].

The fully automated factory is Topsoe's largest single investment, amounting to a couple of billion kroner. Here Topsoe will produce ceramic-based electrolysis cells, which the company currently produces in small quantities in Lyngby. The factory produces and collects stacks of 100 electrolysis cells. 12 stacks assembled make up a module which is part of the construction of actual SOEC systems for PtX installations [67].

POTENTIAL

SOEC has the potential to be operated flexibly, which is essential in a future with varying renewable electricity generation and electricity prices.

SOEC can, more flexibly than the AEC and PEMC, run up and down in load, i.e. varying hydrogen (H_2) production rates. The flexibility means that integrated plants with both hydrogen production and consumption of ammonia, for example, can be highly efficient. SOEC is thus suitable for producing ammonia in interaction with large, remote energy producing plants with variable energy production such as offshore wind turbines and solar cells, where the raw materials nitrogen and water are easily accessible.
Topsoe also tests pressurised SOEC stacks to reduce the number of costly compression steps as ammonia is compressed to increase the energy density.

The SOEC technology is unique compared to AEC and PEMEC, since SOEC can also electrolyse a mixture of water vapour and CO_2 at the same time (co-electrolysis) to synthesis gas (carbon monoxide and hydrogen i.e. CO and H_2 mixture). Synthesis gas is a valuable gas mixture that constitutes essential building blocks for the chemical industry. Realising competitive SOEC requires upscaled and reproducible production of high-performance cells, stacks, and modules. The path to this is through large-scale testing with a focus on mechanical stability of cells and stacks, studies of material durability over thousands of hours, and the development of efficient sector integration solutions.

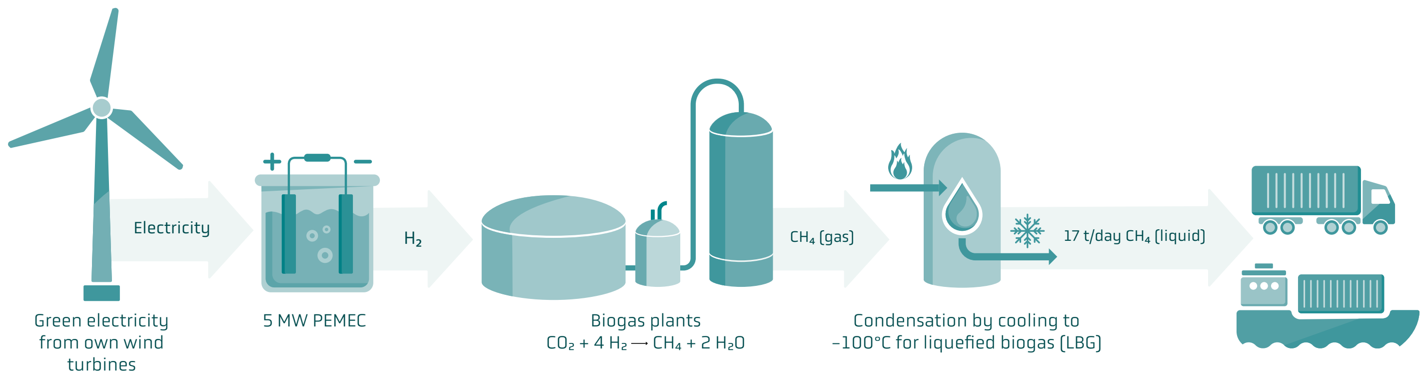
Mere information:
https://www.topsoe.com/processes/green-hydrogen
Anne Hauch, Senior Manager, Topsoe

Case 3

Hydrogen from self-sufficient energy island on land makes road transport and shipping greener

GrønGas Hjørring was established in 2001 and has so far been a biogas plant with electricity production. Now the investment has been made in a new plant that purifies and cools produced biomethane to make it liquid, which increases the energy density. Figure 20 shows the Hjørring plant. Ownership is shared between Jens Peter Lunden and E.ON. The plant processes approximately 100,000 tonnes of biomass annually and produces approximately 5 million Nm³ biomethane. GrønGas Hjørring is part of the North Jutland Business lighthouse named CO_2 vision and has received support from REACT-EU for CO_2 capture.

Figure 21: Concept figure of the GreenGas project. Self-produced electricity supply electrolysis plants that provide bio-gas plants with hydrogen. Hydrogen and CO_2 form biomethane (CH_4), which is condensed into LBG, which is currently intended for shipping and heavy road transport.



CHALLENGE

Biogas contains approximately 40 % CO_2 and 60 % (bio) methane, but CO_2 is often not exploited due to the absence of markets and technologies to use CO_2 from biogas. Danish tax structures limit the use of green alternatives to fossil fuels. The reverse is the case in Germany. The consequence can be a delay in the transport sector's green transition in Denmark.

In addition, electrification of the society means a large increase in electricity consumption and thus load on the electricity grid, which consumption of self-produced electricity can mitigate, but here legislation is often blocking applications behind the electricity meter.

Figure 20: Picture of GrønGas' plant at Hjørring.

SOLUTION

Hydrogen can react with CO_2 and form biomethane through a process called methanisation, which increases the amount of biomethane produced from the biogas plant. The project's applied methanisation technology relies on development collaborations with the knowledge institutions at the AU Foulum Experimental Centre, which have provided the basis for testing the technology on a larger scale.

GrønGas has a vision of making an energy island consisting of its own wind turbines, biogas plants, PEM electrolysis, and cleaning and cooling facilities.
The electrolysis plant consumes electricity from own wind turbines and supplies hydrogen to the biogas plant, where methanisation takes place as shown in Figure 21. The biomethane is cleaned and cooled to liquid biomethane (LBG), a green alternative fuel for diesel trucks and ships. Sales are made to Germany due to favourable tax structures and a well-established market for green diesel alternatives.
Dialogue with authorities and a revision of the electricity supply law (Elforsyningsloven) have directed some regulatory barriers, but remaining barriers continue to limit the opportunities to integrate energy projects and operationally optimize own resource utilisation.

POTENTIAL

The project integrates and utilises multiple green energy sources locally and optimally without connection to the electricity grid. The experiences from the project can kick-start efficient local utilisation of CO_2 in biogas plants, as it eliminates transport costs for CO_2, and replaces climate-harmful fossil gas with biomethane displaces, and improves Denmark's self-sufficiency of gas.

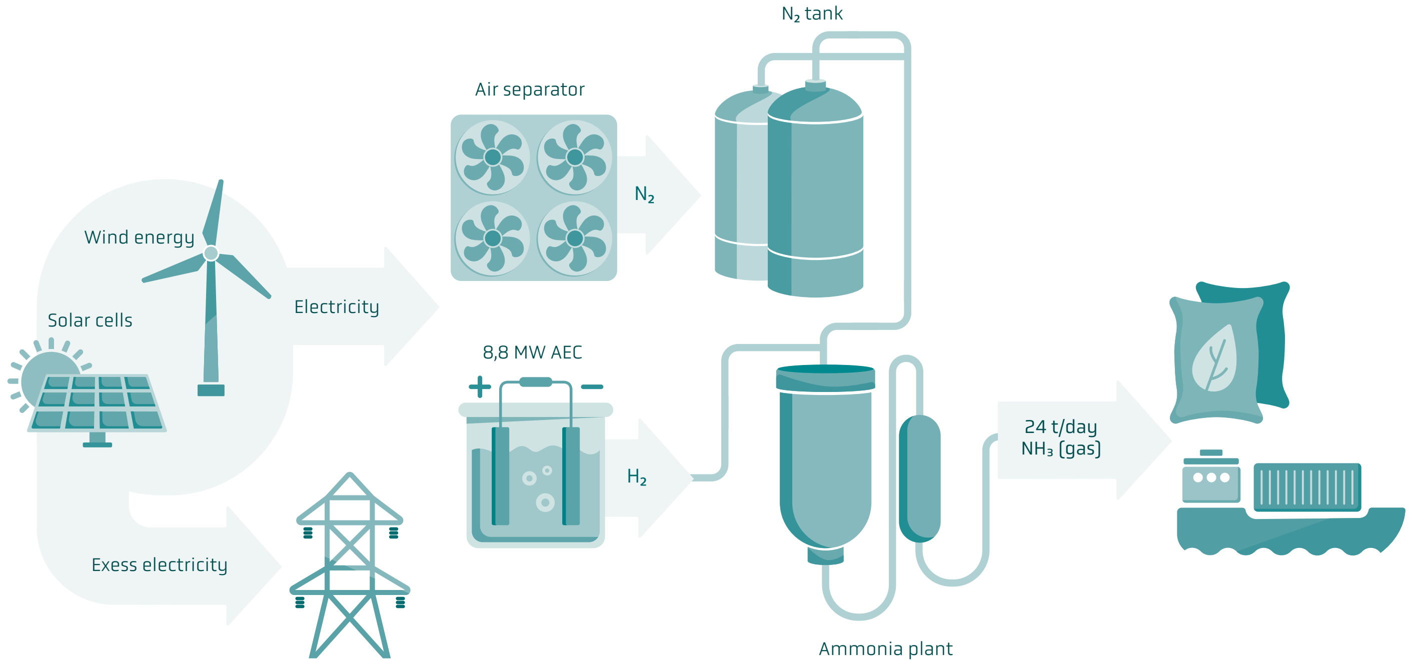
More information:
https://www.grongas.dk
Allan K. Olesen, CEO, GrønGas

Case 4

Dynamic ammonia production reduces electricity grid load and climate footprint from shipping and agriculture

Skovgaard Invest was established in 1999 by Jørgen Skovgaard and changed its name in 2021 to Skovgaard Energy, when the portfolio was expanded from wind turbine projects to solar, PtX, biogas, etc. The company has 19 employees in Lemvig. In 2021, Skovgaard, together with Topsoe and Vestas, were granted EUDP funds, for a four-year Renewable Dynamic and Distributed Ammonia Plant (REDDAP) project. To a large extent, local companies participate in the cooperation to reach targets with the lowest possible use of resources

Figure 22: Diagram of the REDDAP project. Renewable electricity from own renewable energy plants drives hydrogen and nitrogen production, which in the ammonia plant is converted into ammonia (N_2). Excess electricity is sold to the grid.



CHALLENGE

Water, oxygen, and electricity are the easily accessible ingredients for ammonia production, which can therefore be performed at smaller, decentralised plants, although larger upscaled plants offer economies of scale such as lower production prices, and logistics. Dynamic operation is necessary for optimal utilisation of varying electricity generation from wind and solar.

The challenge is to test the integrated, complex interaction of well-known technologies such as weather-driven wind and solar installations, commercial AEC plants and ammonia production in an efficient and realistic environment on a commercial scale.

Previously, legislation required that distribution of own electricity generation and consumption should take place within the cadaster. It severely limited the number of who could feasibly participate in projects and reduced synergies between actors such as owners of renewable energy, electrolysis, district heating and upgrade plants, etc. New legislation partly overcomes this problem

SOLUTION

According to plan, the REDDAP project starts operation in the first quarter of 2024. The project includes its own wind turbines and solar cells, which supply a Topsoe designed ammonia plant with electricity as shown in Figure 22. Hydrogen and captured nitrogen react in the ammonia plant, which is pressurised to 150 bar.

The annual ammonia production of 5,000 tonnes is being stored or sat aside to production of fertiliser and ship fuel [68]. The project integrates well-known components in an innovative way to achieve synergy effects and develop sector integration solutions.

Furthermore, permits have been obtained in a timely manner in relation to technical development of the project, as the project partners have had a constructive, early, and open dialogue with state and municipal authorities.

POTENTIAL

REDDAP can provide experience with dynamic and distributed ammonia plants, which are in high demand globally. Distributed ammonia production can reduce the cost and climate footprint associated with the production and distribution of centrally produced ammonia today.

Applications include green fertiliser, marine fuel, and electricity production in gas engines, gas turbines, and fuel cells. The climate potential is high and can benefit the operating economy of electrolysis plants and renewable energy plants as well as the economy in the form of greater security of supply and reduction of electricity grid expansion.

More information:
www.skovgaardenergy.dk
Pat A Han, CTO, Skovgaard Energy

Case 5

The world's largest e-metanol plant makes toys, medicine and fuel greener

European Energy was founded in 2004 and has green solar, wind, and PtX projects in 29 countries. The company has more than 600 employees. The Kassø project is shown in Figure 23 and will be the world's first commercial e-methanol plant with expected start of operation in 2024. The project involves Northern Europe's largest 340 MW solar park owned by European Energy. The Kassø project has shared ownership (51/49) between European Energy and Mitsui.

Figure 23:
Visualisation of completed e-methanol plant at Kassø in the foreground and photovoltaic park in the background.

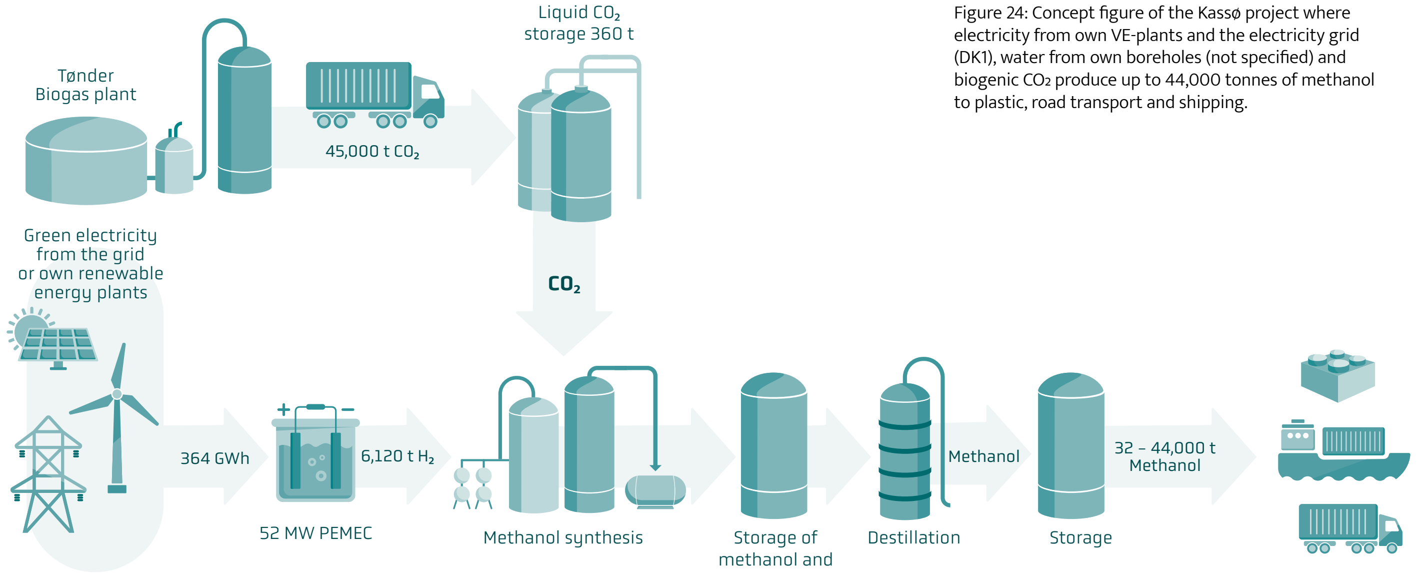


Figure 24: Concept figure of the Kassø project where electricity from own VE-plants and the electricity grid (DK1), water from own boreholes (not specified) and biogenic CO_2 produce up to 44,000 tonnes of methanol to plastic, road transport and shipping.

CHALLENGE

Fossil methanol is among the world's most produced chemicals at around 100 million tons per year, but methanol production is climate harmful and its applications in the plastic industry and heavy transport off- and onshore are difficult to electrify.

Specific challenges in the Kassø project include the supply and handling of water in relation to the electrolysis plant, connection to the electricity grid, and approvals from several authorities without experience with similar projects. Besides, the PtX-market is immature, which calls for build-up of value chains and new legislation.

SOLUTION

The Kassø project converts electricity, CO_2, and water via PEM electrolysis and processing plants into e-methanol as shown in Figure 24. Half of the electricity comes from its own solar park and half from the grid, while 90,000 m^3 of water from own wells and 45,000 tonnes of biogenic CO_2 from Tønder biogas plants constitute the annual remaining raw materials for the PtX plant.
With a capacity of 52 MW and up to 7,000 annual operating hours, the electrolysis plant can produce up to 44,000 tonnes of e-methanol depending on electricity price, own production of connected renewables and other operating conditions.
The methanol is distributed to Maersk (ship fuel), LEGO (plastic), Novo Nordisk (plastic) and Circle K (fuel for road transport).

POTENTIAL

The methanol plant is the world's first e-methanol plant and involve many integrated processes that operational experience can help optimise. The project is unique in that it is done on commercial terms without public support, which is a crucial factor in deploying the solution on a global scale. E-methanol can directly replace fossil methanol and contribute to a climate-neutral transport and chemical industry.

More info:
www.europeanenergy.com
Lotte Lindeloff, Director of PtX Development, European Energy
Martin Sloth Jensen, Project Coordinator, European Energy

SYSTEM INTEGRATION CAN MAKE THE ENERGY SYSTEM STABLE, PROFITABLE, AND GREEN

Historically, Denmark has been supplied with energy from oil and gas production from the North Sea and large central power plants that have consumed domestic and foreign energy sources. Danish oil refineries have produced liquid fuels. In the future, energy supply will become more decentralised in a climate-neutral energy system due to decentralised renewable energy sources, especially from wind, solar, and biomass. This results in a more variable energy supply but also creates new opportunities and challenges for the energy system. Geothermal is a green, stable heat source with low space requirements which presumably also represents a significant role in the future energy system [69].

PtX plants, data centers, heat pumps, and energy storages represent new technologies that partly consume but can also contribute to the storage and conversion of large amounts of energy. The future energy system becomes more complex with the task of integrating otherwise traditionally siloed sectors to create new synergies for the benefit of the whole society. Smart and automated system integration can fulfil synergy potentials that support the economy, improve utilisation of resources, and accelerate the green transition. This requires a dedicated, long-term, and coordinated effort from all stakeholders in the energy system as well as decision-makers, investors, and private and public funds. The efforts must also be cross-border, as Denmark is closely connected with Europe in terms of trade and exchange of electricity and gas.

This chapter unfolds the concept of system integration, which is put into a Danish context with a description of existing system integration solutions at different levels from close to citizens to pan-European. Danish core competencies in system integration are presented with reference to previously described cases in the sections on thermal, batteries, and PtX.

What does system integration mean?

Sector integration concerns electricity, heat, transport and industry, but it can also involve other supply areas such as water, wastewater, and waste. System integration can tie sectors and their energy infrastructure together in a socio-economically optimal way. Denmark is internationally known for integrating electricity and heat into CHP plants as well as identifying and developing solutions across sectors and disciplines. For the overall Danish energy sector, this has already resulted in the roll-out of cost-effective solutions, which, however, still have a potential for development. Key tools to optimise solutions are digitalisation and prediction of energy needs and production.
System integration is at the heart of building the energy system of the future. The interaction can take place at several levels, including transnational, national, industry and citizen, where the level affects potentials and applications.

Transnational level of supply

Denmark's electricity grid and gas systems are closely integrated with those of our neighbouring countries. Integration makes it possible to transport and exchange energy freely and efficiently across borders, improving the use of renewable energy sources, closing price differences between countries, and increasing security of supply in Europe. Energy trade is not only about climate, economy, and security of supply; but also about security and foreign policy, so transnational energy cooperation should be a top political priority. National silo thinking represents a major barrier to pooling forces and developing competitive solutions for the common benefit of climate, economy, and security.

National level of supply

Cogeneration plants demonstrate cost-effective cogeneration of electricity and heat, where Denmark enjoys international recognition. The technology has ensured Danish consumers low, stable electricity and heat prices. Future renewable energy production will mean that the power plants will be used for fewer hours of the year, but it is crucial to continue using and recovering the surplus heat from electricity generation in the reduced hours of operation. Heat pumps and boilers have already become increasingly integrated into the district heating sector with new possibilities for flexible and greener heat production in interaction with heat storage, see the section on thermal energy storage; *Case 2 Flexible and innovative pond heat storage provides cheaper and greener heat for district heating customers.*

Agriculture is another key area where residues are converted into gas in biogas plants that supply Danish gas customers with green gas. Biogas plants have the potential to be integrated with PtX plants, thereby recovering otherwise diverted CO_2 into green fuels, see the section on *Case 5 – The world's largest e-methanol plant makes toys, medicine, and fuel greener; or methane via methane*, see section on PtX *Case 3 – Hydrogen from self-sufficient energy island on land makes road transport and shipping greener.*

Industrial level

Companies in civil engineering, construction, and manufacturing sectors burn gas to drive heat-intensive processes at high temperature but the excess heat is largely not recovered, see the section on thermal energy storage *(Case 3 – Heliac provides cost-efficient, CO_2-free, and flexible storage of renewable and excess heat in stone storage).*
Industries can recover their waste heat by establishing integrated solutions that store and later recirculate heat as process heat for internal use. Another option is to allocate the heat in the district heating network or to other nearby heating demands.
There are few technologies that can deliver green high-temperature heat, but there are developments in the field of high-temperature heat pumps (Technological Institute etc.) and concentrated solar power (Heliac, Aalborg CSP, etc.) that have the potential to deliver green high-temperature heat to the industry.
PtX systems generate heat that can maintain the operating temperature of the plant or be stored to meet later needs or disposed in the district heating network. The result is resource optimisation and the opportunity to earn revenue from more source than just hydrogen production.

Citizen level

Renewable energy communities may consist of citizens, associations, SMEs, municipalities, authorities, etc., but not electricity distribution companies, and engage in the consumption, generation, storage and supply of energy also using the collective electrical grid [70]. The Communities are the basis for realising local synergies between otherwise standalone legal actors, who cannot themselves carry the financial burden of renewable energy installations and systems. Community-owned energy systems equipped with local renewable energy systems can replace fossil-based energy supply by actors in remote areas such as holiday homes and support the electrification of society.
For many years, Denmark has had local operations and ownership of district heating companies rooted deep in the local community. This very form and approach should continue to be supported through local ownership and trust through supportive and sensible regulation, as we propose in recommendation 2.3 on batteries. E.g., cars can flexibly charge electricity from the grid using digital tools thus contributing to balancing electricity consumption and supply.

Realising synergies in system integration

Unconnected electricity grids operate in island operation, see PtX Case 3 section, which is generally less efficient than interconnected and transnational electricity networks that exchange electricity and optimise the generation, consumption, storage and transmission of electricity. Separated energy sectors should be replaced by coupled energy sectors, which pave the way for flexibility provided by different consumption units and types. This enables the system to handle increased volumes of fluctuating energy production. Addressing mismatches between energy production and consumption may involve energy conversion such as electricity for heat or green fuels.

Different types of energy storage can facilitate switching and conversion, so energy storage should be promoted with an eye for their value from a system perspective and from an overall societal perspective.
Realisation can be done by:

1. Co-location of energy production and consumption
   a. Energy storages can promote colocation, which may reduce transport costs and increase the possibility of local use of self-generated energy which would otherwise be unused or require expensive infrastructure to transport. Examples are the thermal energy storage sections Case 3 and PtX Case 3.

2. Energy efficiency
   a. Examples include electricity rather than fossil fuels for transport purposes and heat pumps as a substitute for oil and gas boilers for heating households. Energy storage can make energy efficient solutions more profitable.

3. Residual heating and electrification
   a. Energy storage should be considered across sectors to optimise the utilisation of residual heat and support direct electrification.

Analyses of leading Danish researchers show how otherwise unused energy flows; such as waste heat, excess electricity, and more; can be utilised through energy conversion and storage [71] [72] [73]. Such holistic analyses are crucial to achieving a cost-effective, secure, and climate-neutral energy sector.

Research and development support is needed for the management, modelling, and integration of energy systems, where energy storage and flexible energy consumers play key roles. Optimised system solutions also require the development of components in the energy infrastructure and digital tools to predict energy consumption, production, and storage to act on based on it.

In the coming years, we will learn from existing and new demonstration plants in different technology areas as described in the previous cases. We must recognise that the realisation of new market designs also entails errors. Demonstration of solutions is a prerequisite for later commercialisation and requires simple, transparent framework conditions that promote the appropriate integration of energy markets at all levels. In addition, the Danish Energy Agency's objective technology catalogue of energy storage solutions can be used by investors and industry owners to compare storage solutions and thereby help speed up the development of central system solutions.

System understanding leads the way to a climate-neutral energy system

Sector integration is key to achieving a cost-efficient and resource-optimising green transition [74]. The realisation requires research, development, and demonstration of innovative and digital system solutions across sectors, technologies, and levels supported by energy models and infrastructure components. In addition, there is a need to promote investment in energy storage by establishing clear tax structures and framework conditions for energy storage.
Danish power plants have a capacity of 4-5 GW with production in 30-40% of the hours in a year [26]. The capacity may be combined with large energy storage to ensure backup in the green energy system of the future, but the number of operating hours can be halved through electrification and massive expansion of wind and solar [75].
However, the solutions cannot alone meet the synergy potential, but must be part of a strategic energy planning that identifies appropriate areas for flexible and inflexible energy consumption, renewable energy plants, PtX plants, data centers and more. At the same time, system integration creates dependencies between sectors that energy storage, flexible operation, and energy infrastructure can alleviate and exploit.

Below are three tools that are essential to achieving a climate-neutral society. However, several tools are needed and the list is therefore not exhaustive.

1. New consumption (electric vehicles, PtX, large heat pumps, etc.) must be flexible in such a way that they can increase the volume and use of renewable energy sources

2. Establish and utilise energy storage flexibly and across sectors by dimensioning storages to store energy production for identified end-use

3. More renewable energy and flexible electricity consumption means fewer operating hours of power plants moving towards 10-25 % of the hours in a year depending on the weather, but with about 5 GW capacity as today. The power plants must be flexible and able to start and stop energy production quickly.

Need for energy storage in a climate-neutral energy system

Energy storage supports a flexible energy system in different sectors, as shown below.

- Heat storage and conversion below 100ºC are commercial solutions that contribute significantly to the supply of district heating. Molten sodium salt is also on the market and can store heat at high temperature while hot rocks (see section thermal energy storage Case 3) and hydroxide salt are under development, see section thermal energy storage *Case 4 – Hyme stores renewable electricity in molten salt for power supply and industrial process heat.* Energy storage solutions at even higher temperatures require additional technology development.

- Chemical storage is cost-effective on a large scale, as demonstrated by Denmark's two gas storage facilities in Lille Torup and Stenlille. In the future, chemical storage could also include green fuels such as:
    - e-metanol, see the section on PtX Case 5
    - e-ammoniak, see section on PtX Case 4 – *Dynamic production of ammonia reduces electricity grid load and climate footprint from shipping and agriculture*
    - e-kerosene obtained by electrolysis and chemical synthesis

- Electricity storage in the form of batteries is too costly and resource-consuming for large-scale deployment for energy storage. Batteries, on the other hand, can solve local bottlenecks and deal with short-term imbalances in the power grid. Batteries are already an increasingly part of the transport sector, where many people store electricity during periods of low electricity prices to consume later for mobility needs, see more in the section on batteries.

PROFESSIONAL AND ACADEMIC EDUCATION IS A PRIORITY FOR THE GREEN TRANSITION

Denmark has a strong green sector with many employees, creating great value, growth and supporting export. It is a good starting point for delivering solutions and value for a green transformation of the whole society by 2050 [76].

However, the green transition, including energy storage, is challenged by skill shortages in particular in the industrial and construction sectors, where demand of 10,000 full-time equivalent is expected to increase by 2030 [77]. The construction projects in the infrastructure plan alone are expected to require approximately 60,000 FTEs [78].

By 2030, it is expected that we will be short of 78,000 skilled and 20,000 engineers and technical/ IT graduates. Similarly, there will be a shortage of 26,000 with medium or long education in the field of social science [79]. The green transition accelerates the need to update skills across all levels of education and industry and at all stages of the value chain. However, analyses do not point to major sectoral shifts, with some sectors becoming very large at the expense of others, and Denmark must therefore primarily upskill – not re-educate [80].

The public procurement of continuing education and training for the green transition is lacking. This applies both in relation to the content of the training programmes, the competences of the professional teachers, and the flexibility and the possibility of accessing the courses digitally [76].

More employers are therefore using private upskilling, internal courses, networks, etc. and fewer and fewer people use the public continuing education system (VEU). Several companies use external consultants and buy knowledge without necessarily focusing on their own learning.

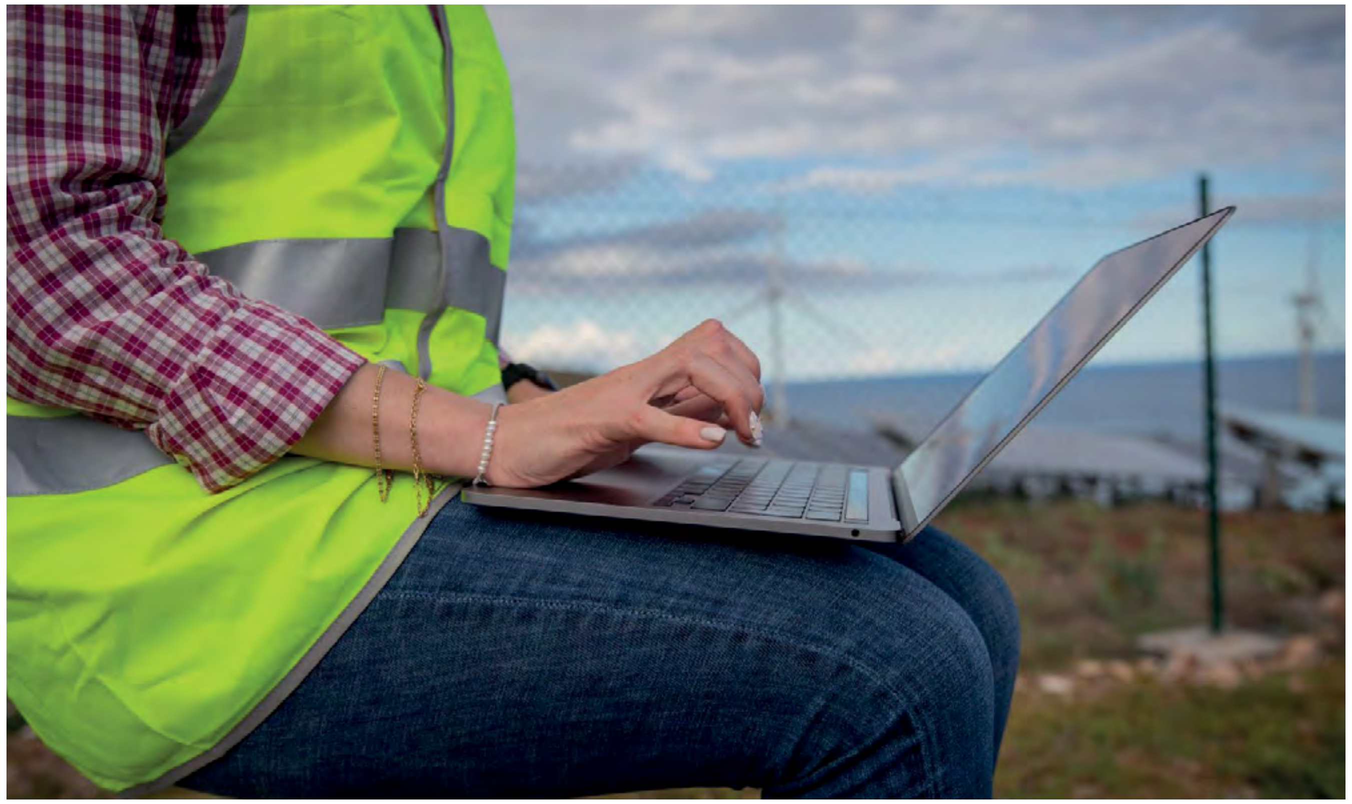
Digitalisation plays a crucial role in the green transition and places additional demands on competences. Fortunately, Denmark and Danish companies have a strong digital starting point, which to a large extent already uses advanced digital technologies. Here too, however, labour shortages are challenged, and SMEs in particular are lagging behind in both the digital and green agendas [80]. Digital competences, interdisciplinarity, a green mindset, knowledge of reporting and documentation of sustainability, as well as innovation are competences for the green transition across sectors [77]. In addition, specific skills are required for the development and implementation of specific technologies.

Many companies want to change to the green but are waiting because the technology and knowledge of which path to go is not yet ready. In particular, SMEs lack knowledge of what it will require of skills to lift the green transition. What green technologies and solutions are you looking for? What materials and what fuels?
Large companies point out that the challenge is, among other things, that politicians do not direct the work on the green transition, so there are no political green agreements and initiatives for energy-intensive industry, the financial sector, defence, trade, life-science and biotech, aviation, production, service and IT business [77].

Education

Denmark has a reasonably adaptable education system. However, there is a systemic delay from the recognition of a need for new skills and the readiness of the graduates. The steering mechanisms are not geared to quickly transform the content of training and respond to a situation where the demand for skills changes faster than in the past [82].

Denmark is behind in terms of educating enough people in the field of education, which is central in the green transition. Too few young people choose vocational training, and too few young people choose STEM in higher education [7].



There is great potential in bringing business and universities closer together. In particular, the large companies have a desire to get closer to research and development, exchange experiences and translate knowledge into business and growth.

In DaCES Working Group for Education, representatives from key companies and universities have worked to identify the need for skills in energy storage.

The work in the group has so far resulted in an individual customised flexible master focusing on upgrading skills and continuing education. Here, individuals with minimum a Bachelor of Technology or Science, followed by two years of relevant professional experience, can take courses from four Danish universities. The programme is flexible both across universities and in duration. It is thus possible to take courses offered by AAU, AU, DTU and SDU, and the programme must be completed within 6 years. The courses are divided into three subject areas: Energy storage technologies, P2X, and system integration. Read more about the flexible master on DaCES' website.

It is also the idea to establish a study community under the auspices of DaCES for the future master students. DaCES' Education Working Group will also establish a project fair where companies, universities, and students can propose projects and find inspiration and collaborators. The project exchange will bring together existing initiatives from the four universities as well as companies.

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