RESULTS FROM AN URBAN LIVING LAB

ENERGYLAB NORDHAVN

Terminology

Energy flexibility: Energy flexibility can be in time, place, or form—displacement of the energy flow in time, energy flow transfer to another location, or the switch between using different energy carriers for the same energy service.

Energy sectors: Sectors are electricity, heat, and gas supply as well as consumption in buildings, industry, and transportation.

Energy services: Energy-based services that the customer needs—not energy, but the services that the energy provides, e.g. comfort (rather than heating/cooling).

Fuel shift: Provision of the same energy service with a shift between energy carriers. This could be the production of domestic hot water based on either district heating or electric power.

Integration: Integration of the energy system includes 1) conversion between sectors 2) more energy sources for the same service and 3) market integration.

Interoperability: Characteristic of a product or system, whose interfaces are completely understood, to work with other products or systems, at present or in the future, in either implementation or access, without any restrictions.

Low-temperature district heating: District heating at a temperature level where the hot water can be produced through a direct heat exchange (flow temperature around 55°C).

Peak shaving: Controlled consumption reduction when other consumption in the area is maximized, e.g. around the cooking peak between 17:00 and 20:00, but also for district heating peak loads, which are traditionally handled by increasing production.

Smart energy: A cost-effective, sustainable, and secure energy system integrating and coordinating renewable energy production, infrastructures, and consumption through energy services, active players, and new technologies.

Stable and robust system: The energy system operation should be stable in any anticipated operating situation as well as be robust in unforeseen incidents and development over time (e.g. technology, prices, conditions).

Ultra-low temperature district heating: District heating at a temperature where boosting (temperature increase) is necessary to produce hot water (flow temperature around 45°C).

Contents

Copenhagen, 20 January 2020

Preface

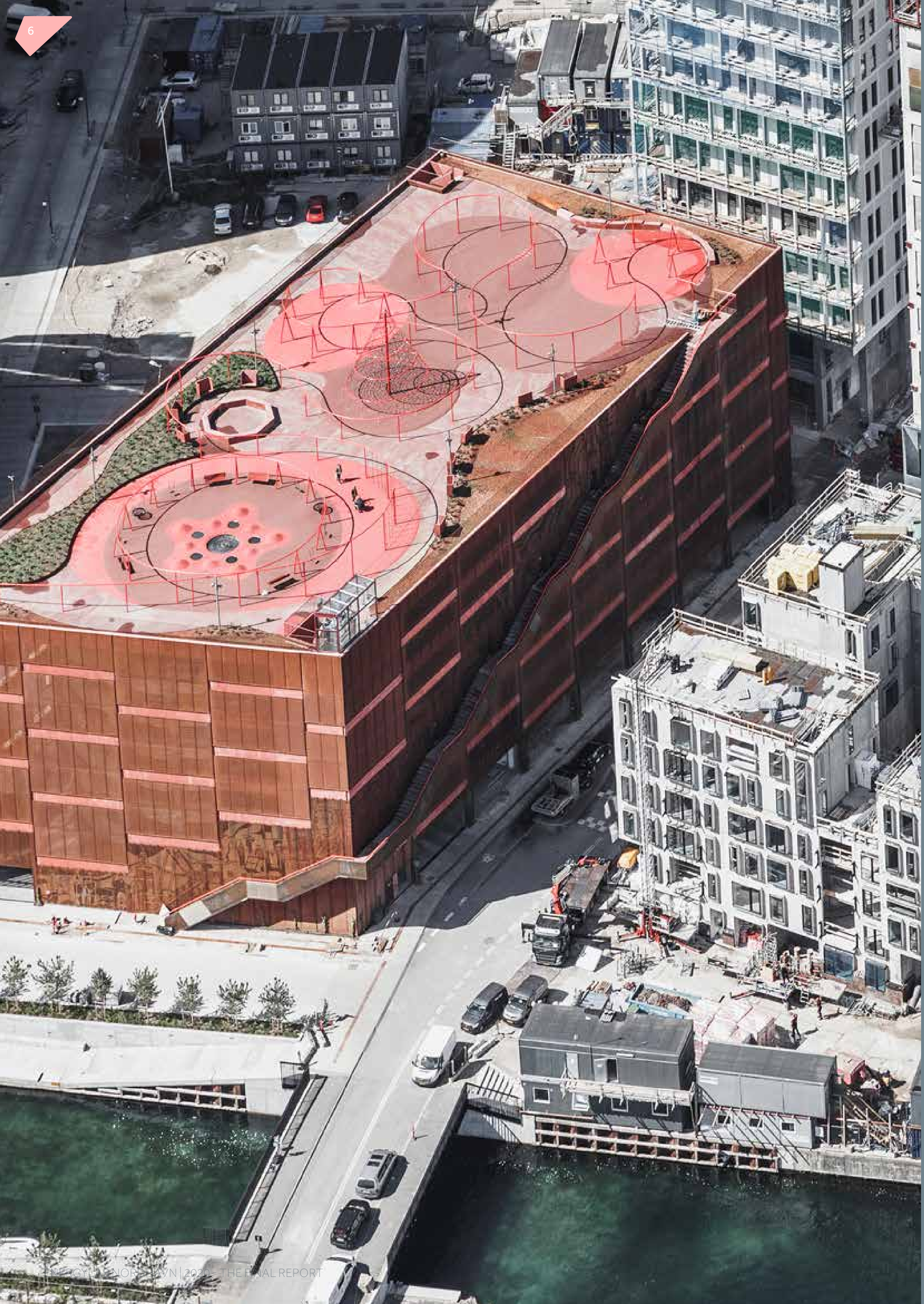
EnergyLab Nordhavn was formed in 2015 as a triple helix, bringing together academia, industry, utilities, and local government to pursue solutions for the design and operation of a cost-efficient and integrated energy system for the future—all based on our living lab in Nordhavn in Copenhagen and the innovation power that such a physically integrated place can offer. The project builds on Copenhagen's power grid and district heating network, but also ventures far into the built environment and private dwellings to co-model and co-simulate these in order to unlock their flexibility potential.

Over the course of the project, the public, private partnership has proven its worth. New ways to unlock heating flexibility will reduce the need for peak-load boilers in the district heating network. New clustering and disaggregation methods will allow the power grid operator to plan and operate with new types of electricity consumption patterns. New grid services are being demonstrated using a smart, large ammonia-based heat pump system. Going forward, these and a number of other solutions will be implemented and scaled by HOFOR, Radius, ABB, Danfoss, and METRO THERM, and the experience gained from e.g. the battery and the large heat pump is being used by the industrial partners in their value proposition. The living lab will be allowed to continue as a local network organization with the EnergyLab Nordhavn name and brand, continuing to use showroom, and opening it up to other stakeholders working within sustainable city development.

The project has shown how important it is to carry out demonstrations in real life, to not only explore technical aspects, but also to identify regulatory barriers, and to unveil routines and organizational bottlenecks for the necessary transformation. I hope that you will be inspired to take a closer look at the work of the great team behind EnergyLab Nordhavn, including the results which require significant expertise in order to fully grasp them.

It has been a fantastic journey, and I would like to thank everyone involved for all their efforts and creativity. I'm looking forward to following our methods and solutions as some of them scale to contribute to decarbonizing our energy consumption. With the recently announced ambition of reducing Danish emissions by 70% in 2030 compared to the level in 1990, we need all the tools in the box.

Christoffer Greisen
Project Manager, EnergyLab Nordhavn



Introduction

For four and a half years, 12 partners in Denmark's largest and most ambitious smart energy project, EnergyLab Nordhavn, have worked together to develop new methods and solutions for designing and operating tomorrow's flexible and integrated energy system based on Copenhagen's Nordhavn as a living metropolitan laboratory—solutions that will accelerate an effective green transition.

This report brings together selected results and lessons learnt from the project. Most of the results were hypothesized before the start of the project in April 2015, but new opportunities emerged in the course of the project, leading to the development of new solutions.

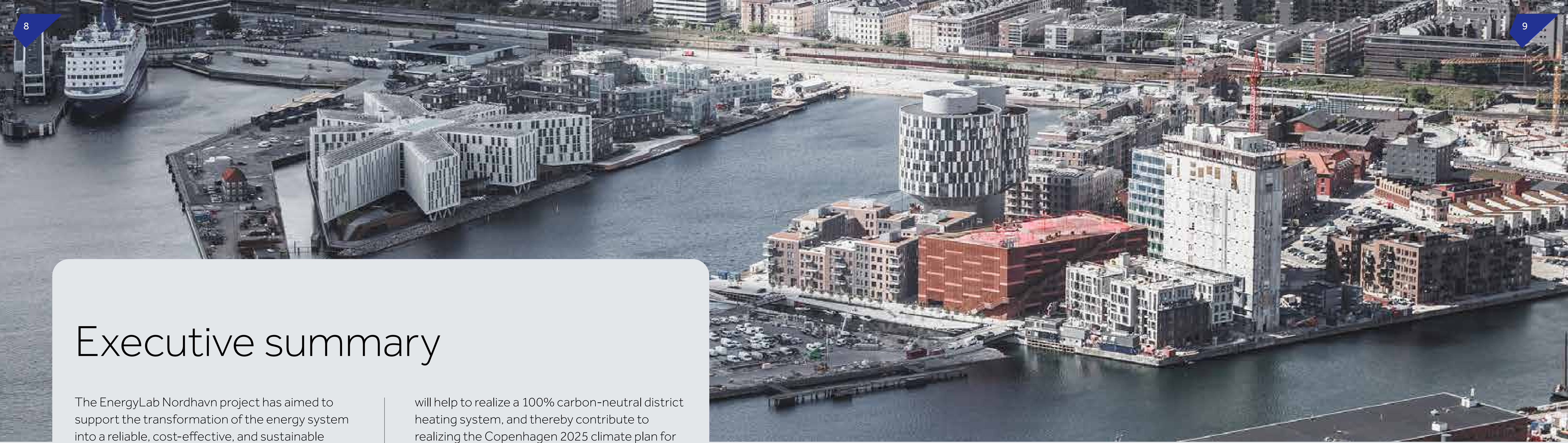
In October 2019 we published a report with 28 recommendations aimed at the authorities, municipalities, utility companies, building consultants, and technology. The recommendations show how we can realize the potentials of sustainable, flexible, and sector-linked energy solutions, for example by providing input for changing a number of obstacles currently inherent in the existing Danish legislative and fiscal structure—obstacles identified by EnergyLab Nordhavn through its work to create a flexible digital energy system in the Copenhagen district of Nordhavn. Examples include the harmonization of energy taxes across energy types and exploiting the potential of buildings for storing energy, which can subsequently be made available to the energy system. In addition, access to data from energy suppliers must be ensured as a basis for continued innovation and development within this field.

Throughout this report we will refer to those of our recommendations that are connected to the results described.

It is no secret that bringing together 12 partners from different companies and organizations can lead to disagreements and cultural clashes. However, as one of our project partners so rightly said: "It's OK if you don't always agree when developing new solutions—in fact it's an advantage". As it happens, our cooperation and the overcoming of barriers across sectors have been some of the greatest strengths of the project, and this is what helps make research and demonstration projects like EnergyLab Nordhavn so valuable to society.

Enjoy the read.

This report was prepared with contributions from the project participants of the EnergyLab Nordhavn partnership. Views, analysis, conclusions, and recommendations are based on the collaboration project, and some of these may not be fully aligned with all the project partners' established policies, assessments, statutory mandates, etc.



Executive summary

The EnergyLab Nordhavn project has aimed to support the transformation of the energy system into a reliable, cost-effective, and sustainable system based on renewable energy utilizing the benefits of closely integrated and coordinated energy infrastructures (electricity, heat, transport, etc.) and the benefits offered by intelligent energy solutions based on innovative technology and new operational and commercial approaches. The project was designed as a large-scale demonstration and research project based on experimental activities with integrated research-based technology development. The project set out to create substantial commercial impact by leading the way for new innovative products, attract new energy businesses, and create knowledge-based jobs. It is also set out to create societal impact by developing a future energy system, guide new rules and emerge new market designs, and create scientific impact through new knowledge breakthroughs and the expansion of the Danish knowledge-base.

Based on this mission, the overall objective of the EnergyLab Nordhavn project has been to develop new methods and solutions for the design and operation of a cost-effective, multi-carrier energy system (electricity, thermal, and transport) of the future based on Nordhavn as a highly visible real-life laboratory.

The project has yielded a number of results, including the following specific demonstrations:

- We have demonstrated how the varying energy needs of buildings can be exploited when coordinated by a district heating company to enable energy-efficiency improvements and a reduction in the use of peak-load boilers. This will help to realize a 100% carbon-neutral district heating system, and thereby contribute to realizing the Copenhagen 2025 climate plan for district heating—a solution now implemented for 7,000 citizens in Copenhagen.
- This heating flexibility has also been demonstrated through the use of home automation systems.
- With FlexHeat, we have demonstrated what is probably the smartest large ammonia-based (800 kJ/s) heat pump in the world.
- We have demonstrated how district heating at ultra-low temperatures combined with a booster heat pump can supply housing blocks (buildings) with hot water, while ensuring a low return temperature.
- New algorithms have been developed and tested with a view to using water heaters in single-family homes to provide network services to the electricity grid as well as the heating network.
- Our grid-connected battery has demonstrated how batteries can be integrated in a city and used for frequency regulation and local peak shaving.
- Through the coordinated operation of battery and heat pump, we have demonstrated a unique control concept that spans utilities by using a shared data platform.
- We have created an energy data warehouse that supports secure real-time data sharing between stakeholders, thus supporting the realization of a smart energy system which encompasses electricity, heat, buildings, transport, and residents. The ability of the system to support real control applications has also been demonstrated.
- Along with our partners, we have created EnergyHub, a groundbreaking new concept in the form of an innovation hub that combines communication, stakeholder dialogue, international marketing, incubation, and innovation under one roof. This platform has enabled us to spread awareness of Danish energy technology to several national and international delegations.

The most readily applicable results are the flexible heat consumers and the application of new profiling and clustering methods to support more intelligent grid management and design.

Furthermore, a new heat dispatch method has been proposed which includes a stochastic model of the electricity market. With this approach, it is possible to save up to 10% of the total energy cost at 50% renewable electricity production.

Three DTU departments—DTU Civil Engineering, DTU Mechanical Engineering, and DTU Electrical Engineering—have contributed research centred on nine PhDs and four post docs.

There have been a few changes to the partner group during the course of the project. In 2018, Nerve Smart Systems acquired all the activities from their sister company CleanCharge, and in summer 2019, COWI joined the consortium to complete the work related to the built environment and to anchor the results. This was possible because a large part of the technical team was recruited by COWI after their former employer Balslev discontinued operation.

> "I think it is one of the most visionary projects in Europe, and that it will continue to serve as an inspiration for many years to come"
>
> *Michael Koller, Chief Technology Officer, EKZ*

One of the main challenges has been the establishment of the data warehouse and the data streams, which were delayed significantly, with some of the intended streams only becoming available during the last year of the project. Another significant challenge was finding a way of realizing the ambitions of the integrated control and market solutions. This was addressed by introducing a process to develop a number of use cases. However, it has not been possible to fully achieve the expected level of coherence within the area. It has also meant that we did not manage to demonstrate a new local market design in practice, and that the PhD work has not been sufficiently anchored with the utilities.

A living urban laboratory

As something completely unique, EnergyLab Nordhavn has had the opportunity to test the new solutions in real-life situations with real people. And this is why we call ourselves a 'living laboratory'. It has, of course, restricted us in some ways, but fortunately it has opened up many more possibilities. Because when you are dealing with real people, you soon find out which are the right solutions.

The residents have contributed with consumption data, have had meters and sensors installed in their homes, and for periods they have relinquished control of, among other things, their heating system to the project. This has been a unique opportunity for us to test the solutions in real-life conditions and with real consumers.

The residents in the new area in Nordhavn who have been involved in the project have been very positive, for which we are very grateful. At the same time, we have been met with a great deal of interest, and not least a desire to contribute actively to the green transition. This augurs well for the future.

Recommendation #28

The development and operation of smart buildings can involve customers and end-users much more

"We are a family af two adults and one girl, so I was very anxious in the beginning wether or not we would freeze during the demonstrations, but our everyday life has not been affected in any way. Considering this it is easy, and feels great being able to make a green difference, " says Mette Engelbrechtsen residents of Havnehuset in Nordhavn

1 P-HUS LÜDERS

A large battery is integrated in the power grid and supports the supply of electricity especially during peak loads. The battery utilizes the power produced from fluctuating renewable sources such as wind and sun.

2 FAST CHARGING STATIONS

The building management systems provides data and controls, allowing for activation of the energy flexibility of the building. Moreover, the school is equipped with the largest set of solar panels in Nordhavn, making it a large prosumer.

3 COPENHAGEN INTERNATIONAL SCHOOL

The building management systems provides data and controls, allowing for activation of the energy flexibility of the building. Moreover, the school is equipped with the largest set of solar panels in Nordhavn, making it a large prosumer.

4 HAVNEHUSET VEST

A district-heating substation in combination with a heat pump help raise ultra-low temperature district heating to a suitable level for hot tap water use. A storage tank provides flexibility for the energy system depending on the load.

5 FRIHAVNSTÅRNET

Twelve apartments contribute with data on their energy consumption, obtained through advanced home automation systems. The purpose is to demonstrate how the flexibility of the homes and their users can contribute to optimized operation of the overall energy system – without compromising the comfort of residents.

6 HARBOUR PARK

Without influencing the comfort levels for the customers, short-term (3-10 hours) reductions or interruptions of the district heating supply are performed allowing the thermal heat capacity of the building to be added as a flexible element in the energy system.

7 HAVNEKANTEN

Smart control of heating systems in 85 apartments and measuring of thermal capacity in four apartments. Room temperature is used to improve indoor comfort and shift the load in time in order to provide flexibility.

8 FRIKVARTERET

In a row of townhouses, water heaters provide flexibility through their ability to shift between district heating and electric heating, based on the amount of wind power in the grid or load on the district heating network Learn

9 MENY

Today, the waste heat from the cooling systems in the local supermarket is not used, but vented to the air. This heat can be exchanged with local heat consumers by exchanging it over the district heating network.

10 FLEXHEAT

At the new cruise terminal, the functionality of a large heat pump is expanded with added controls and extended heat storage, to be used as a flexible element on the electricity market while optimizing the supply of heat to the local heat network.

11 SUNDMOLEHUSENE

In 11 houses at Sundmolen the advantages of fuel shift is demonstrated. Each installation includes a district heating unit with a hot water tank but with added direct electric heating in the storage tank. This will allow a shift in fuel depending on what sources are most renewable.

12 ENERGY.HUB

Energy.Hub is a co-working platform for companies working towards a more sustainable future with a focus on urban development and energy solutions. Energy.Hub hosts the EnergyLab Nordhavn showroom which is located in the heart of the hub.

Data access

As part of EnergyLab Nordhavn, a data warehouse solution has been established which collects detailed data on energy consumption and the indoor climate in 30 selected flats in Nordhavn. Moreover, energy supplies by the utility companies and detailed information on the weather, energy prices, and carbon footprint are also available via the data warehouse solution. The data warehouse solution makes it possible to control who is able to access the individual data, so that sensitive personal information is protected, while business-critical data is only shared with those who require access.

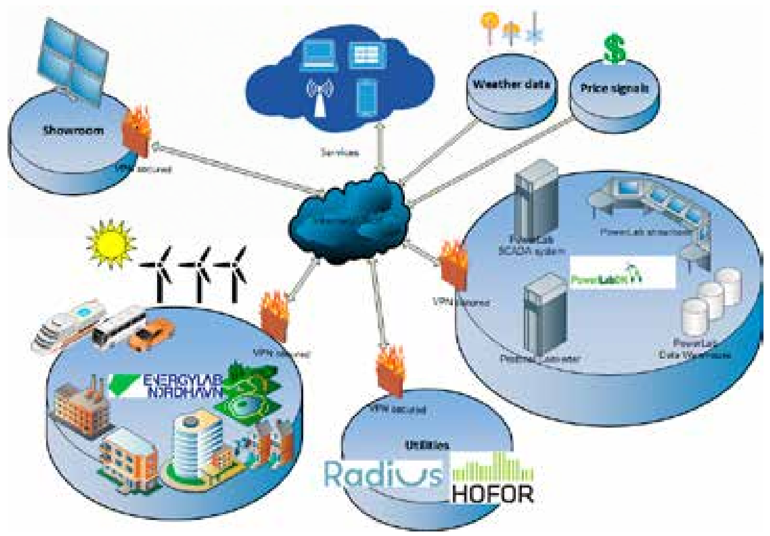
The data warehouse solution also makes it possible to manage pilot plant installations in Nordhavn. In this way, for example, experiments have been conducted which have involved periodically controlling the temperature inside specific flats based on data from otherwise separated data sources.

The data warehouse solution contains data from 15 different data sources and more than 12,000 data series.

Experience: It has been difficult to access data. Initially, there was a great deal of caution concerning the supply of data from the utility companies, but also with regard to allowing 'external' access to the systems. The utilities have not been used to exchange customer data with each other, and the operations departments were concerned about leaks of personal sensitive data through researcher access. It was difficult, but we finally found models for data exchange that can also be used after the project is finished.

Recommendation #8

Municipalities should be proactive in providing access to data



Recommendation #18

Utilities should share their meter data with each other and generally provide greater data access

A NEW DATA PLATFORM—ENERGYDATA.DK

As part of the EnergyLab Nordhavn project, a data platform was developed to collect data from consumption meters, indoor climate meters, heat exchange stations, transformer stations, etc., and to manage the installations. The platform is called EnergyDataDK and will be used to support similar projects in the future.

Today, EnergyDataDK forms the basis of the Digital Energy Lab platform, which is a digital infrastructure to PowerLabDK's physical test facilities at DTU. In addition to data from Nordhavn, Digital Energy Lab will include data from a number of other living laboratories in Denmark, and will be made available to companies, researchers, and students wishing to use data to develop or test new solutions.

DATA-DRIVEN PROFILING OF ELECTRICITY CONSUMERS

Traditionally, consumers are classified based on categories that are defined by experts, depending on their main activities and asset types. These might, for instance, be 'apartments with electric heating', 'bank', etc. These categories and classifications are then used for grid planning, for instance to obtain an idea of the type of load profiles to be expected when designing new distribution grids (or parts thereof). However, since electricity usage may be complex and dynamic, while those categories may not be meaningful in the long term, it is of the utmost importance to challenge this approach to how consumers are classified and profiled. This is while a lot of data is being collected simultaneously thanks to the deployment of smart meters, which offer considerable opportunities.

With this in mind, we have developed novel data-driven approaches to the profiling and classification of consumers, based on adaptive clustering approaches. What makes this approach so interesting is that it is completely data-driven, hence yielding typical consumer profiles and groupings which are directly informed by the data. Also, it allows for these categories to evolve with time, since consumption habits, as well as their groupings, may be different e.g. between summer and winter, and from one year to the next. Additionally, instead of having a set number of well-defined categories, the type and number of categories may also evolve by themselves with time. The approach has been demonstrated based on data for both electricity and heat, and on both small and larger datasets.

Consequently, we showed how these data-driven profiles and categories can be used to obtain typical load profiles and 'worst-case' profiles for using as input for planning. All in all, this opens up many interesting perspectives for a more data-driven view on how to categorize customers, and for using this information in operations and planning. This has been covered in detail by Guillaume le Ray in his PhD dissertation.

Electrification of energy services

In step with the installation of more wind turbines and solar cells, more energy is being produced in the form of electricity. It therefore makes sense to shift a greater proportion of our energy consumption to electricity.

RECHARGING POINTS

For over a year, Nerve Smart Systems has collected data from EV (electric vehicle) charging stations during the EnergyLab Nordhavn project. Thousands of charging sessions have been analyzed and visualized. The results show that peak power consumption from EV charging stations coincides with household peak consumption.

A projection of the average future consumption (in 2025 and 2030) while taking into account variables such as EV market penetration, technology improvements, number of public chargers, and usage frequency, etc. shows that stresses on the grid will increase further in the coming years.

The findings confirm our initial expectations when committing to research into intelligent charging solutions. Experience from direct end-customer management of EV charging stations in car parks underlines that customers do not want to wait to have their EV charged once they plug it into the EV charger. Consequently, a different approach to facilitating intelligent EV charging has been proven which involves meeting electricity peak consumption by discharging battery buffers that charge during hours of electricity surplus on the grid.

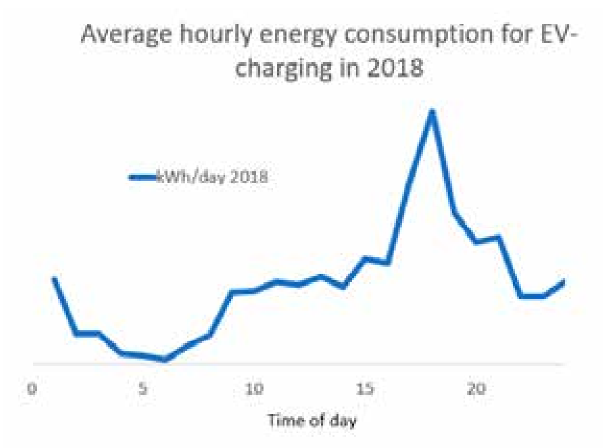
The findings of Nerve Smart Systems synergize well with the integration of renewable energies. Ever since the electricity grid has needed to match the demand for electricity with supply, and ever since more renewables have been integrated into national electricity grids, supplies have fluctuated to an increasing extent. Furthermore, the increase in demand caused by the electrification of societies needs to be met, especially at peak hours.

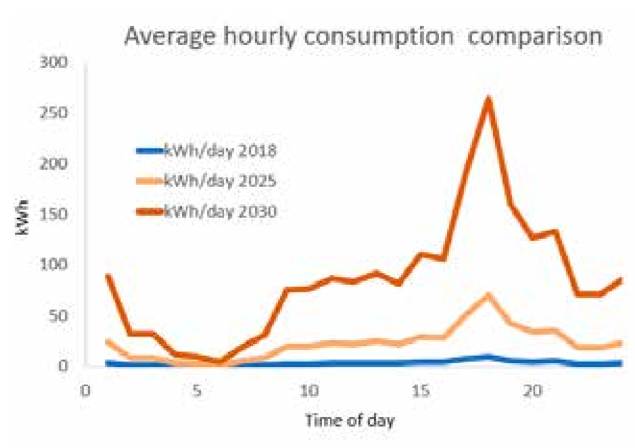
Integrating large-scale battery energy storage systems (BESS) can stabilize the energy supply and match demand. Nerve Smart Systems can supply a BESS which can stabilize energy supplies from the grid while meeting increased demand by charging when demand is low and discharging when demand is high—while at the same time also acting as a buffer for EV charging.

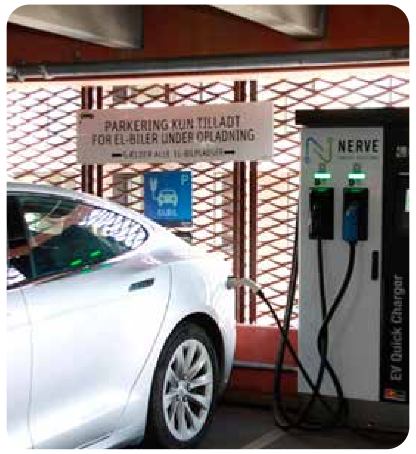
With a small IOT metering device, developed by Nerve Smart Systems, real-time metering of electricity consumption directly from the energy meter at parking house Lüders is facilitated and transferred directly to a data management system.

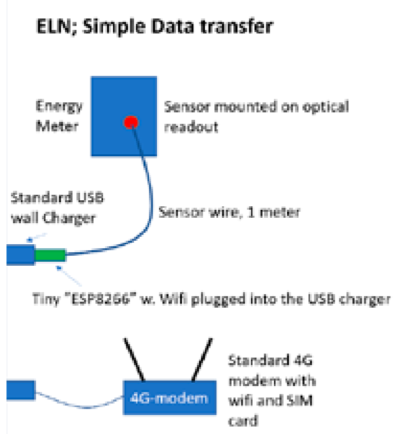
Based on metering from the car park, it was possible to demonstrate using a local Nerve Switch®-equipped BESS in the PowerLabDK at DTU that it is possible to support the load demand of an EV charging infrastructure in a situation with limited grid connection. The main prerequisites for such an intelligent load management system are a shared communication system for control as well as monitoring between the different subsystems. In interpreting the results from the different test runs in the PowerLabDK at DTU with respect to the actual system design in parking house Lüders and at EnergyLab Nordhavn, we have arrived at the following specific recommendations for parking house Lüders:

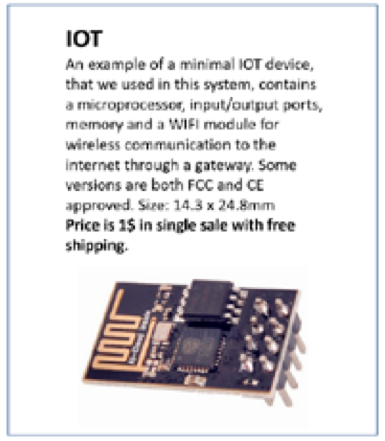
- For only supplying the EV charging infrastructure, the grid connection at the parking house Lüders is considerably over-dimensioned; if the central BESS at EnergyLab Nordhavn is used for buffering peaks from the load side, a grid connection of about 130 kW (-40%) is sufficient.
- For only meeting the EV charging consumption in 2019 at theparking house Lüders, the energy of the central BESS at EnergyLab Nordhavn is heavily over-dimensioned; with the existing 220 kW grid connection, a battery energy of about 55 kWh is enough.





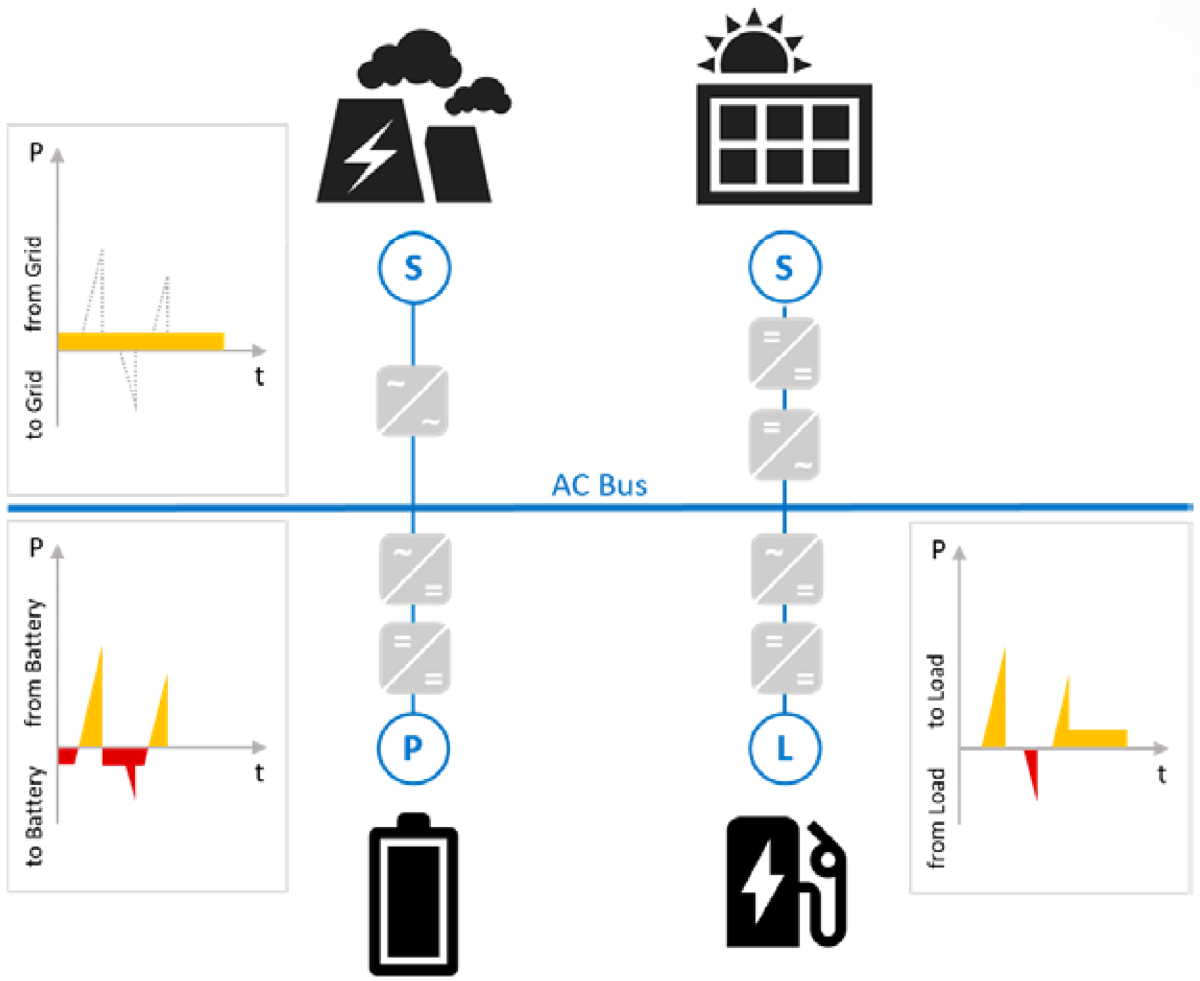






- Optimum dimensioning of both the grid connection at parking house Lüders and the energy of the central BESS at EnergyLab Nordhavn can be achieved by including techno-economic conditions; in particular, when additional renewable energy supplies such as photovoltaics are included:

To meet the high demand which is anticipated in 2030, it is recommended that distributed electrical energy storage system configurations are specified which take into account electricity consumption, population density, and EV utility. The BESS can be placed in 10-foot standard shipping containers, mounted on walls or even placed in lofts, and which allow for grid peak shaving and intelligent EV charging.



Conceptual drawing of an electric grid (AC bus) such as that found at the Lüders car park at ELN with a BESS as prosumer (P) for buffering peak loads and volatile dynamics between the load side (L) and the supply side (S) including volatile renewable energy sources.

Recommendation #15

Electric heating for hot water production is also part of the solution

MICRO-BOOSTER HEAT PUMP

Together with PowerLabDK, METRO THERM has developed an advanced control system for hot water tanks in single-family houses. The control system makes it possible to switch between district heating and electricity depending on what is most optimal based on the price of energy and/or the climate impact from supplying the energy. The control system has been demonstrated in an ultra-low-temperature district heating scenario, i.e. where the district heating temperature is not sufficient to make hot water without supplementary electrical heating.

Based on the EnergyLab Nordhavn project, METRO THERM has also developed and started producing a completely new type of micro-booster heat pump in Denmark, which is already being marketed and sold in Denmark and Europe. The micro-booster is manufactured in Denmark and has resulted in job creation in Denmark. Moreover, METRO THERM has used the lessons learnt from the project to launch a new low-temperature district heating container. This is now being offered to the first genuine low-temperature district heating areas in Denmark.

Advanced fuel shift control algorithms were designed, developed, and demonstrated in order to use the flexibility of fuel-shift equipment to provide smart energy network services to both electricity networks and district heating networks, e.g. power balancing, peak reduction, and efficiency improvements, etc. These solutions also create new revenue streams for end-users without impacting their comfort requirements.

Low-temperature district heating

The project has explored new possibilities for the collective supply of heating in a large area comprising only low-energy buildings—Nordhavn being an example of such an area.

The space heating in these buildings can be met with district heating with a lower temperature than normal, while the heating of domestic hot water for health reasons requires a temperature of 55°C. The district heating system in such an area can therefore either run at a temperature which is sufficient to heat the domestic hot water and ensure Legionella disinfection e.g. 65°C (low-temperature district heating, LTDH)—or at a temperature only sufficient for space heating, but too low to produce hot water—e.g. 45°C (ultra-low-temperature district heating, ULTDH). When using ULTDH, the appropriate temperature for the domestic hot water is ensured with a micro-booster heat pump, which increases the temperature of the water from 45°C to the required 55°C.

The project has demonstrated three different new heat supply solutions in Nordhavn: 1) a building equipped with ultra-low-temperature district heating with central hot water production, where the hot water is heated by means of a micro-booster heat pump; 2) a building with central hot water production, where the temperature of the circulating hot water is maintained by means of a circulation booster; and 3) an area with low-temperature district heating isolated from the district heating network, which is supplied via a large heat pump (FlexHeat).

FLEXHEAT—A CENTRAL TECHNOLOGY HARVESTING RENEWABLE SOURCES FOR HEATING

A heat pump is able to extract energy from a heat source at one temperature which it supplies to a heat sink at a higher temperature. Heat pumps can extract energy from sources such as groundwater, sewage, and seawater, and which can potentially be used for supplying Copenhagen with district heating in the future. Heat pumps will enable HOFOR to integrate more renewable energy sources in the district heating system, paving the way for a future in which our district heating—and energy system in general—gradually becomes greener and more flexible.

Electric heat pumps open up the possibility of coupling the electricity and heating systems together, as heat pumps consume electricity from the grid. By means of this coupling, it is possible to control how much electricity is supplied from the grid to the heat pump in an intelligent manner, and so that the heat pumps can help the electricity grid to balance solar and wind power production. First, more experience needs to be gleaned from using heat pumps in order to build heat pumps on a larger scale. This experience relates to testing the relevant heat sources for district heating, and to examining how reliable, economically viable, and flexible the heat pump technology currently is as well as its future potential.

HOFOR builds heat pumps as demonstration plants with a view to ensuring the future supply of green, reliable, and affordable district heating.

HOFOR has built and commissioned two large heat pumps—one in Nordhavn and one in Sydhavn, Copenhagen.

FlexHeat is the name of the plant which has been tested in Nordhavn. This is a flexible heating system with a two-stage groundwater heat pump that uses ammonia as the refrigerant. The solution includes a large heat storage tank and two electric heating elements for maximum flexibility. The heat output capacity of this heat pump is 800 kJ/s.

INTELLIGENT CONTROL OF HEAT PUMPS

HOFOR has examined the extent to which a heat pump can be controlled intelligently, as more intelligent control leads to improved operational economy for the facility. Tests indicate that it is possible to save 13% of the utility's heating costs with flexible operation of the FlexHeat heat pump.

The figure below shows the different levels of intelligent control. Level 1 is the heat pump in operation without intelligent control as a reference, and then, as the levels increase, more intelligence and sector coupling are enabled. Level 2 enables the thermal flexibility of the tank, grid, and consumers to utilize the cheapest electricity prices. Level 3 builds on level 2 by also directly assisting the local distribution grid through the upward or downward regulation of services. At level 4, the complexity of level 2 is increased by delivering ancillary services to the overall grid by means of frequency regulation. At level 5, multiple assets are considered for synergy effects: heat pumps, large-scale batteries, and electric vehicles.

Intelligent operation cuts operating costs by a maximum of 13% for the heat pump systems. To realize this potential, an intense test scheme has been implemented which, among other things, included innovation in faster ramping of heat pumps. The preliminary results indicate that FlexHeat can regulate most of its capacity within 1.5 minutes instead of 4 minutes in the early test stages. These results indicate that heat pumps might play a key role in stabilizing the electricity grid in the future energy system.

Tests indicate that it is possible to save 13% of the utility's heating costs with flexible operation of the FlexHeat heat pump.

LEVEL 1

The heat pump operates normally without any synergies.

LEVEL 2

The heat pump operates according to the cheapest electricity prices by utilizing the thermal flexibility in the heating system.

LEVEL 3

The heat pump assists the local electricity grid in electricity overload situations, for example by consuming excess electricity from wind turbines.

LEVEL 4

The heat pump assists the overall grid by keeping the grid frequency at a stable level by delivering ancillary services.

LEVEL 5

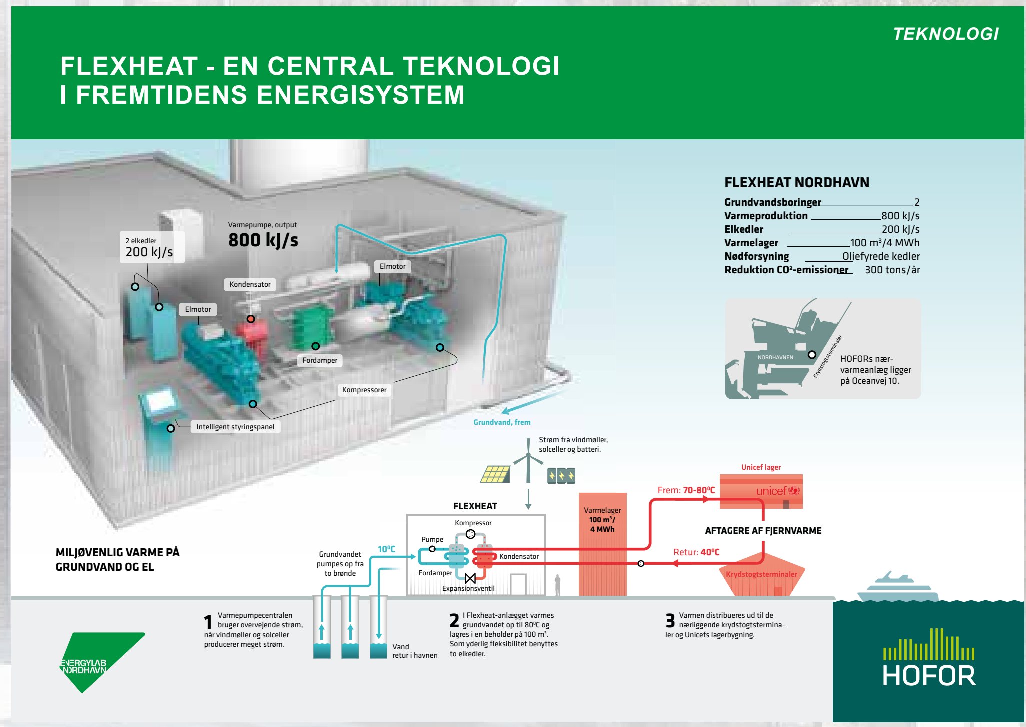
The heat pump connect directly with other flexible electricity units; electric cars, batteries, sunpanels and wind turbines.

ELECTRIC HEAT PUMP BOOSTERS MAKE IT POSSIBLE TO USE ULTRA-LOW-TEMPERATURE DISTRICT HEATING

Traditionally, district heating has a flow temperature above 70°C. For health reasons, domestic hot water should be heated to 55°C to avoid Legionella bacteria, while homes can be heated with lower-temperature heating. A potential therefore exists for reducing the flow temperature to the properties, which is possible if one installs a substation and heats the water locally using, for example, a heat booster.

As part of the EnergyLab Nordhavn project, Danfoss has installed a heat booster substation (HBS) in a multifamily building named Havnehuset.

The substation operates with ultra-low-temperature district heating (ULTDH) at supply temperatures of 35–45°C. It comprises a heat pump for enabling domestic hot water (DHW) to be heated to temperatures above the ULTDH supply temperature as well as a storage tank. Reducing the district heating (DH) temperature level is highly relevant when looking ahead to the fourth generation of DH, where lower temperatures are a key enabler for utilizing a higher share of available low-grade heat sources. In addition, the concept of load shift is an important part of fourth-generation DH. Some of the benefits of reducing the DH supply temperature include reduced heat losses in the network and the easier integration of available surplus heat at low temperature levels such as geothermal heat, solar heat, industrial surplus heat, supermarket excess heat, etc. ULTDH HBS may be an important enabler for integrating higher shares of renewables and waste heat in the DH network. Furthermore, it increases the efficiency of central plants, e.g. heat pumps.



With a significant part of the DHW heat demand used for DHW recirculation, i.e. maintaining a high comfort level and ensuring short waiting times for hot water, it is likely that the DHW circulation may impact the DH accumulation tank through the loss of thermal stratification and rapid discharge. To prevent this, a separate heat pump was applied, its primary purpose being to maintain the DHW circulation temperature.

Based on the experience gained over a period of more than 12 months, it can be concluded that the HBS unit has been successfully installed, tested, and operated. DHW is produced at 55°C, DHW circulation is raised continuously from 50–55°C, with a DH supply temperature of 45°C and a DH return temperature of typically 30°C. The share of electric energy consumption for DHW and the DHW circulation service is 14% at an average DHW production volume of 1,700 litres/day. DH accounts for the remaining 86%. Due to the daily variation in DHW draw-off over the year, the electric share varies from e.g. 12% at a DHW production volume of 2,500 litres/day, to 17% at a DHW production volume of 1,000 litres/day. Note that the electric share is based on DHW as well as DHW circulation production.

The daily average DHW load shift potential is 75 kWh/day for the 22-flat building, of which electricity accounts for 7 kWh/day, and thus DH accounts for the remaining 67 kWh/day. On a yearly basis, it is at least at the same level as the load shift potential for the heating system in the building. With regard to capacity flexibility, this equates to 3 kW of electricity and 30 kW of DH realized for e.g. a period of 1 hour and 10 minutes before the morning DHW peak and before the evening DHW peak on average over the year.

A prognosis and economy-based scheduling of the HBS charging has been implemented, which optimizes for lowest energy costs for the building's occupants. With cost-reflective prices for electricity and district heating, the system will automatically shift operation to hours where capacity limitations are low and the performance of the production units is high. By charging the tank as late as possible, the heat loss from the tank is reduced due to a lower surface temperature.

A number of feasibility studies have been carried out for the HBS concept relative to the LTDH concept with different energy sources, which show that under the current tariffs and with existing production technologies, the concept is economically feasible to a very limited extent. However, conditions already exist today for this type of system to become feasible. For a new urban development area, such as Nordhavn's Levantkaj, the HBS concept could be relevant. An area of this type could be designed for ULTDH, where the DH energy input could be the DH return water from the existing DH system. The temperature of this water is typically 35–45°C, and thus relevant for the HBS concept. In this case, adjustments to the current energy price structures will be needed for the concept to become feasible. Also, where the DH energy source is at a low temperature level, e.g. solar thermal, geothermal, industrial surplus heat, and data centres, the concept of HBS in combination with underfloor heating is worth considering. Furthermore, the value of the load shift potential, temperature-dependent DH energy prices for both supply and return streams, and the electric energy prices will determine whether the HBS concept is feasible in each individual case.

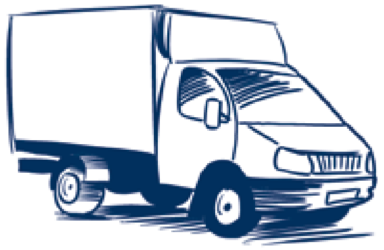
SUPPLY OF DOMESTIC HOT WATER—HEAT PUMP IN BUILDINGS WITH SEVERAL FLATS AND CENTRAL DOMESTIC HOT WATER HEATING FACILITY.

The domestic hot water is usually maintained at a constant temperature throughout the building by continually circulating the hot water. The energy consumed to maintain this constantly high temperature usually accounts for as much as half of the energy consumed to heat the water. Most of the year this represents a waste of energy.

The circulation booster (CB) was installed at Strandboulevarden in December 2018, a multi-family building with 15 spacious apartments. The CB boosts (heating) the DHW circulation water from 50°C to 55°C in two steps by means of a direct heat exchange and a heat pump booster, using DH at normal temperatures (70–100°C) as the energy source.

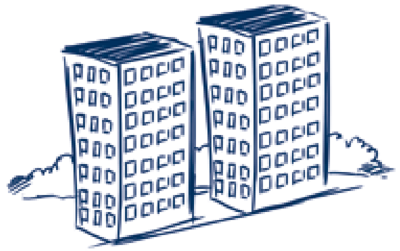
The testing has been successful, and mapped out the feasible operation range and the electric power which is required. A number of economic scenarios have been analysed, focusing on different bonus structures related to reduced DH return temperatures and electric energy costs. The current tariff structure does not provide a feasible economic case for the CB concept. However, if considering a more progressive bonus scheme for providing a low DH return temperature, the market potential could be interesting in the segment for existing buildings and to some extent also for new buildings with DHW circulation systems. This is also supported by having the simple retrofit demands in mind, and driven by the argument that a low DH return temperature is a precondition for a low DH flow temperature, as specified by the fourth-generation DH concept.

THE BATTERY IN IMAGES



The battery takes up as much space as a small truck

The battery's energy content equates to 250,000 AAA batteries



The battery can supply approx. 200 apartments with electricity when consumption is at its highest

Energy storage provides flexibility

Energy storage will be greatly needed in tomorrow's energy systems. Energy storage is one way of achieving energy flexibility in the energy system. An energy storage system releases energy in the same form as it is received—unlike energy conversion systems, which transform the energy from one form to another. There is a big difference between storing energy in different forms. Electricity storage (in the form of batteries) is obviously highly valuable, but it is expensive and requires a lot of space. Storing energy as heat is cheap, but also takes up a lot of space. In some cases, heat storage capacity can be achieved at no additional cost—for example by using the inherent heat storage capacity of buildings and district heating systems.

FLEXHEAT WITH STORAGE

The FlexHeat unit, which has been demonstrated as part of the project, combines an electric heat pump with thermal storage. The thermal storage in the FlexHeat unit comprises a vertical, cylindrical water tank with the possibility of having variable temperature zones in the tank with different temperatures—hottest at the top and coldest at the bottom. This makes it possible to maintain a consistently high temperature at the top of the tank, which is sufficiently high for the district heating supply, and a constantly low temperature at the bottom of the tank—independent of the stored energy. When the storage unit is supplied with or delivers heat, the zone between the hot and the cold water in the tank moves up and down in the tank.

Thermal storage makes it possible to periodically disconnect the heat pump from supplying heat to the local heating system. This means that the heat pump can to a certain extent be started and stopped depending on the variable electricity prices on the electricity markets, and not simply in response to the current demand for heat.

As part of the project, HOFOR (Greater Copenhagen Utility) has developed and demonstrated an advanced control system for the heat pump unit. The control system seeks to optimize the operation of the heat pump in relation to predictions of electricity market prices, heat demand, and the heat storage status. HOFOR trades in parallel on different electricity markets with different time horizons, and, as part of the project, has improved the adjustability of the heat pump so that heat pumps can now also offer rapid adjustments of electricity consumption.

BATTERIES RELIEVE THE GRID

Through the EnergyLab Nordhavn project, we have demonstrated that energy storage using a battery system can relieve grid load and optimize grid operation, for example through peak shaving, frequency control, and voltage control. We have gained valuable insights and results from the installation and commissioning of a battery system at the Lüders car park in Nordhavn, for example:

- New knowledge about the construction and commissioning of a battery system in an urban environment. This applies, in particular, to aspects relating to fire safety. Using lithium-ion technology requires a high level of fire safety. Therefore, the battery system was placed in a concrete fire-proof cubicle behind a steel door with two fire-suppression systems to protect the surroundings in the event of a fire. The solution was designed in collaboration with relevant fire authorities.
- New opportunities for demonstrating specific solutions for integrating increasing volumes of renewable energy into the grid. There has been huge local and international interest in the battery system.
- Greater knowledge about areas where battery systems are particularly suitable for grid support. This not only applies to grid companies, but also to large companies where battery systems might well replace back-up diesel generators.
- Software for three new IT systems. The systems can help us learn more about the grid in different geographical areas where battery systems might be installed.

A battery system can pave the way for the greater integration of wind and solar energy into the electricity grid, but other obvious uses have also been demonstrated.

WHAT IS THE FUTURE OF BATTERIES?

WHO IS ALLOWED TO OPERATE BATTERIES IN THE GRID?

The EU has passed the 'Clean energy for all Europeans package'. According to this legislation, grid companies are not permitted to own or operate batteries similar to the one installed in Nordhavn in Copenhagen.

SO WHAT DOES THE FUTURE HOLD FOR BATTERIES AND GRID COMPANIES?

The grid companies are still allowed to provide power balancing services (peak shaving) to commercial players who are allowed to own and operate a battery. The EnergyLab Nordhavn project is thus highly relevant in terms of equipping the grid companies to provide the right specifications for tender rounds.

SEVERAL OBVIOUS ROLES FOR BATTERIES IN THE ENERGY SYSTEM

The price of battery technology has decreased considerably since the battery system in Nordhavn was ordered, giving rise to new positive business models for companies wanting to store energy in batteries.

This is interesting, because we are facing a future in which vehicle and road transport in general will become electrified, and where we need to integrate increasing volumes of renewable energy from solar panels and wind farms into the grid.

Buildings as heat stores

During certain periods, Copenhagen's district heating system comes under a lot of pressure due to excessive demand. To ensure the stable and secure supply of heating and domestic hot water to all citizens, peak-load production kicks in. Peak-load production is expensive, and results in considerable CO_2 emissions as it is primarily based on oil and natural gas.

As a part of the solution to eliminate CO_2 emissions in Copenhagen, HOFOR has signed agreements with several multi-family blocks in Nordhavn and Nørrebro to limit their heating supply for shorter periods of time when peak loads occur in the system.

During normal heating supply, the walls, floors, and ceilings of these multi-family buildings are charged with heat, so that during peak-load periods the heat stored in e.g. the walls is released into the rooms in the building, and the indoor temperature is maintained at the same level for several hours. The aim is to investigate and demonstrate to what extent it is possible to exploit the heat that is stored in the building mass, instead of having to start up expensive and CO_2-emitting peak-load production.

Most of the time, the demand for heating in the capital area is covered by base-load boilers that use carbon-neutral fuels. However, for some periods, usually when it is very cold or when a lot of people are taking showers in the morning and heating systems are being started up in office buildings, these base-load boilers are unable to meet the demand for heat and heating.

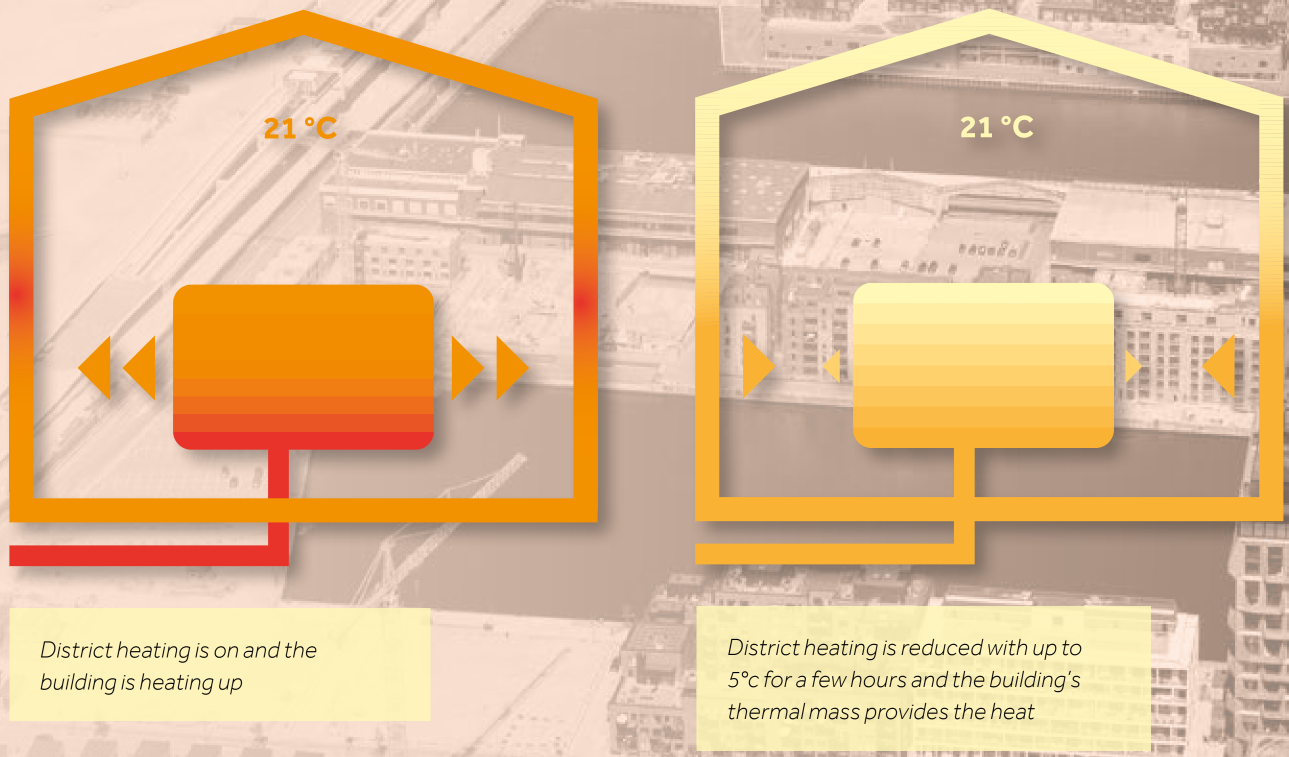
During these periods of high demand, fossil-fueled peak-load boilers are started up to meet the need for extra heating. By making the most of the short-term heat storage capacity in buildings, it is possible to reduce heating consumption in selected buildings for shorter periods in order to shift heat consumption from high-demand to low-demand hours. The occupants of these buildings are therefore called flexible heat customers.

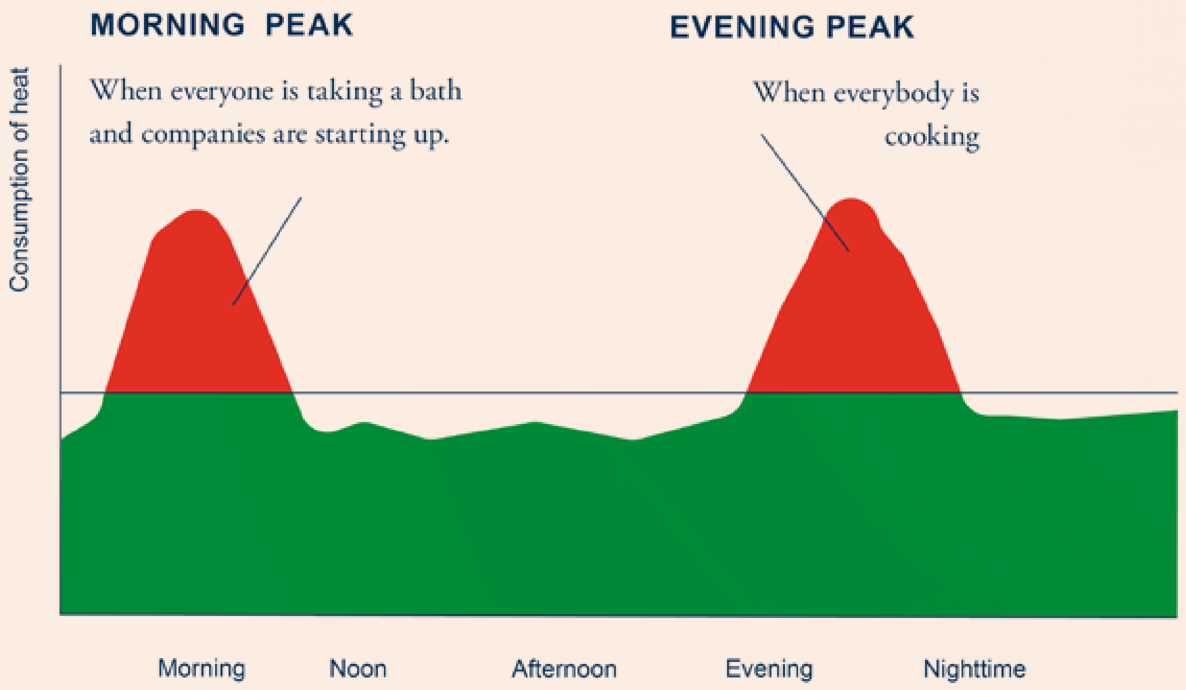
When buildings are heated, heat is stored in the buildings' thermal mass (walls, ceilings, roofs, and floors). Thus, if the heating is temporarily reduced, the accumulated heat in the thermal mass is released, and the building can maintain a satisfactory thermal environment for shorter periods. This process is called sensible heat storage, or perhaps more commonly short-term heat storage, and occurs naturally in all heated buildings.

It is on average possible to reduce the peak load by 12% at building level, by reducing the supply temperature to the heating system by only 5 degrees for up to four hours.

7000
CITIZENS

are currently helping HOFOR by making their buildings available for demonstrations of flexible heating supply. The families live in new buildings in Nordhavn or in older buildings in Nørrebro.

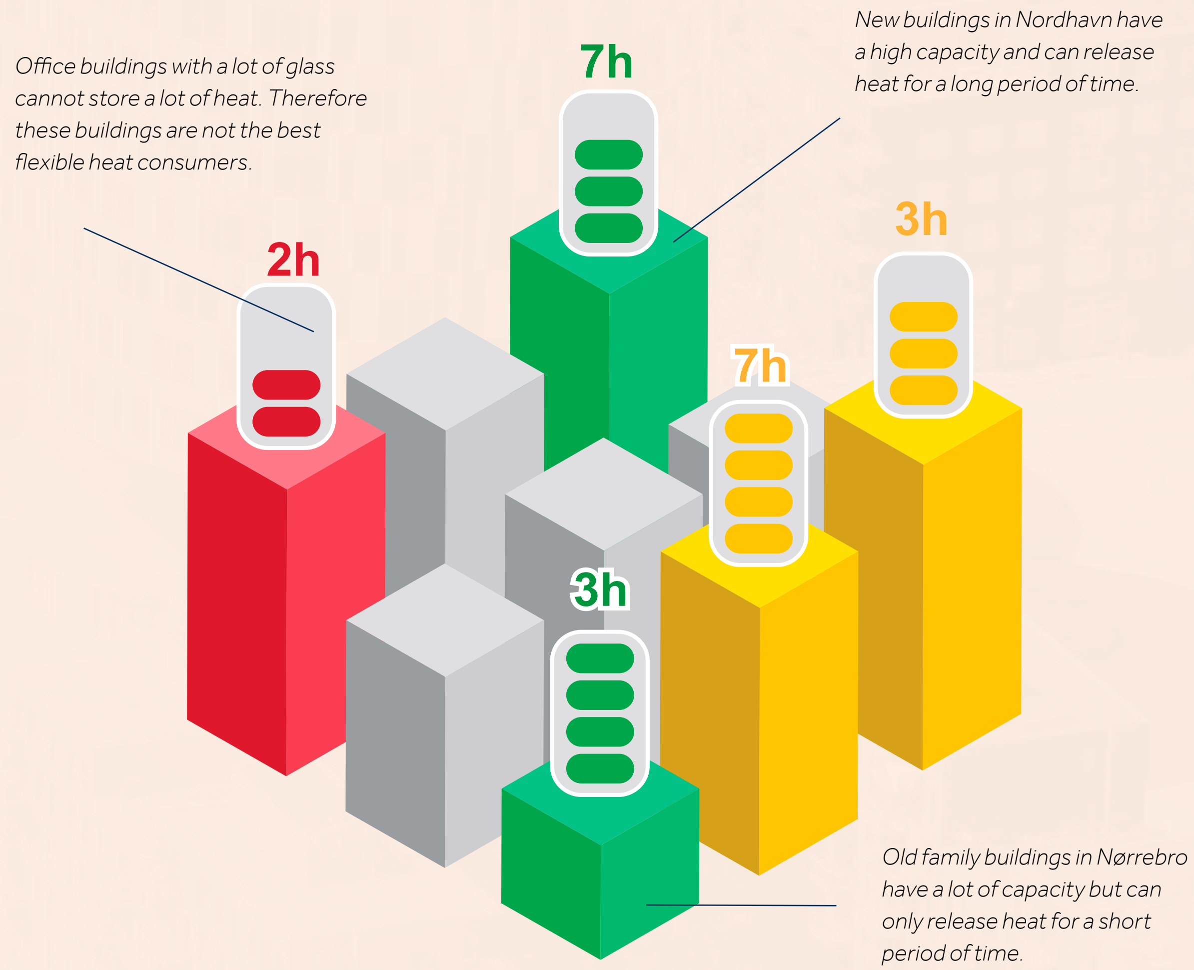




During the EnergyLab Nordhavn project we have experienced how the framework for smart integration across the energy sector can be improved. By framework, we are referring to laws, acts, etc. as well as the regulation of trading in the energy market.

Furthermore, we have developed ideas on how to promote energy savings and use of renewable energy.

It is on average possible to reduce the peak load by 12% at building level, by reducing the supply temperature to the heating system by only 5 degrees for up to four hours.



How much heat capacity a building can release in relation to its size, and for how long the heating supply can be reduced without affecting the occupants depends on the building's construction, degree of insulation and heating system. An old, solid multi-family apartment block in Nørrebro might be able to release just as much, if not more, heat as a new building in Nordhavn, but for a shorter period of time.

In the figure on the right, buildings with the highest heat capacity are green, and those with the lowest are red. The battery on top of each building indicates for how long the specific building is able to release heat. The purpose of the figure is to show how the city of Copenhagen is made up of buildings of varying sizes, shapes, and functions, and that considerable potential exists for exploiting the existing building mass during peak-load periods.

Flexible heating customers

ROOM TEMPERATURES REMAIN STABLE FOR SEVERAL HOURS EVEN IF THE HEATING IS SWITCHED OFF

A high demand for heating often forces district heating systems to draw on more energy sources, including fossil fuels. This is especially true on cold winter days between 6:00 and 9:00 in the morning and again at the end of the day between 17:00 and 20:00.

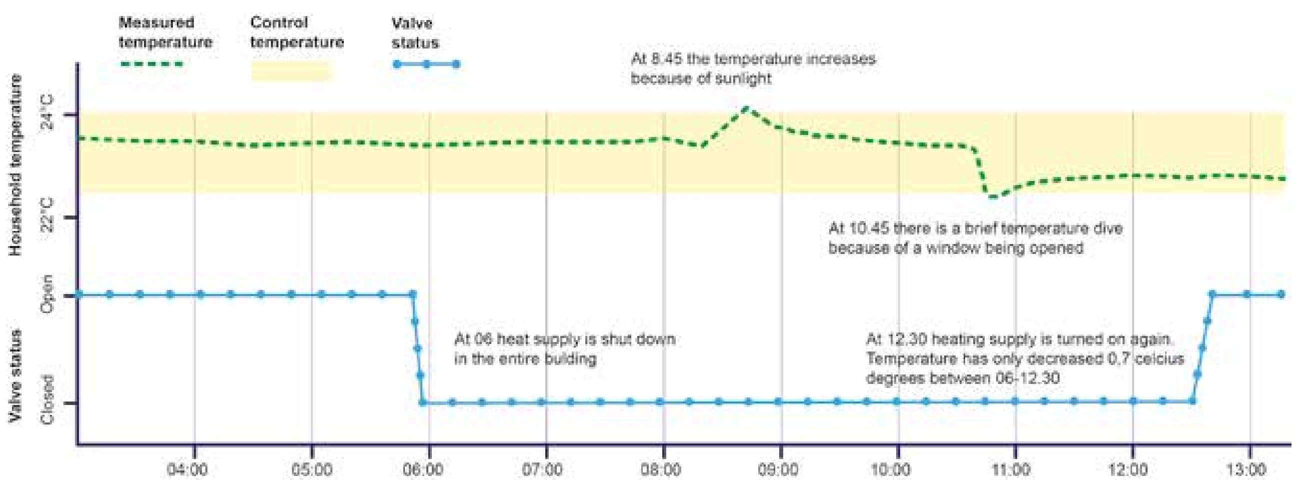
HOFOR, DTU, COWI and ABB have all looked at whether it would be possible to reduce the use of fossil fuels in the district heating system by switching off the supply of heating to selected flats without significantly impacting room temperatures.

ABB installed KNX building automation in 19 flats in Nordhavn (Sundmolehusene) in order to collect relevant data on the indoor climate, including CO2 levels, temperatures, ventilation, and light. The measuring points supplying the data were connected to a data management system at DTU. It was thereby possible to automatically regulate the temperature in the selected rooms at specific times of day.

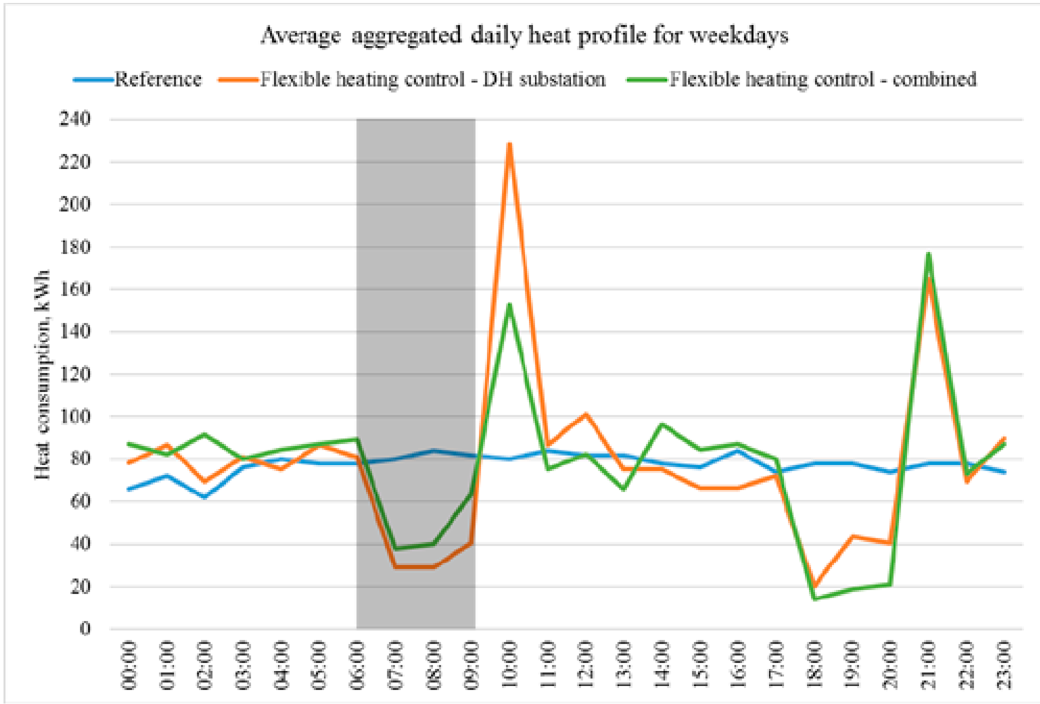
The demonstration showed that it was possible to switch off the heating supply for more than six hours (from 6:00 to 12:30) without the room temperature falling by more than 0.7°C. An algorithm was developed to control the heating valves in the rooms based on two inputs: room temperature and temperature setpoint. These methods can be implemented in other residential properties with building automation, where the district heating is controlled via room thermostats.

This concept can be utilized to lower the heating production in peak periods, thereby cutting the use of fossil fuels at the power plants.

This functionality has been used in a dedicated demonstration, combining data from the heat system and the individual homes, both of which were shared through the project data management system. This is a good example of the value of a shared observability obtained in the course of the project. The flexibility can either be activated by direct commands to the home automation systems alone, or through a coordinated action, where the home automation systems are used to control the rebound effect. In the figure below, this concept is compared to operation solely on heat exchanger substations.



Graph is based on data from the EnergyLab Nordhavn project.



Comparison of how operating flexible heat consumption can be controlled in a coordinated way. Direct control in the apartment in conjunction with controlling the heat exchanger substation can reduce the rebound by up to 44%. Graph is based on data from the EnergyLab Nordhavn project.

Integrated energy systems

We developed a series of use cases demonstrating new, innovative, and integrated solutions across the energy sectors, and with the smart and coordinated operation of several ELN assets. Some of these were demonstrated in real time.

COORDINATED OPERATION OF BATTERIES AND HEAT PUMPS—BATTERIES AND HEAT PUMPS AS PART OF AN INTEGRATED ENERGY SYSTEM

As part of the project, HOFOR, Radius, ABB, and DTU have examined the potential for integrating heat and electricity by coordinating operation between a heat pump facility, FlexHeat, and the grid battery. Initial calculations proved that certain assumptions had to be made to facilitate the cooperation:

- Neglect double-tariff structure
- Evaluate investment and O&M costs for the battery as sunk costs
- Introduce a premium to facilitate the cooperation (this premium could be supported by a CO2-emission incentive obtained by utilizing the grid battery).

There are two different scenarios for this cooperation—complete coordination and soft coordination:

Complete coordination: The battery is situated at the FlexHeat facility, essentially becoming a part of the facility. Here, the cooperation is quite feasible, and at a premium of DKK 0.4 for every delivered kWh of electricity from the battery to FlexHeat, it is possible to have sufficient cooperation.

Soft coordination: FlexHeat buys electricity from the battery at a remote location. This scenario is substantially less viable than complete coordination. However, at a premium of the same level, an acceptable level of cooperation could be achieved.

In EnergyLab Nordhavn, the soft coordination scenario was adapted for site-specific tests. Here, data communication was developed as part of the project to coordinate operation. Radius delivers price signals for the battery to FlexHeat, which in turns optimizes its operation by either utilizing the battery or consuming from the grid. Here, it instructs the battery based on the electricity purchased from here. The signal from FlexHeat was facilitated by DTU using microSCADA, and the battery could be instructed from an RTU at the site, which was programmed by ABB to follow the logic of FlexHeat. Site-specific tests showed the validity of the technical set-up, although its economic viability is still questionable.

These deliverables provide evidence of the challenges associated with the cooperation. Significant improvements to battery efficiency and costs are required. The DSO must allow the units to utilize the grid infrastructure without paying a double tariff in the set-up. Lastly, it is necessary to issue a premium to facilitate the cooperation, or work towards a CO2-emission-based strategy for cooperation—there is little evidence that this would be feasible, however.

Recommendation #11

Better possibilities for activating heat flexibility should be introduced so that flexibility can contribute more to the integration of the electricity and heating systems

Recommendation #13

Heat pumps in district heating systems should be implemented from an overall system perspective

Recommendation #14

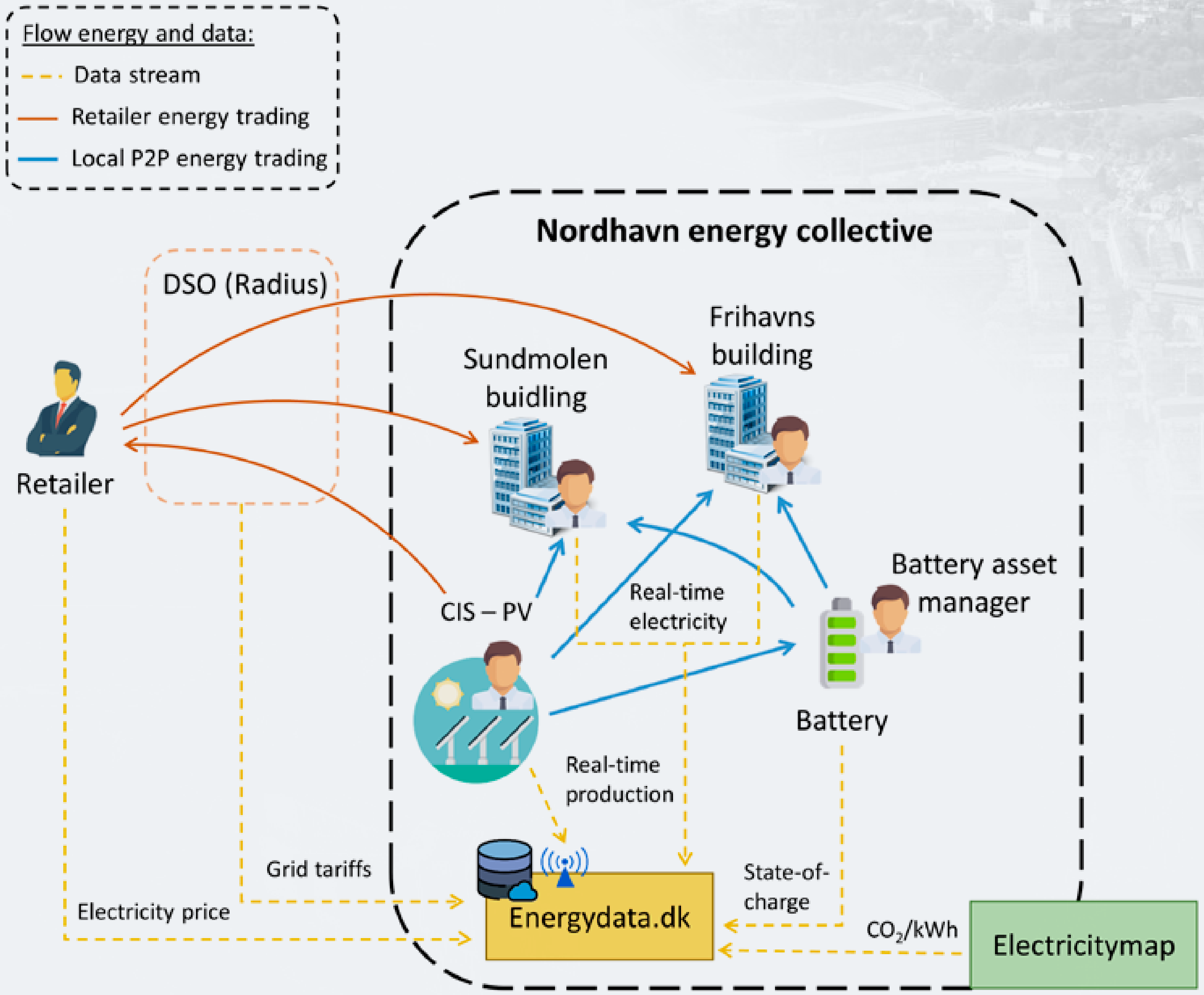
The value of heat pumps in the district heating grid can be increased if the heat pumps contribute to both the electricity and heating systems in a flexible way

Rules and frameworks get in the way

In the course of the EnergyLab Nordhavn project, we have gained experience of how the framework for smart integration across the energy sector can be improved in order to promote integration. Furthermore, we have developed ideas on how to promote energy savings and renewable energies where barriers may exist to sensible socio-economic development.

By frameworks we mean legislation, ministerial orders, etc. as well as rules for energy trading in the energy markets.

Furthermore, we have developed ideas to promote energy savings and the use of renewable energy.



New business models

The ELN project also explored the potential of new business models for new forms of customers—using the advent of prosumers as proactive customers with production and storage capabilities. We looked at how prosumers could work together to form new energy communities in order to better exploit their assets and contribute to CO2 reductions. As yet, no business model exists to exploit the potential from prosumers, where traditional roles (e.g. aggregators) have unclear plans on how to integrate prosumers. The energy community concept is thus introduced to bridge this gap as new business models that look to the final customers as prosumers.

DTU explored the potential of having an energy community comprising the existing prosumers in Nordhavn. We considered installing photovoltaic panels on Copenhagen International School and residents from two smart energy buildings in Nordhavn. A grid battery operated by Radius is also used in the proposed energy community. This business model allows a direct peer-to-peer (P2P) exchange, in terms of the financial and energy aspects between prosumers in our energy community:

Recommendation #1
Energy taxes must be reformed to reflect the climate impact and so they can also be dynamic

Recommendation #3
Market rules on consumption and distribution systems should be adjusted

Recommendation #22
Contribution to the specification of the new regulatory testing zones

Recommendation #26
Take advantage of the upcoming regulatory test zones

Simulation results show there are economic benefits for the residents in Nordhavn while maximizing the use of local production in Nordhavn. The residents in our simulation realized cost savings of approx. 9% compared to the business model of buying everything from a traditional retailer. Scaling up this business model will result in greater economic benefits for the prosumers. We used a local community comprising 11 prosumers for the simulation. However, adopting an energy community has to take into account conflicts with traditional players (e.g. retailers and system operators). Such communities cannot be seen to be external business models that will exploit the energy system without contributing to the overall cost of the system. A correct adoption of energy communities will create the proper framework for prosumers contributing to overall CO2 reductions in the energy systems. This new business model encourages more prosumers to invest in renewable technologies and to adopt a more flexible behaviour. The energy community internalizes prosumer flexibility in order to maximize the share of localized renewable production by all members of the community.

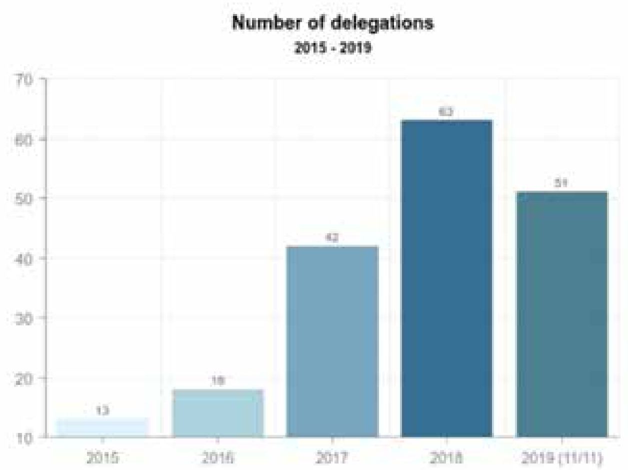
Innovation and showcasing of Danish strongholds

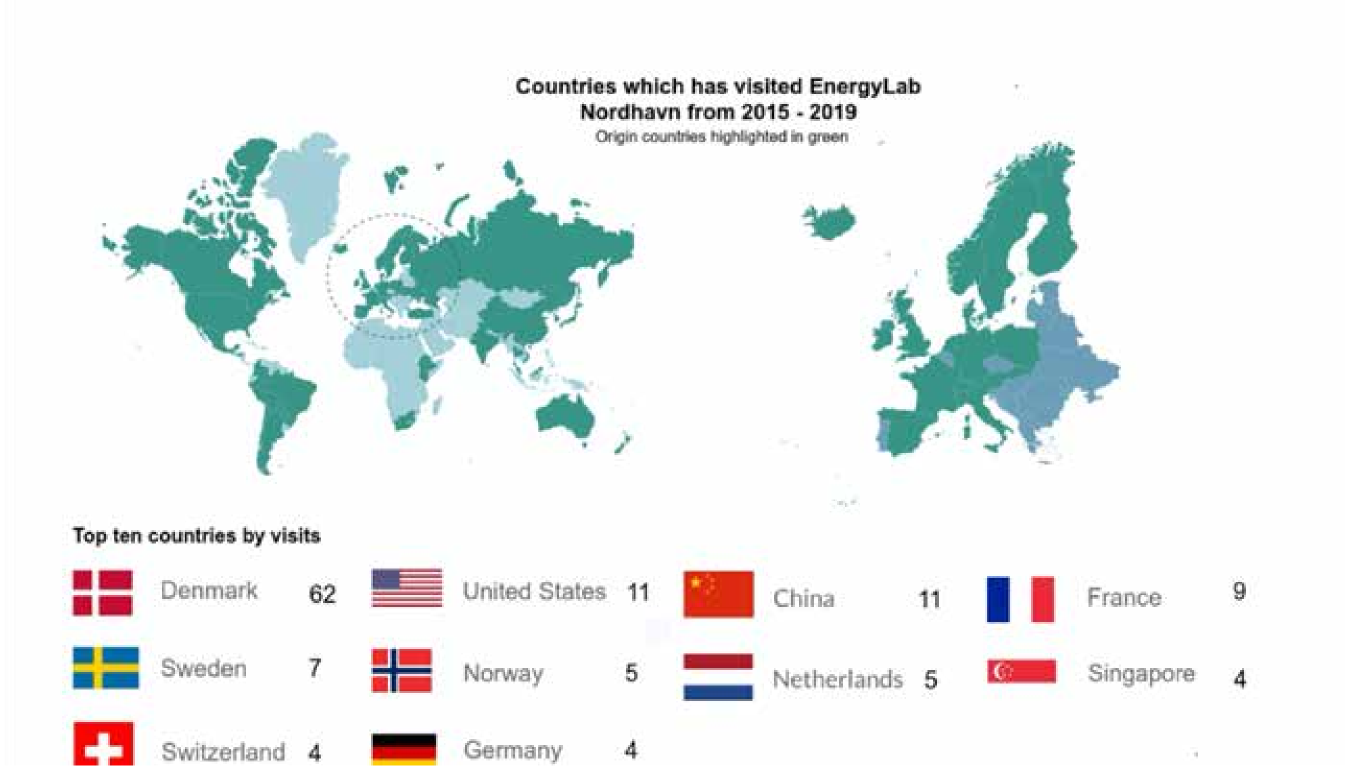
In 2017, EnergyLab Nordhavn inaugurated its new showroom as part of the new shared office and innovation environment EnergyHub Nordhavn. During its first two years, the showroom has welcomed around 10,000 visitors as well as hosting events in connection with the Nordic Clean Energy Week in May 2018 and the C40 World Mayors Summit in autumn 2019.

An important part of disseminating and showcasing the results of the EnergyLab Nordhavn project has been to welcome the many delegations visiting the showroom at EnergyLab Nordhavn. The showroom has been a key factor in communicating project results to external stakeholders, as having a physical presence at the location of the implemented technical solutions creates relevance and gives the project a more tangible dimension.

From when the EnergyLab Nordhavn project started in 2015 until November 2019, 187 delegations from 46 different countries have visited the showroom at Nordhavn, with a steady increase in number of delegations per year from 2015 to 2018. The number of delegates per visit varies greatly, with 20 visitors on average. The huge interest clearly reflects the considerable international interest being shown in the solutions which have been developed as part of the project and by Danish companies in general.

One third of the delegation visits were local stakeholders from Denmark, while the remaining two thirds were stakeholders from many different parts of the world. A delegation visit from a country is represented in the figure below with the country being highlighted in green. As illustrated, most parts of the world are represented, which shows that knowledge about the project has reached far and wide.





PROJECT MEETING PLACE

In addition to serving as a meeting place for the many visitors we receive, our EnergyHub showroom has also served as a venue for numerous project meetings, workshops, and large conferences over the years. Moreover, thanks to a number of permanent office workplaces on the site, it has been possible for project participants to spend a working day there in connection with activities in the showroom or to simply meet with other members of the project team. Having a permanent and shared meeting place has undoubtedly facilitated cooperation between the 12 project partners, which has been excellent, and perhaps contributed to more solutions being created across sectors. At the same time, strong synergies have been achieved with the other companies operating out of EnergyHub.

In EHub, InforMetics has found a dynamic environment that manifests and brings to life the Smart City concept, and which has welcomed our water company with open arms. All the international delegations have made us aware of global needs, and inspired us to think further ahead, and even given us contacts that may well evolve into tomorrow's customers and partners. EHub gives us a real opportunity to show our potential customers the rather uniquely Danish way in which we embrace and make the most of the open cooperation that exists between public, private, and research institutions.

Peter Rasch, CEO, Informetics

For ABB, the EnergyLab Nordhavn showroom and EnergyHub meant that there was a place to rendezvous, offering the necessary facilities, as well as an opportunity to showcase ideas and results right where the project is carrying out its experiments and demonstrations.

It has been possible to meet with project partners for meetings, seminars, workshops, and with customers to talk about future energy scenarios, where the focus is on smart housing, energy storage, and sector coupling.

Benny S. Hansen, ABB

About EnergyLab Nordhavn

EnergyLab Nordhavn is a four-year project aimed at developing the energy solutions of the future. The project uses Nordhavn as a living urban laboratory to demonstrate how electricity, heating, energy-efficient solutions, and electrical transport can be incorporated into an intelligent, flexible, and optimized energy system.

The aim of the 'EnergyLab Nordhavn—new urban energy infrastructures' project has been to develop and demonstrate future energy solutions. The project has utilized Copenhagen's Nordhavn as a full-scale smart city energy lab, and demonstrated how electricity and heating, energy-efficient buildings, and electric transport can be integrated into an intelligent, flexible, and optimized energy system. The project participants are: DTU, City of Copenhagen, CPH City & Port Development, HOFOR, Radius, ABB, COWI, Danfoss, Nerve Smart Systems, METRO THERM, Glen Dimplex, and the PowerLabDK facilities.

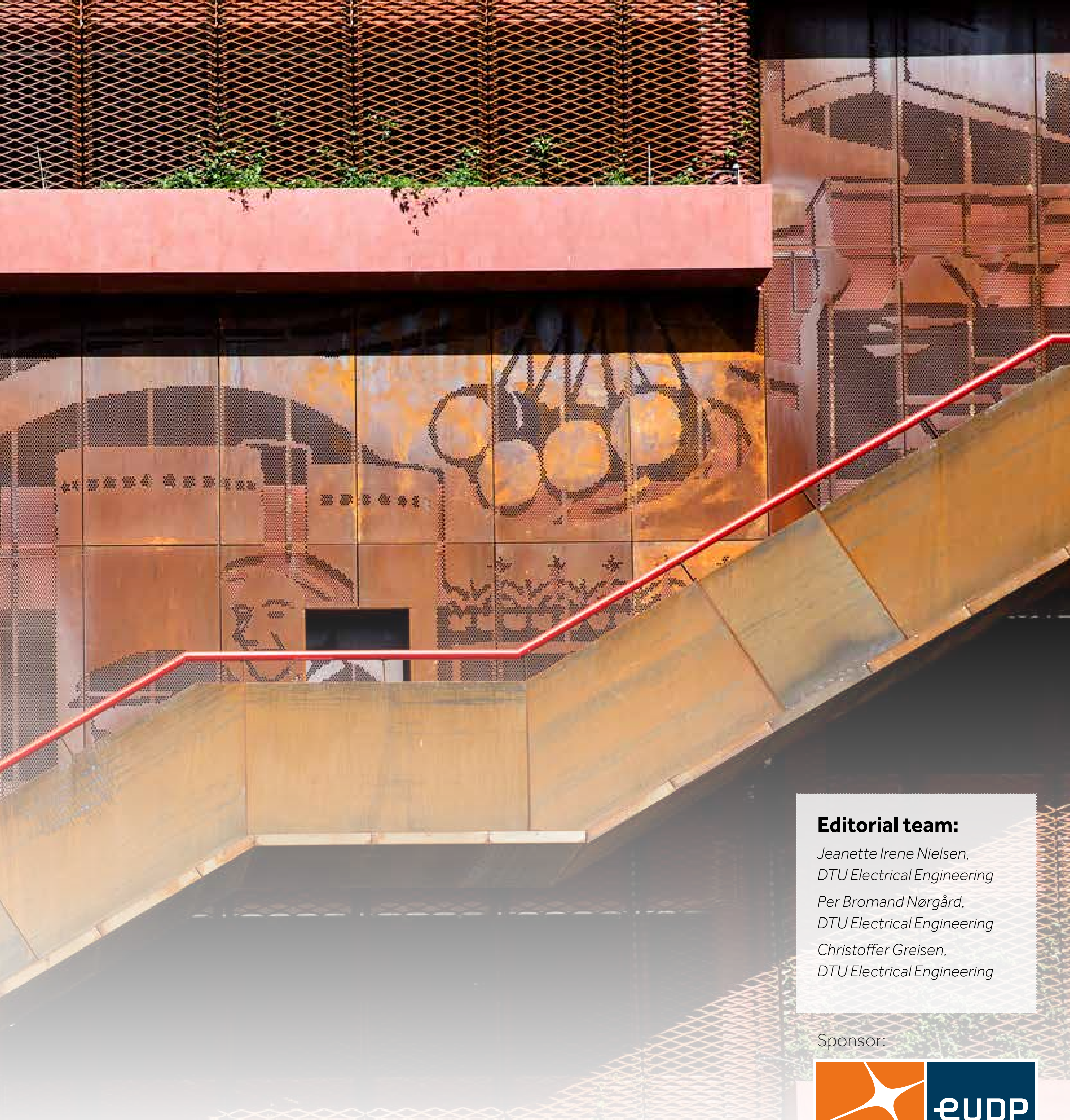
The project is supported by EUDP, runs from 2015 to 2019, and is headed by the Center for Electric Power and Energy (CEE) at DTU Electrical Engineering.

REFERENCES

This report has been compiled on the basis of various data and analyses from the project partners: DTU, City of Copenhagen, CPH City & Port Development, HOFOR, Radius, ABB, COWI, Danfoss, Nerve Smart Systems, METRO THERM, Glen Dimplex, and the PowerLabDK facilities.

References includes: deliverable reports, annual reports, scientific publications, PhD and master theses and our recommendations. All information can be found on the EnergyLab Nordhavn website on the Reports and Downloads section: http://www.energylabnordhavn.com/reports-and-downloads.html

If you want to know more about the results please contact the project management at eln@dtu.dk.



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