Final report

1. Project details

Project title	Planning and comprehensive renovation to energy neutral level of government/public areas with multiple buildings - Danish participation in IEA Annex 73.
File no.	64017-0589 and 64018-0548 (which is an extension of the Annex 73 project)
Name of the funding scheme	EUDP
Project managing company / institution	BUILD, AAU
CVR number (central business register)	29102384
Project partners	Kirsten Engelund Thomsen and Jørgen Rose (BUILD, AAU), Anders Dyrelund and Søren Møller Thomsen (Rambøll), Oddgeir Gudmundsson (Danfoss), Anders Andersen (EMD International), Jens Peter Sandemand (Danish Ministry of Defense, Estate Agency), Niels Vilstrup (Ministry of Foreign Affairs of Denmark)
Submission date	23 April 2024

2. Summary

In English:

The main purpose of IEA Annex 73 was to develop guidelines and tools that support the planning of Net Zero Energy Resilient Public Communities and that are easy to understand and execute. To achieve this, Annex 73 focused on the decision-making process and computer-based modelling tools for achieving net zero energy resilient public-owned communities (e.g., military garrisons, universities, etc.).

All primary project objectives have been fulfilled, e.g.:

- assessing existing case studies regarding technical solutions, costs and performance data,
- developing a database of energy utilization indexes (EUI) of relevant building types and communities,
- developing energy targets,
- summarizing, developing, and cataloguing representative building models by building use type,
- summarizing, developing, and cataloguing representative energy supply and energy efficiency scenarios,
- developing guidance for Net Zero Energy Master Planning (NZEMP),

- developing a functional modelling tool to facilitate the Net Zero Energy Master Planning Process.
- Provide dissemination and training in the participating countries to end users, primarily decision makers, local planners and energy managers

The new NZEMP tool, E^2RIN, can enhance currently used building modelling tools to also address resiliency, collecting and describing relevant business and financial aspects and legal requirements and constraints and finally providing dissemination and training in participating countries.

Several reports and papers for international conferences have been produced (see under publications). Eleven Danish case studies have been described and documented in the book of case studies (see under publications), i.e., 1. Air base Skrydstrup, 2. District Heating Based on CHP and Waste Heat in Taarnby, 3. District Cooling in Symbiosis with District Heating and Wastewater in Taarnby, 4. District Energy in Greater Copenhagen, 5. District Energy from Waste for Vestforbrænding, 6. University Campus of Technical University of Denmark (DTU), 7. District Quaanaap in Greenland, 8. Company Campus of Danfoss, 9. Energy Planning in Urban Development, Favrholm, 10. Gram District Heating Solar Heat, Storage Pit and 11. Nymindegab Military Camp.

Rambøll A/S, leader of Subtask C, were responsible for developing the extensive Excel technology database which features data for all the relevant technologies needed for modelling/simulating district energy supply, distribution, and storage. Dissemination of project results were carried out on the project website (annex73.iea-ebc.org), but also through participation in a wide range of workshops, conferences, and stakeholder forums.

In Danish

Hovedformålet med IEA Annex 73 var at udvikle retningslinjer og værktøjer, der understøtter planlægningen af Net Zero Energy Resilient Public Communities (energineutrale robuste offentligt ejede områder), som er lette at forstå og udføre. For at opnå dette fokuserede Annex 73 på beslutningsprocessen og computerbaserede modelleringsværktøjer til opnåelse af net-zero energy resilient public communities (f.eks. militærinstallationer, universiteter osv.).

Alle primære projektmål er blevet opfyldt, dvs.:

- vurdere eksisterende cases og udvikle energi-benchmarks for repræsentative bygninger
- opbygge en database over energiudnyttelsesindeks (EUI) for de forskellige bygningstyper (offentlige, akademiske, og militære)
- udvikle energimål: definitioner, matrix, pengeværdier
- opsummere, udvikle og katalogisere repræsentative bygningsmodeller ift. bygningstype, bygningernes anvendelse, herunder bygninger med blandet anvendelse, som ofte ses for offentlige samfund eller militære installationer
- udvikle vejledning for Net Zero Energy Master Planning (NZEMP)
- udvikle funktionelle beskrivelser af modelleringsværktøjer som kan anvendes i NZEMP
- indsamle og beskrive forretningsmæssige og finansielle aspekter og retlige krav og begrænsninger for NZEMP varedisponering til offentlige samfund i de deltagende lande
- levere formidling og uddannelse i de deltagende lande til slutbrugerne, primært beslutningstagere, lokale planlæggere og energiansvarlige.

Der er udarbejdet adskillige rapporter og artikler til internationale konferencer (se under publikationer). Elleve danske casestudier er beskrevet og dokumenteret i bogen om case-studies (se under publikationer), 1. Flyvestation Skrydstrup, 2. Fjernvarme baseret på kraftvarme og spildvarme i Taarnby, 3. Fjernkøling i symbiose med fjernvarme og spildevand i Taarnby, 4. Distriktsenergi i Storkøbenhavn, 5. Distriktsenergi fra affald til Vestforbrænding, 6. Danmarks Tekniske Universitets Universitetscampus (DTU), 7. Distrikt Quaanaap i Grønland, 8. Danfoss virksomhedscampus, 9. Energiplanlægning i byudvikling, Favrholm, 10. Gram Fjernvarme, solvarme og varmelager og 11. Nymindegablejren.

Rambøll A/S, leder af Subtask C, var ansvarlig for udviklingen af den omfattende Excel-teknologidatabase, som indeholder data for alle de relevante teknologier, der er nødvendige for at modellere/simulere fjernenergiforsyning, distribution og lagring. Formidling af projektresultater blev udført på projektets hjemmeside (annex73.iea-ebc.org), men også gennem deltagelse i en lang række workshops, konferencer og interessentfora.

3. Project objectives

The overarching goal of IEA Annex 73 was to develop guidelines and tools that support the planning of Net Zero Energy Public Communities.

The key objectives of IEA Annex 73 were to:

- Assess existing case studies with regard to technical solutions, costs and performance data
- Develop a database of energy utilization indexes (EUI) of Public, Academic, and Armed Forces building types and communities
- Develop Energy Targets
- Summarize, develop and catalog representative building models by building use type, including mixed-use buildings, applicable to building stocks of national public communities/military garrisons
- Summarize, develop and catalog representative energy supply and energy efficiency scenarios
- Develop Guidance for Energy Master Planning
- Develop functional modeling tool to facilitate the Net Zero Energy Master Planning Process, which will enhance currently used building modeling tools to address resiliency of combined energy supply and energy efficiency solutions, integrate a capability for computation of thermal and electrical network characteristics (capacity, losses, availability and cost), and offer sufficient visualization of different scenarios to support resilience decisions without significant post processing.
- Collect and describe business and financial aspects and legal requirements and constraints relevant for the implementation process of NZE concepts for public communities in participating countries
- Provide dissemination and training in participating countries and the end users, mainly decision makers, community planners and energy managers and other market partners in the proceedings and work of the Annex Subtasks.

The Annex subtasks were structured as shown in figure 1.

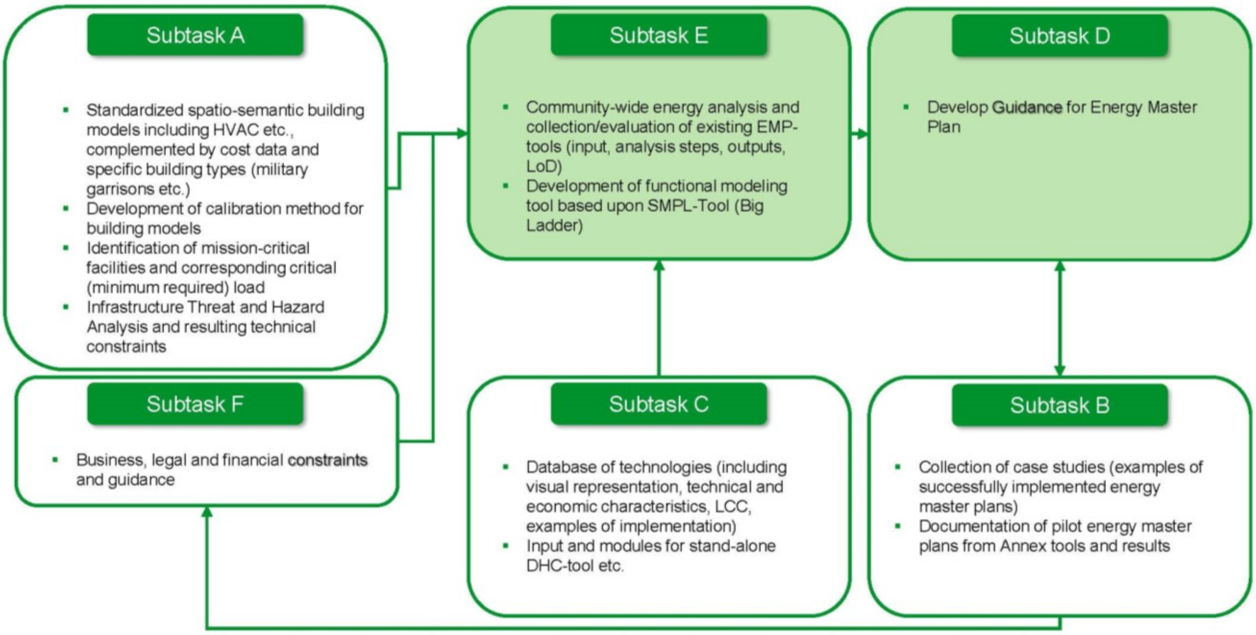


Figure 1. Structure of subtasks in IEA EBC Annex 75.

Below is a detailed description of each subtask.

A. **Collection and evaluation of input data for NZEMP**
   Subtask A focused on collecting the critical country-specific input data needed for the development of NZEMP. Subtask A would:
   1. Research, summarize and develop representative energy benchmarks and energy-related goals for the individual building types.
   2. Collect and develop, catalogue, and establish databases of representative building models (e.g., based on type of use, including buildings with mixed use), covering national public areas/military installations, etc.
   3. Collect financial prerequisites for individual measures and total costs for building renovation, HVAC, energy supply, and renewable energy technologies, etc.

B. **Collection of existing case studies and implementation of pilot studies**
   Subtask B would collect examples of successful cases that have been fully or partially implemented. Subtask B would also document pilot studies to demonstrate tools and guidelines that emerge in connection with IEA Annex 73's research. NZEMP is part of the long-term community planning, and therefore it was not expected that all cases or pilot projects under IEA Annex 73 would demonstrate a complete or large-scale realization of NZEMP.

   Subtask B would build on:
   1. the results of IEA Annex 51,
   2. cases developed by the US Army ERDC team performed using the NZP tool (ASHRAE),
   3. cases included in the ESTCP demonstration program report or the U.S. Army report, on examples of advanced energy systems collected for the District / Central Solar Hot Water Systems design guide, and
   4. best practice examples from Rambøll, Danfoss, and other of the project's industrial partners.

C. **Description of existing and innovative technologies, architecture and select calculation tools for performance of central energy systems**
   Subtask C dealt with technology solutions. The choice between decentralized heating and/or cooling supply solutions for individual buildings, central options for the whole community, areas, or clusters of buildings with central energy system and common energy distribution network (or a mixture of

both), depends on the level of energy intensity, existing networks, energy systems configuration etc. The applicability of the different options depends on local conditions, and different scenarios need to be evaluated. Among the main factors influencing the choice of such scenarios are:

1. The scenario where the consideration depends on choosing a solution that will help achieve specific energy goals (primary energy, reduction of fossil fuels, energy security, reliability, etc.).
2. The cost-effectiveness of centralized and decentralized options based on LCC analyzes, which take into account energy prices and the investments to be made in distribution networks, maintenance and replacement, etc. To make it easier to optimize the future planning and construction or renovation of public buildings (e.g., military installations, universities, etc.), holistic and cost-effective methods should be used.

D. **Develop guidance for NZEMP**
Subtask D would establish the concept and method of the Energy Master Planning process as part of the area planning. Subtask D would describe the input data required to implement NZEMPs and their sources, outline the NZEMP process and its algorithm, and provide a description of the different phases of the NZEMP, including:

1. Benchmarking
2. Baselining
3. Scenarios to be analyzed / considered
4. Comparison and selection principles.

Subtask D would also include dissemination and training activities needed to implement EMP in the participating countries.

Energy-related goals and other core values established in connection with Subtask A would define the framework for the Energy Master Plan and create the boundary conditions to be used in connection with the development of the method.

E. **Develop a functional description of the role of modeling tools in the NZEMP Process**
Subtask E would collect information on existing modeling tools for holistic energy planning and identify how each tool would fit into the overall process. For each tool, the following information were described:

1. Input
2. Analysis steps
3. Output
4. The level of detail for each step

This would provide an overview of standard inputs, outputs, and functionality for existing tools, and form the basis for a description that could be used in the further development of existing tools and the development of, e.g., web-based tools that used for Net Zero Energy Master Planning processes.

Subtask E would also identify deficiencies and necessary improvements and modifications to existing Master Planning Computer tools and would develop at least one prototype to demonstrate the capabilities of modeling tools. In IEA Annex 73, the focus was on integrating a module for simulation of district heating systems, an LCC cost calculation module, and a design module for implementation in the NZP tool.

F. **Business, legal, and financial aspects of NZEMP**
Subtask F would develop a structured example for each participating country of a financial model and a business model for public areas. The developed business models were performance-based and

would address the economic benefits that go beyond the Business-as-usual approach (i.e., clean energy savings). Financial models were designed in a way that minimizes the impact on the economy of public owners and administrators (universities, ministries, etc.).

Subtask F also collected and described the legal requirements for Risk Management plans in the participating countries, and defined the regulatory framework to be considered in re-designing existing areas in terms of spatial planning, energy needs, etc.

The analysis of funding models focused on single-owner areas (Ministries of Defense, universities, hospitals, etc.), and the typical funding sources used in the participating countries such as public, public/private, and private funding sources; bank loans, closed and open funds; or more specific approaches such as PACE (Property Assessed Clean Energy) or utility bill payments (used in the US), where companies pay for the energy improvements and in return are repaid through the property tax bill over, e.g., 20 years.

4. Project implementation

The Danish participation in Annex 73 started 1. July 2018 (project phase) and the international and Danish project ended officially 30. April 2022.

The following meetings and seminars were held (see table 1).

Table 1. Meetings and seminars held in IEA EBC Annex 73.

NUMBER AND LOCATION	HOST PARTNERS	DATE	MEETING FOCUS
1ST – FRANKFURT	KEA	16.4.2018 – 19.4.2018	Kick off meeting
2ND – GRAZ	AEE Intec	2.9.2018 – 5.9.2018	
3RD – NEW ORLEANS	USACE	25.2.2019 – 1.3.2019	
4TH – COPENHAGEN	Rambøll	12.9.2019 – 13.9.2019	
5TH – VIRTUAL	NTNU	28.4.2020 – 29.4.2020	
6TH – VIRTUAL	USACE	22.9.2020 – 23.9.2020	
7TH – VIRTUAL	KEA	25.5.2021	
8TH – VIRTUAL	USACE	14.10.2021	
9TH – GRAZ	AEE Intec	5.4.2022	Final meeting

Some of the meetings were held in connection with seminars and conferences. However, due to the COVID-19 pandemic, unfortunately four of the planned international meetings had to be held online.

The 2nd meeting was held in Graz in conjunction with the ISEC 2018 (International Sustainability Energy Conference) which focused on “Renewable Heating and Cooling in Integrated Urban and Industrial Energy Systems”, giving project participants the opportunity to participate and contribute in/to the conference. The Danish team contributed with several conference papers.

The 3rd meeting was held in New Orleans in conjunction with the CampusEnergy2019 conference which was arranged by International District Energy Association (IDEA).

The 4th meeting was held in Copenhagen in conjunction with the Smart Energy Conference 2019. Again, the Danish team contributed with a conference paper and Anders Dyrelund (Rambøll) gave a keynote speech.

The 9th meeting was held in Graz in conjunction with the conference ISEC 2022 (International Sustainability Energy Conference) arranged by the Annex 73 partner from AEE INTEC.

Figure 2. Photos taken at the meeting held in Copenhagen at Rambøll in 2019.

All milestones of the project were achieved. The project was delayed 4 months due to COVID-19.

5. Project results

All primary project objectives have been fulfilled, e.g.,

- assessing existing case studies regarding technical solutions, costs and performance data,
- developing a database of energy utilization indexes (EUI) of relevant building types and communities,
- developing energy targets, summarizing, developing and cataloguing representative building models by building use type,
- summarizing, developing, and cataloguing representative energy supply and energy efficiency scenarios,
- developing guidance for Net Zero Energy Master Planning (NZEMP),
- developing a functional modelling tool to facilitate the Net Zero Energy Master Planning Process, which can enhance currently used building modelling tools to also address resiliency,
- collecting and describing relevant business and financial aspects and legal requirements and constraints and finally
- providing dissemination and training in participating countries.

Several reports and papers have been produced as part of the project. In the following the main findings of each subtask is described.

5.1 Subtask A: Collection and Evaluation of Input Data for Energy Master Plan (EMP)

The focus of Subtask A was on critical nation-specific input data required for the development of an EMP. The purpose of the subtask was to:

- Establish internationally recognized community-oriented definitions for EMP goals, such as: Efficiency, Security, Independence, Resilience, Reliability
- Research, summarize, and develop representative building energy benchmarks and energy-related targets: definitions, matrix, and monetary values.

- Collect and, when necessary, develop, catalogue, and establish a database of representative building models (by building use type, including mixed-use buildings) applicable to national public communities/military garrisons building stocks.
- Collect and develop energy efficiency incremental and total costs for building, heating, ventilating, and air-conditioning (HVAC), supply, and renewable technologies, etc.

The overarching goal of Subtask A was therefore to derive the necessary information relevant for Net Zero Energy Master Planners regarding, i.e., a common set of definitions, metrics, benchmarks, targets, and models to establish a common framework.

In Subtask A Denmark has supplied information on the regulatory framework for building energy use in Denmark and delivered representative benchmarks and targets for individual buildings. Unfortunately, there were no relevant European building energy archetype models available (i.e., the TABULA project only includes a very limited selection of residential building types) and therefore no input could be delivered regarding this.

The results of the Subtask A work are documented in chapter 4 and Appendix A of the EMP guide and in the conference paper “Energy Master Planning: Identifying Framing Constraints that Scope Your Technology Options.” (See publications).

5.2 Subtask B: Collection of Existing Case Studies and implementation of pilot studies

The overarching goal of Subtask B was to collect and document best-practice examples of successful energy master plans and derive the lessons-learned from these examples so that they could feed into the development of the description of technology approaches in Subtask C and the development of guidance for Net Zero Energy Master Planning in Subtask D. Subtask B results also contributed to development of “Business, Legal and Financial Aspects of Net Zero Energy Master Planning” (Subtask F).

A total of 31 case studies were collected in Subtask B. Denmark contributed with eleven case studies, i.e., 1. Air base Skrydstrup, 2. District Heating Based on CHP and Waste Heat in Taarnby, 3. District Cooling in Symbiosis with District Heating and Wastewater in Taarnby, 4. District Energy in Greater Copenhagen, 5. District Energy from Waste for Vestforbrænding, 6. University Campus of Technical University of Denmark (DTU), 7. District Quaanaap in Greenland, 8. Company Campus of Danfoss, 9. Energy Planning in Urban Development, Favrholm, 10. Gram District Heating Solar Heat, Storage Pit and 11. Nymindegab Military Camp. As an example, the Danfoss case is briefly described in the following. The remaining ten examples can be found in the book of case studies (see publication list).

Danfoss Nordborg energy renovation story - Smart energy renovation of an industry campus

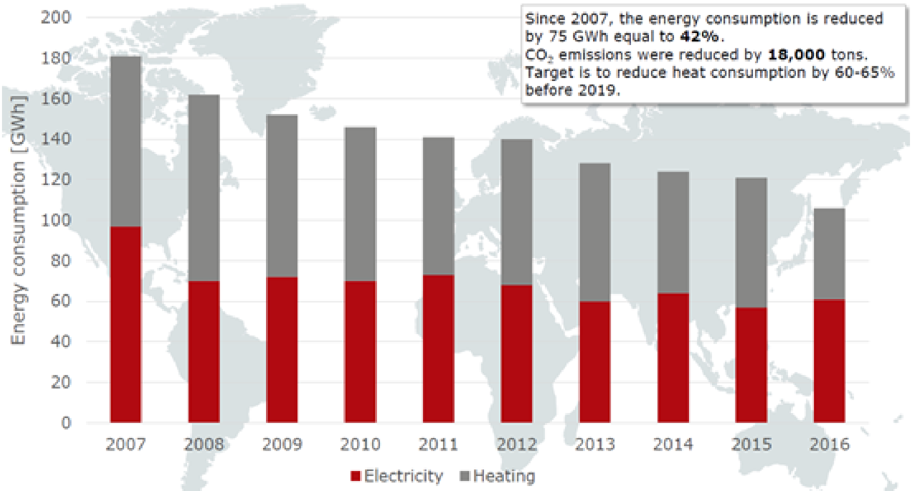
In 2007 it was decided to investigate and implement energy saving measures in Danfoss campuses around the world. In this case study the energy renovation process in the Nordborg campus is discussed.
The Danfoss campus in Nordborg is the initial production campus of Danfoss. The buildings were built in the 1950s to 2000. The buildings are a mix of production facilities and office buildings, in total there are 27 buildings with a total of 250.000 m^2 floor area. Over the years the facilities have been changed to fit the evolving production processes as well as generally changing usage of the buildings. The campus has its own natural gas CHP plant that has been used for generating power and heat for the campus area. Additionally, the campus is connected to the national power grid for operational security and resilience reasons.

Energy market and the campus energy supply
The campus has its own natural gas CHP plant that has been used for generating power and heat for the campus area. The campus has its own microgrid district heating system. Additionally, the campus is connected to the national power grid for operational security and resilience reasons. In 2016 the national power grid fuel mix was 37.2% was fossil fuel based, 2.3% from non-renewable sources and 60.5% from renewable energy source. From 2020 the municipality plans to install a district heating system connecting the towns Nordborg, Guderup and Ketting. As the Danfoss Nordborg

campus is situated in the middle of the planned network it will host the biomass heat plant that will supply the district heating in the campus area and become an anchor load customer.

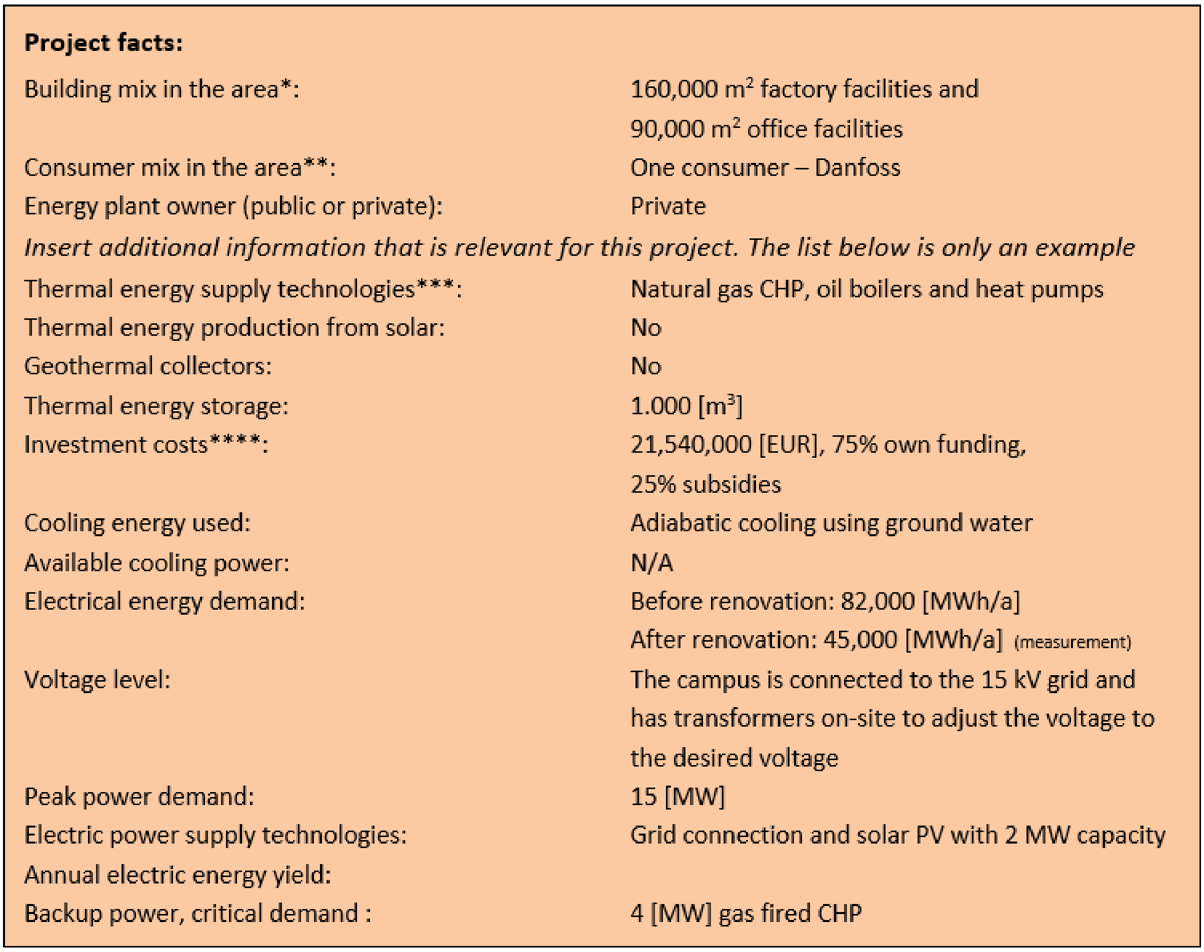
Campus energy supply

Prior to the energy renovation work the campus had two distribution networks, a high temperature network, supply 152°C and return 137°C, supplying buildings that required process heat, space heating and domestic hot water preparation, and a separate lower temperature network, supply 92°C and return 85°C, to buildings that only had space heating and domestic hot water preparation requirements The high temperature requirements made the system both inefficient and not capable for utilization of waste heat from local manufacturing processes. In 2007, the reference year, the heat demand of the campus was 83,550 MWh, fully supplied by a natural gas boiler. In 2017 the heating degree day normalized heat demand was 29,900 MWh, where 67% was based on natural gas and 33% from waste heat that had been temperature enhanced by a heat pump. In addition to the thermal energy savings, efficiency improvements on the electric side have led to almost 45% electricity savings.



Since 2007, the energy consumption is reduced by 75 GWh equal to **42%**.
CO_2 emissions were reduced by **18,000** tons.
Target is to reduce heat consumption by 60-65% before 2019.

Figure 3. Development in electricity and heating consumption for Danfoss campus.



Project facts:

Building mix in the area*:	160,000 m^2 factory facilities and 90,000 m^2 office facilities
Consumer mix in the area**:	One consumer – Danfoss
Energy plant owner (public or private):	Private
Insert additional information that is relevant for this project. The list below is only an example	
Thermal energy supply technologies***:	Natural gas CHP, oil boilers and heat pumps
Thermal energy production from solar:	No
Geothermal collectors:	No
Thermal energy storage:	1.000 [m^3]
Investment costs****:	21,540,000 [EUR], 75% own funding, 25% subsidies
Cooling energy used:	Adiabatic cooling using ground water
Available cooling power:	N/A
Electrical energy demand:	Before renovation: 82,000 [MWh/a] After renovation: 45,000 [MWh/a] (measurement)
Voltage level:	The campus is connected to the 15 kV grid and has transformers on-site to adjust the voltage to the desired voltage
Peak power demand:	15 [MW]
Electric power supply technologies:	Grid connection and solar PV with 2 MW capacity
Annual electric energy yield:	
Backup power, critical demand :	4 [MW] gas fired CHP

Figure 4. Project facts for Danfoss campus.

Prior to the initiation of the energy efficiency renovation project the general consensus was that the campus was running efficiently. The project was part of a local initiative, Project Zero, which is aiming for zero CO$_2$ emissions for the local community as well as to prepare for connecting the campus to the district heating system that will be built in the area. The first part of the analysis was to increase the energy consumption measurement points to allow for tracking where the energy was being used. After detailed analysis, based on the measured data, had been performed on all aspects of the energy consumption it was realized that with well-known and proven technologies the heating energy consumption could be more than halved and the electricity consumption could be reduced by up to 40%.

The energy objectives were to:

- Save energy on ventilation and air conditioning
- Increase process energy efficiency and capture/reuse waste heat
- Upgrade the heating installations, insulate buildings and run with low supply temperature heating
- Renovate the campus heating system to facilitate future connections to the planned district heating system
- Install LED lights and implement light control system

The overall objective was to achieve 34% savings in energy consumption through cost sustainable energy efficiency measures. The main measures are described in the following.

Ventilation

Installation of a large industrial ventilation systems with heat-recovery by connecting exhaust heat from production processes into the main ventilation system. The realized energy savings varies from area to area – but are between 30% to 75%.

Figure 5. Left: large ventilation system installed in the production halls to collect exhaust heat from machinery. Right: Main ventilation system.

Process heat

Prior to the energy efficiency projects the process cooling water was cooled by use of cooling towers, resulting in ~10.000 MWh of heat vented to the atmosphere every year. To recover this heat from the process cooling water four 500 kW ammonium-based industrial heat pumps were installed. The heat pumps are optimized with a Turbocor® compressor. The heat pumps are cooling ~250-350 m3 per hour from 26-30°C down to ~21°C. Energy consumption of the pumps driving the process water was further reduced by optimizing the flow with Danfoss VLT® AQUA Drives.

Figure 6: One of the installed 500 kW heat pumps.

Heating system energy saving measures

By taking a system optimization approach to energy efficiency, a diversity of improvements and retrofits have been implemented in the central heating system over the years. The improvements included separating the process demand from the space and domestic hot water heating demand, new central control of space heating in production halls (no individual settings), new thermostatic control valves on radiators in office buildings, increased insulation of critical buildings, increased energy awareness of users by aware-ness raising and systematically monitoring for uncontrolled air exchanges, i.e., opened doors and windows.

The results were that the operating temperature for building heating could be reduced, supply temperature from 92°C to 77°C and return temperature below 37°C. The reduced temperature requirements opened for the possibility to harness industry waste heat in the campus, 26-30°C, and boost it via heat pumps. The heat pump is currently supplying 33% of the campus heat demand. The reduced supply temperature further increases the efficiency of the campus CHP plant, which is now used as peak and backup boiler.

Once the heat saving potential in the Danfoss campus was identified in 2007 the originally proposed business model for the district heating system became unsustainable and needed to be reconsidered. After re-considering the district heating business model to consider the significantly reduced heat demand from Danfoss the decision was made to construct the network. Once the district heating system becomes operational, planned for 2021, it will replace the current natural gas-based heat supply in the campus with green heat from a biomass boiler.

Rationales for the energy savings projects

The key motivator for the energy savings has been to take responsibility of own energy consumption and provide a economically sustainable showcase on energy efficiency improvements for the industry using well proven technologies. Additional rationales have been to reduced emissions from energy consumption to comply with national requirements, fulfil local government targets, free resources, increased resilience, and competitiveness.

Key learnings

- Ensure that energy consumption measurements are performed at relevant locations
- Identify the energy saving potential before considering changing of the heat supply.
- Energy efficiency makes a great business case for industry and business, but regulatory push is needed.

5.3 Subtask C: Description of existing and innovative technologies, architecture, and calculation tools for performance of central energy systems (power and thermal)

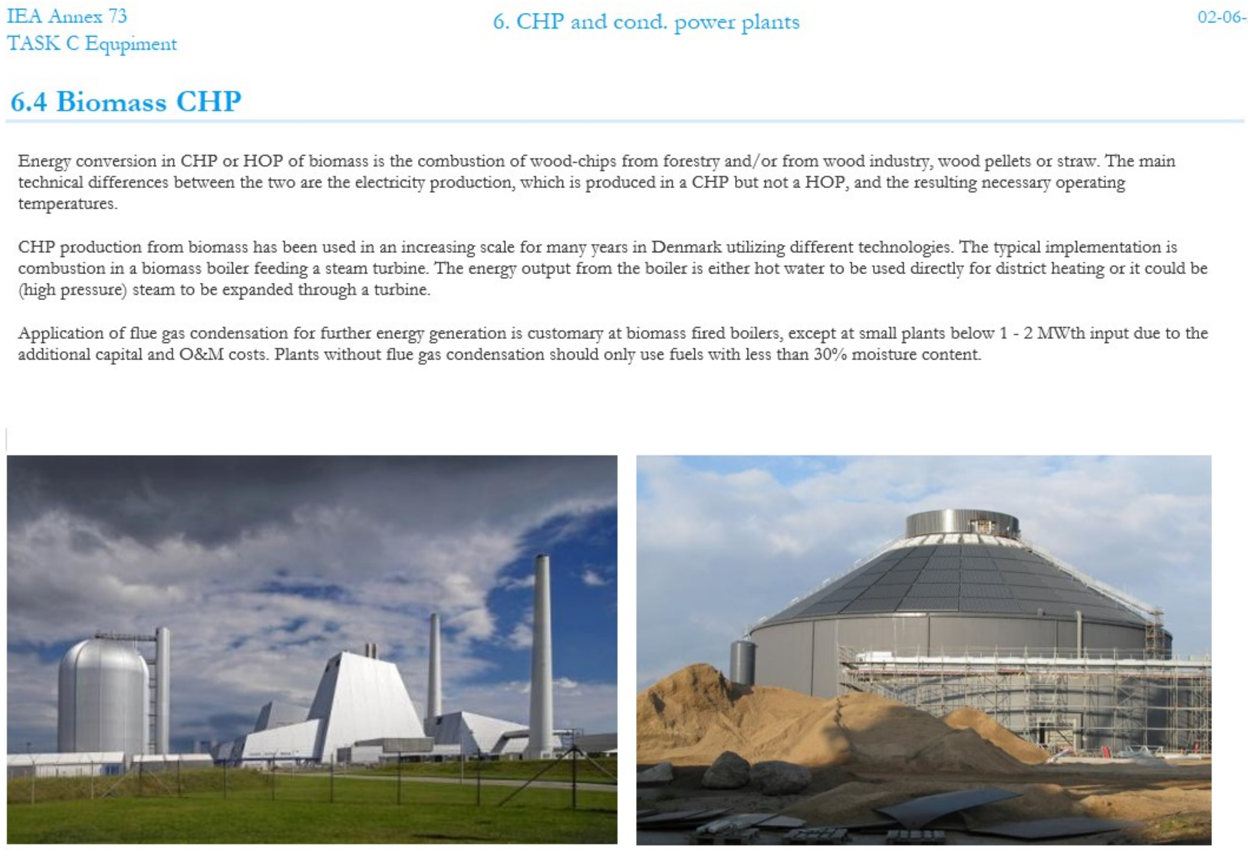
Rambøll A/S was the leader of Subtask C and therefore a large proportion of the Danish efforts were invested into this Subtask. The work was particularly focused on developing a database of technologies relevant in relation to district energy planning and detailing typical best-practice examples of district energy architecture.

The main outcome of the work in Subtask C is an Excel Spreadsheet database (see publications). The Excel database was developed in a way that it can be used in conjunction with district energy calculation software, i.e., as a library of technologies covering both technical characteristics such as efficiencies, peak, and base capacities etc., but also data on costs of purchase and maintenance and levelized cost of energy (LCOE), i.e., a measure of the average net present cost of energy generation for a generating plant over its lifetime. The database features information on mature (first generation) technologies and state-of-the-art technologies available on the market for supplying electricity, heating, cooling and natural gas.

The technology database was developed based on information available from various sources. These included: NZP/SMPL tool, MIT LL ERA tool, REOpt tool, U.S. Department of Energy CHP factsheets, Danish Energy Agency Technology Catalogue and information provided by the International District Energy Association, EATON, Schneider Electric, TKDA, and GEF. The database is comprised of multiple energy conversion, distribution and storage technologies which can be integrated by energy planners into energy system architectures to create different alternatives of community energy systems.

The database contains general data, which is accurate enough to support comparison of different concepts on the planning level, but is not designed for making specific investment decisions, system design, or equipment specification. Information is supported by references and links to examples of technology implementation, including case studies (see publications).

Figure 7 and 8 shows an example from the database, i.e., first a general description of biomass CHP and below data for three sizes of biomass CHP corresponding to large, medium, and small plants. This way the economy-of-scale is also available to planners.



IEA Annex 73
TASK C Equpiment

6. CHP and cond. power plants

02-06-2022

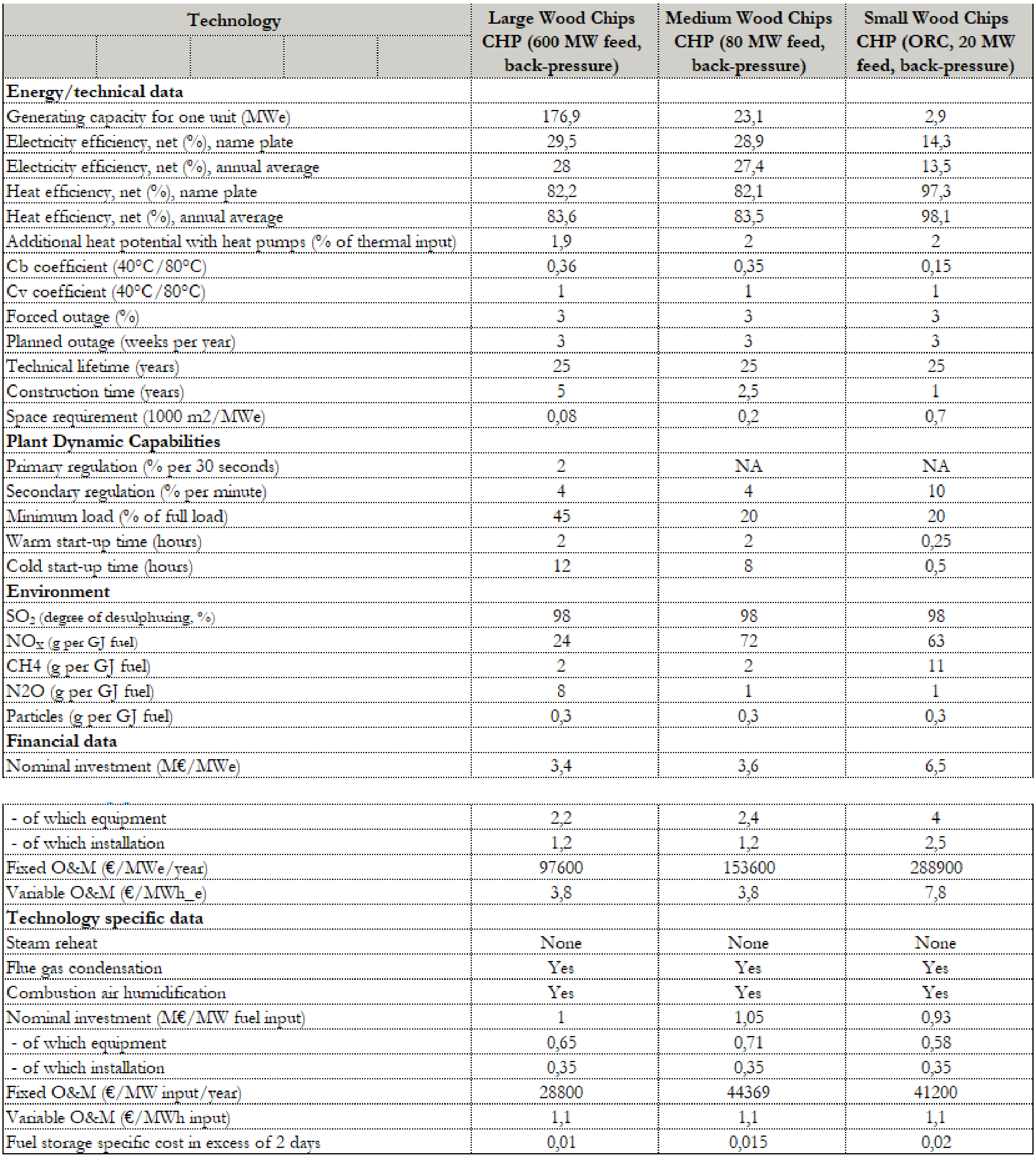
6.4 Biomass CHP

Energy conversion in CHP or HOP of biomass is the combustion of wood-chips from forestry and/or from wood industry, wood pellets or straw. The main technical differences between the two are the electricity production, which is produced in a CHP but not a HOP, and the resulting necessary operating temperatures.

CHP production from biomass has been used in an increasing scale for many years in Denmark utilizing different technologies. The typical implementation is combustion in a biomass boiler feeding a steam turbine. The energy output from the boiler is either hot water to be used directly for district heating or it could be (high pressure) steam to be expanded through a turbine.

Application of flue gas condensation for further energy generation is customary at biomass fired boilers, except at small plants below 1 - 2 MWth input due to the additional capital and O&M costs. Plants without flue gas condensation should only use fuels with less than 30% moisture content.

Figure 7. General description of biomass CHP (from the Subtask C database).



Technology	Large Wood Chips CHP (600 MW feed, back-pressure)	Medium Wood Chips CHP (80 MW feed, back-pressure)	Small Wood Chips CHP (ORC, 20 MW feed, back-pressure)
Energy/technical data			
Generating capacity for one unit (MWe)	176,9	23,1	2,9
Electricity efficiency, net (%), name plate	29,5	28,9	14,3
Electricity efficiency, net (%), annual average	28	27,4	13,5
Heat efficiency, net (%), name plate	82,2	82,1	97,3
Heat efficiency, net (%), annual average	83,6	83,5	98,1
Additional heat potential with heat pumps (% of thermal input)	1,9	2	2
Cb coefficient (40°C/80°C)	0,36	0,35	0,15
Cv coefficient (40°C/80°C)	1	1	1
Forced outage (%)	3	3	3
Planned outage (weeks per year)	3	3	3
Technical lifetime (years)	25	25	25
Construction time (years)	5	2,5	1
Space requirement (1000 m2/MWe)	0,08	0,2	0,7
Plant Dynamic Capabilities			
Primary regulation (% per 30 seconds)	2	NA	NA
Secondary regulation (% per minute)	4	4	10
Minimum load (% of full load)	45	20	20
Warm start-up time (hours)	2	2	0,25
Cold start-up time (hours)	12	8	0,5
Environment			
SO_2 (degree of desulphuring, %)	98	98	98
NO_X (g per GJ fuel)	24	72	63
CH4 (g per GJ fuel)	2	2	11
N2O (g per GJ fuel)	8	1	1
Particles (g per GJ fuel)	0,3	0,3	0,3
Financial data			
Nominal investment (M€/MWe)	3,4	3,6	6,5
- of which equipment	2,2	2,4	4
- of which installation	1,2	1,2	2,5
Fixed O&M (€/MWe/year)	97600	153600	288900
Variable O&M (€/MWh_e)	3,8	3,8	7,8
Technology specific data			
Steam reheat	None	None	None
Flue gas condensation	Yes	Yes	Yes
Combustion air humidification	Yes	Yes	Yes
Nominal investment (M€/MW fuel input)	1	1,05	0,93
- of which equipment	0,65	0,71	0,58
- of which installation	0,35	0,35	0,35
Fixed O&M (€/MW input/year)	28800	44369	41200
Variable O&M (€/MWh input)	1,1	1,1	1,1
Fuel storage specific cost in excess of 2 days	0,01	0,015	0,02

Figure 8. Data on biomass CHP plants for three different sizes (from the Subtask C database).

Another important outcome from Subtask C was the best-practice examples on energy systems architecture. The library of energy system architecture templates comprises more than 50 examples for different use cases depicting energy system designs for different climate zones or fuels, for densely populated communities and small, remote communities, for communities with or without critical buildings.

Figure 9 shows an example of an energy systems architecture corresponding to the power, heating, and cooling network in the Greater Copenhagen area.

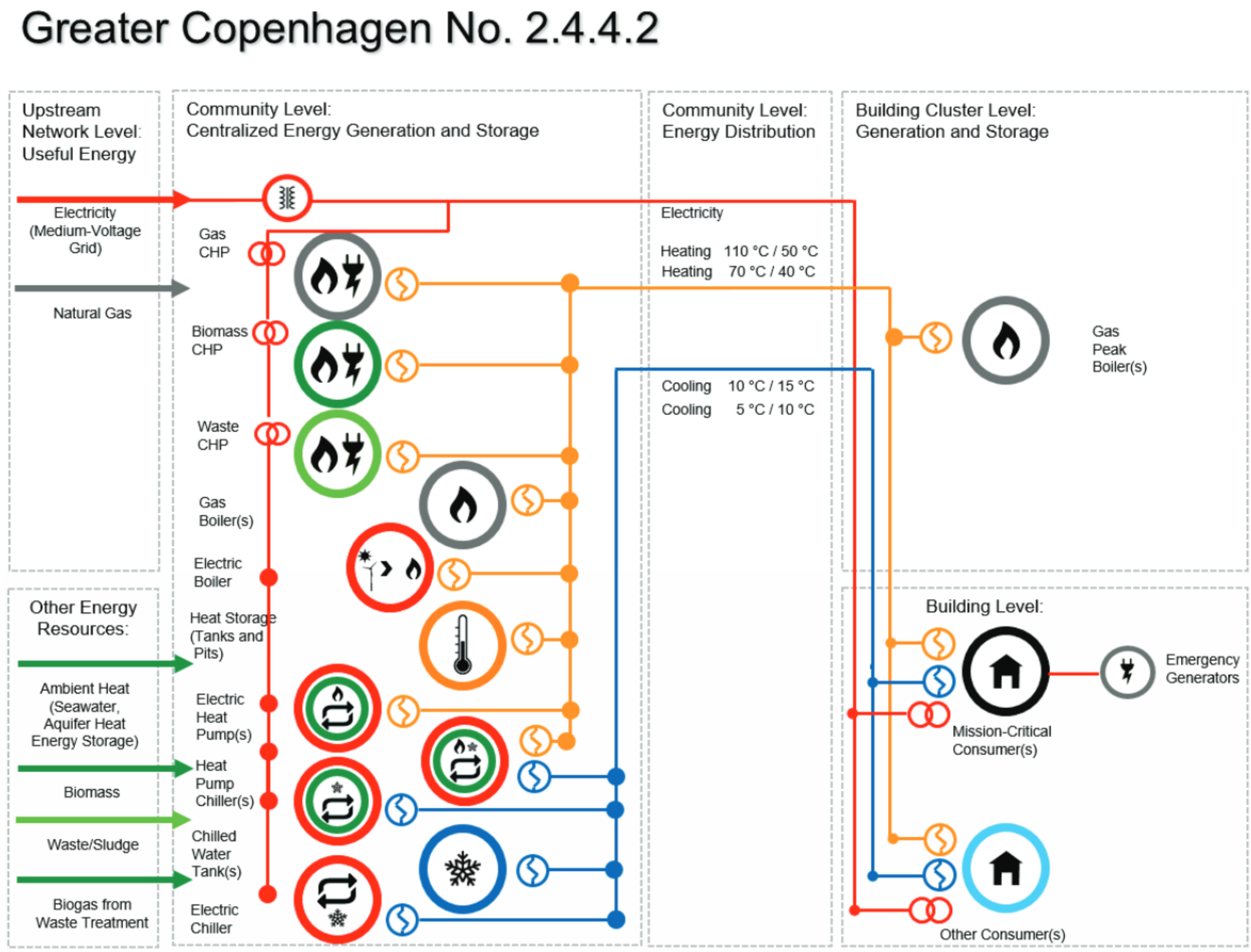


Figure 9. Energy systems architecture for the Greater Copenhagen area (taken from the guidebook).

The two boxes on the left show energy inputs from outside the boundaries of the community. The upper left box shows different types of grids that supply the community (e. g. electricity, gas, district heating, district cooling) the lower box is used to illustrate input of energy resources that are not grid-bound (e.g., fuel oil, diesel, biomass, solar radiation, wind, ambient heat, etc.).

The four remaining boxes contain system components within the community:

- **Centralized Energy Generation and Storage at Community Level**. In this box, different generation equipment like boilers, combined heat and power generation (CHP), electric chillers and tanks for storing hot or chilled water are represented by symbols. Coloured circles are used to illustrate fuel input into the equipment (grey = gas, red = electricity, green = biomass). Colours also indicate energy output of each element (red = electricity, yellow = heat, blue = cool).
- **Energy Distribution at Community Level**. This box shows the grids that exist within the community to supply the buildings. Grid types include electricity, steam, heating (hot water supply) or cooling. Supply and return temperatures can be specified. Gas grids – which may exist within the community to supply buildings – are not represented to keep the schematic simple.
- **Building Cluster Level**. Many – especially larger - energy systems have distributed the generation equipment to several locations, serving building clusters.
- **Building Level**. In the energy system schematic, buildings are included, but with a lower level of detail, showing the network connections and – in case of decentralized supply options – components like decentral boilers, chillers, or emergency generators. Details of the equipment with the buildings (e.g.,

HVAC details) are not illustrated. Mission-critical buildings are represented by a black symbol (higher resilience to “black sky” conditions required), other consumers are represented by a blue symbol (building functions need only be maintained in “blue sky” conditions). All critical buildings are fitted with a dedicated building-level backup generator to serve critical loads when utility power is unavailable.

The Subtask C deliverables are available as an Excel spreadsheet database and as input to the Net Zero Energy Master Planning Guide (see publications).

5.4 Subtask D: Develop Guidance for Net Zero Energy Master Planning

Subtask D was responsible for developing guidance for Net Zero Energy Master Planning, i.e., the main outcome from the IEA EBC Annex 75 project, and it has collected and synthesised all the relevant information from the other Subtasks and established the concept and methodology for the Energy Master Planning process as part of community planning. The overall concept of the EMP process is briefly described in the following (based on the Energy Master Planning Guide).

The Energy Master Planning process can be divided into twelve separate steps:

1. Establishing boundaries of the analysis
2. Establishing framing goals and constraints
3. Establishing Baseline
4. Establishing the Base Case
5. Establishing energy system alternatives
6. Mission criticality assessment
7. Threat assessment
8. Mission-critical loads and energy resiliency matrix
9. Resiliency analysis and gap evaluation
10. Comparing alternatives
11. Multicriteria decision analysis
12. Developing implementation strategy

Re 1. During the initial step of the EMP, the project team meets with the stakeholders to develop the vision, goals, constraints, requirements and expected outputs, and the development timeline. Energy and environmental performance and security goals shall be based on the national, regional, and community energy and sustainability policies, and shall meet resilience requirements that support the energy systems’ ability to provide mission-critical functions. This step is critical since it provides a framework for the rest of EMP development.

Re 2. It is important to clearly define long- and short-term energy goals at the beginning of a study, as well as important constraints and community priorities. Long-term energy goals can be expressed as the reduction by a desired percentage of site or source energy use against a Baseline in a given year, or the achievement of a Net Zero site/source energy community within a given timeframe. These goals lead to decision metrics that will be used to decide between alternative solutions, described later. They help to focus the study and define “success.” It is entirely possible that the goals will turn out not to be feasible, in which case the goals can be adjusted once quantitative data are available.

Re 3. The Baseline is defined as the current energy consumption profile. It is essential that the Baseline capture the quantity and type of energy used (transformed) by the community/installation such as grid electricity, natural gas and energy generated from renewable sources (e.g., solar and wind etc.). It is also important to understand how the energy is used, whether for heating, cooling, plug loads, or industrial processes.

Re 4. The Base Case is defined as a future “business as usual” alternative that includes all existing and already planned facilities. Facilities marked for demolition in the Baseline are not included. The Baseline models of buildings and energy systems shall be adjusted to reflect all planned modifications. The Base Case shall include the data on site and primary energy use and energy cost with categories similar to ones used for the Baseline. It is important to present the data showing the cost of implementation of the Base Case as well as changes in site, and source energy use, energy cost, and GHG compared to the Baseline.

Re 5. Once the Baseline and Base Case have been established, energy planners can start exploring options or alternatives. A handful of alternatives shall be selected that will be analysed in depth. Electric and thermal energy systems consist of four major elements: energy generation, energy distribution, energy storage, and energy demand. The goal is to find the optimum balance of these elements for the entire energy system, where each element is considered in the calculation of the amount of energy delivered and lost, in various forms, by the energy systems as well as its impact on energy system resilience.

Re 6. Mission-critical facilities are defined as facilities that are vital to the continuation of operations of the organization or agency. In addition to core critical facilities and operations, there are critical facilities that, if not maintained, impact the safety of the public and its property during and after a disaster.

Re 7. Threats may come in the form of natural disasters, accidents, and manmade threats. Threats that the community has chosen to incorporate within the EMP are called Design Basis Threats. Energy systems resilience will be analysed against this limited number of Design Basis Threats. It is important to include the threats that occur with low frequency but pose a potentially high consequence. Design Basis Threats should be evaluated individually but may also be evaluated in combinations depending on anticipated impacts to the given area.

Re 8. For a community/campus/military installation to be resilient, it must serve the energy demands that will be present during the disruption scenarios. The planner must understand the dynamic demand of each asset or building in the disruption scenarios and scale up to demand for each critical function to plan, develop, and evaluate resilient designs. This contrasts with standard Energy Master Planning process that uses historic data or models to calculate energy demands for a blue-sky day. The characteristics of the critical energy load can vary significantly between functions. For example, a communications function may require a large but steady supply of power to meet its equipment and conditioning needs. A shelter, on the other hand, may have little to no critical power demand, but have a large but variable heating demand to protect occupants from environmental conditions.

Re 9. In the resiliency analysis, the first step is to evaluate the baseline. Comparing the values for both energy availability and maximum outage duration allows the planner to see where gaps exist between the Baseline values and the requirements. Gaps between required resilience levels to Design Basis Threats and Baseline resilience levels should be addressed by planners through investments in the system. Proposed changes are captured in conceptual designs that can then be compared to the Baseline and each other. The Base Case design is the first conceptual design developed to improve resilience and includes the most basic and common ways of improving the system.

The alternative conceptual designs discussed in 5 are the primary integration point for traditional EMP. These designs should integrate blue sky goals with resilience goals such that performance is co-optimized for the planner. These designs should explore additional technologies beyond the Base Case conceptual design and should also consider alternative system configurations.

Re 10. For each alternative, it is important to present the data showing the cost of its implementation, operating costs, life-cycle costs, and changes in site and source energy use, energy cost, GHG and harmful emissions, system resilience compared to the Baseline, Base Case, and energy requirements and constraints. This information will allow to find the optimum solution for the entire community energy system and for those servicing mission-critical facilities that will meet the established energy and resiliency goals at the lowest life-cycle cost.

Re 11. Quantitative data from the Baseline, Base Case, and alternative designs analysis is used to compare them against framing goals formulated at the beginning of the Energy Master Planning process and to determine how close the planners were able to come to achieving their goals. The level of achieving different goals will vary for different alternatives. A Multicriteria Decision Analysis (MCDA) tool can be used to create weighted decision models and support traceable decision processes that integrate quantitative and qualitative factors. It is usually the case that the decision criteria are not equally important to each other.

Re 12. As part of the implementation strategy, long-term goals are transitioned into medium-term goals (milestones) and short-term projects, which must have tangible results. It is important to recognize that many decision makers have limited-term assignments or duties and will more likely commit to projects that can be realized during their tenure. Furthermore, short-term projects satisfy the short-term (1–5 years) planning process. It is important to get commitment from both decision makers and funding agencies since they play key roles in achieving the long-term goal. The main restriction is that 100% of the short-term projects fit on the roadmap towards the long-term goals.

Through input to Subtask A (nation-specific input to Energy Master Planning) and Subtask B (case studies) and in particular through the development of an extensive database and a large number of best-practice examples on energy system architecture, the Danish team has delivered a substantial amount of relevant data and knowledge into the guide for Net Zero Energy Master Planning.

5.5 Subtask E: Develop a functional modelling tool to facilitate the Net Zero Energy Resilient Communities Master Planning Process

Subtask E has developed a modelling tool for determining the resilience in the Net Zero Energy Resilient Communities Master Planning Process called E^{2}RIN. The purpose of the tool itself is to simulate the energy flows through a district energy system composed of an interacting network of components. The main contributions of this tool are as follows:

- The tool accounts for both reliability (failure and repair) as well as resilience to various scenarios (design basis threats)
- while also accounting for topology and interaction between an open-ended number of energy networks
- while providing key energy usage, resilience, and reliability metrics for the modeler/planner.

The resilience calculation tool is available as open-source software written in C++ (Nutaro 2011) and can be used through either a minimal user interface written in Microsoft Excel or through a text editor (see publications). The tool is meant for implementation/cooperation with other tools and handles only the resiliency factors. The tool draws information from the database developed in Subtask C, i.e., with a structure as shown in figure 10.

Figure 10. Structure of database used in E^{2}RIN.

A short users guide is available in the Guidebook's appendix H (see publication list).

The Danish team did not participate directly in this subtask, since the development of the E^{2}RIN-tool was undertaken by the company "Big Ladder Software". However, the Danish team has delivered input indirectly towards the development of the program through other Subtasks, particularly Subtasks A, B and C.

5.6 Subtask F: Business, legal and financial aspects of Net Zero Energy Master Planning

Subtask F has addressed three major challenges for the practical implementation of low or net zero energy districts: legal requirements, business models and funding sources.

Legal requirements

Planning of an NZE community usually must account for the legal aspects being defined by national energy requirements and the spatial or urban planning requirements. Currently, national energy requirements focus primarily on the building level. Spatial planning in urban regions does not usually consider specific energy requirements, nor is it likely to raise barriers for the development of NZE communities. The definition and execution of “resilience” concepts are, if they exist at all, not yet well defined, neither for buildings nor for communities. To address these barriers, Subtask F has collected information on relevant legal requirements through Subtasks A and B.

Business models

Business Models are tools for the implementation of EMPs into reality such as energy supply, energy savings performance contracting, leasing etc. The Guide describes scopes and typical use cases of different business models and discusses pros and cons. In general, many public agencies and communities do usually provide insufficient funding and staff capacities to carry out complex EMPs over time. The use of well-introduced business models may support especially the public sector to implement EMPs in a given budget and with guaranteed targets lined out in the Master Plan.

Funding sources

In addition to the limited understating of technical aspects of NZE communities, shortage of funding is the major obstacle for the implementation of this concept. In the public and military sectors, scarce appropriate funding and limited access to bank loans must be considered as the major financial impediment. In the private sector, e.g., in business parks and housing areas, the lack of experience and performance data combined with the difficulty in estimating technical and financial risks prevent private investors from spending money in NZE projects.

The Danish team did not participate directly in Subtask F, however, the Danish team has delivered input indirectly through Subtasks A, B and C.

5.7 Conference papers

Several conference papers were prepared, submitted, and presented during the project. The following list includes only the Danish contributions.

AEE Intec arranged the ISEC 2018 (International Sustainability Energy Conference) in Graz 3-5 October 2018. ISEC 2018 focused on the role of the heat sector and on resource efficiency in an interconnected sustainable energy system. The conference pointed out the resulting enormous opportunities for technology and innovation-oriented research institutions and enterprises, and offered a platform for exchange between research, enterprises, and energy policy. Rambøll contributed with 4 papers to the conference:

Ulbjerg, F., Thomsen, P.D. and Dyrelund, A. 2018. *How heat and cooling storages benefit from economy of scale*. ISEC 2018, International Sustainability Energy Conference, 3-5 October 2018, Graz, Austria.

Abstract: Almost all energy sources, which can replace fossil fuels, are of low quality or not always available when needed. We have excess heat in summer and too much free cooling during the winter. Likewise, we have surplus of 10 electricity in some hours, days and weeks and deficits in others. In the future there will be increasing demand for energy storage on a system basis - in particular thermal storages for storing heat and cooling directly, stimulating district heating (DH) and district cooling (DC) while shaving uncontrolled peaks in the power systems. Thus, smart integration of storage in the thermal systems can replace and eliminate the need for expensive electric batteries. The bigger, the better is often used as a guiding term describing different topics, where size or scale matters. In the case with thermal storage technology, this is absolutely true.

The two main drivers for investing in thermal storages are:

1. The marginal capacity investment goes down when size goes up.
2. The energy losses in pct. of the volume from a thermal storage decrease, as size is increased. All energy losses from the thermal storage can be attributed to the construction surfaces. When lengths increase, surface increase by second order, whereas the storage volume increase by third order.

Investments in large cost-effective thermal storages will stimulate development of DH and secure that all available surplus heat is collected. That will in turn stimulate development of DC showing the way for an efficient and cost-effective transformation to a low carbon society.

Rønn, T. and Dyrelund, A. 2018. *Energy Planning at National and Community Level is the Key to Integrate Cost Effective Renewable Energy*. ISEC 2018, International Sustainability Energy Conference, 3-5 October 2018, Graz, Austria.

Abstract: Unlike the fossil fuels, renewable energy is of low quality and fluctuating. Almost no efficient and renewable energy source can be used at the building level in a cost effective and environ friendly way to meet the demand. However, at campus, city and national level, there is an opportunity to identify and utilize a wide range of sources benefitting of economy of scale. Careful energy planning is the key to harvest these sources considering the campus, the local community, or the state as one profit centre optimizing the energy system including the power, gas, district heating and district cooling system. The integrating energy system opens for an opportunity for storing and utilizing energy, which else would be wasted and it improves the local environment, not least the air quality. We will show three cases on how the energy planning of district heating and cooling (DH&C) which is obvious for any campus owner also is of interest for local communities and governments.

Dyrelund, A. and Hansen, T. 2018. *Large-Scale Heat Pumps – The Key Technology in Efficient Urban Heating and Cooling*. ISEC 2018, International Sustainability Energy Conference, 3-5 October 2018, Graz, Austria.

Abstract: Large-scale heat pumps in the district heating (DH) and district cooling (DC) systems are becoming a key-technology in the energy system, as they integrate three of the four energy carriers. Moreover, due to economy of scale they will normally be connected to heat and cold storages and back-up capacity, which allows it to react on the fluctuating electricity prices. They can use large amounts of electricity for heating in a smart way without overloading the power system.

Thomsen, S. M. and Dyrelund, A. 2018. *Integration of Renewable Energy into the Energy System – The Virtual Battery*. ISEC 2018, International Sustainability Energy Conference, 3-5 October 2018, Graz, Austria.

Abstract: Two global mega trends are in focus in this article; the awareness of climate change (sustainability) and urbanization. Thus, the challenge arises of how to mitigate climate change, while at the same time establish cost-effective energy systems in the large cities. Our solution is to use existing technologies and create an energy system of electricity, district heating, district cooling, natural gas and building HVAC systems that better integrates low quality variable renewable energy sources, benefitting from the economy of scale in urban areas. Our solution is not an electric battery, but with the same response to the power system. Thus, we call it a virtual battery. This is not an alternative to electric batteries, which are vital for the transport sector (cars, trucks, ferries), but it is more cost effective than batteries once the end-use demand is heating or cooling. The major components are heat pumps, electric boilers, CHP plants and thermal storages. We provide two examples on how such systems operate today and how they can be further developed in small villages and large cities.

Smart Energy Systems Conference (4th Generation District Heating, Electrification, Electrofuels and Energy Efficiency), Copenhagen, Denmark, 10-11 September 2019.

Dyrelund, A. 2019. *Keynote: Smart integration of district heating, district cooling, waste water and ground source cooling*. Smart Energy Systems 2019, Copenhagen, Denmark, 10-11 September 2019.

No abstract available.

Thomsen, S. M. 2019. Smart integration of fluctuating renewable energy into the energy system. Smart Energy Systems 2019, Copenhagen, Denmark, 10-11 September 2019.

Ramboll has in several studies analysed the option to integrate renewable energy from wind, solar and waste heat into the energy system. That includes a study for the Danish District Heating Association, Smart integration of renewable energy in the district heating system, a study financed by EUDP on Harmonized integration of electricity, gas and heat in association with Aalborg University and an ongoing EUDP financed study on Sustainable Energy Market Integration, in association with Syddansk University, Aalborg University and DGC. The studies show how the energy system already today has the fully develop technology to transfer the heating and cooling sectors to renewable energy based on biomass, wind and solar and a minor part of natural gas. The only missing technology, P2G is still in the development stage. The key components in the energy system for this integration is the water-based system: namely hot water district heating at modest temperatures, district cooling, large heat pumps, electric boilers, gas CHP and thermal storages for heating and cooling. The presentation will include an overall analysis, a proposal for market incentives and case studies Søren Møller Thomsen is MSc. in Sustainable Energy with a special focus on electrical energy systems, system analysis, feasibility studies and energy markets. Søren has participated in a number of projects within sustainable development, smart energy systems and district heating and cooling.

ASHRAE Winter Conference, Orlando Florida, 1-5 February 2020

Sharp, T., Haase, M., Zhivov, A., Rismanchi, B., Lohse, R., Rose, J. and Nord, N. 2021. *Energy Master Planning: Identifying Framing Constraints that Scope Your Technology Options*. ASHRAE Winter Conference 2020, Orlando Florida, USA, 1-5 February 2020.

Abstract: This paper addresses the framing constraints for building and community energy projects that must be considered when energy master planning (EMP) is conducted. The constraints cover emissions, sustainability, resilience, regulations and directives, and regional and local limitations such as available energy types, local conditions, and project requirements. The paper reflects development results from participants in an International Energy Agency project on energy master planning and in a U.S. Department of Defense project on technology integration to achieve resilient, low-energy use military installations.

It identifies a comprehensive list of framing constraints categorized into locational threats, locational resources,energy and water distribution and storage systems, building and facility, indoor environmental, and equipment in buildings and district systems constraints. In addition, it identifies limits for these constraints that exist in seven participating countries. Some framing constraints can profoundly impact technology selection while others impact the installation of technologies (as in hardening) and have little to no impact on technology selection. Framing constraints can be assessed in different ways and there are resources available to help EMP stakeholders evaluate them. Finally, a case is made that identifying and applying framing constraints early in EMP can bring efficiencies and better focus to the EMP process.

Conclusions include 1) for holistic energy planning, it is essential to identify and assess the framing constraints that bound an optimized EMP solution, 2) framing constraints limits should be evaluated as either hard or soft or promising technologies may fall out of an EMP analysis, 3) to maintain consistent quality in the EMP process, the identification of framing constraints and their limits, and perhaps their evaluation, should be standardized, 4) a standardized approach could establish a baseline that can be used, built upon, and improved, 5) as automated EMP tools are improved or developed, the resources in this paper could possibly contribute to their interworkings relative to technology screening, and 6) continued climate change and resulting aggressive goal setting will likely drive a continued and strong emphasis on EMP.

ASHRAE Winter Conference, Virtual, 9-11 February 2021

Dyrelund, A., Neimeier, R.M., Margaryan, H. and Møller, A.B. 2021. *Energy Master Planning for Resilient Public Communities— Best Practices from Denmark*. ASHRAE Winter Conference 2021, Virtual, 9-11 February 2021.

Abstract: When the oil embargo of 1973 occurred, Denmark, which until that time was totally dependent on imported oil, initiated a long-term energy policy with the support of a solid majority in the Danish Parliament that encouraged and adopted resilient and cost-effective energy solutions for the country. The Electricity and Heat Supply Acts of 1980 started a program of nationwide energy planning that aimed to replace oil and to cost-effectively improve the country's energy resiliency and energy efficiency.

The planning methodology took a team approach that involved the national energy Ministry, regions, and local authorities and utilities, and that established a playing field for regulated competition between the energy infrastructures of district heating and natural gas. In other words, Danish energy infrastructure was redeveloped as if Denmark were a campus.

As a natural result of this "campus approach," 100% of all investments in the infrastructure have been financed with the most competitive financing on the world market. Also, the power system, which is owned by state and consumer cooperatives, has been transitioning from centralized to local power generation; the use of underground electrical transmission and distribution cables has created one of the world's most reliable power sectors. Thus, emergency generators are only used for critical facilities. This process has helped create an environment that fosters innovation in state-of-the-art technologies and architectural design, which contribute to the International Energy Agency's "Energy in Buildings and Communities Program Annex 73," which focuses on developing guidelines and tools that support the planning of net zero energy resilient public communities and research performed under the Environmental Security Technology Certification Program (ESTCP) project EW18-D1-5281, "Technologies Integration to Achieve Resilient, Low-Energy Military Installations."

Four case studies illustrate this transition taking the first steps toward net zero resilient energy:

- Case Study 1: The Greater Copenhagen district heating system, which supplies heat, 95% of which is generated from sustainable biomass-fired combined heat and power (CHP) plants and from waste for energy plants to an area of 754 million ft 2 (70 million m^2) heated floor area. Ninety-nine percent of the heated floor area in Copenhagen is connected to the network.
- Case Study 2: The municipality of Taarnby, which uses optimal zoning of district heating and natural gas and a notable project in which heat pumps, 1222 tons cooling/22.2 MMBtu/h heating (4.3 MW cooling/6.5 MW heat) are used to integrate district heating and cooling, chilled-water storage, wastewater, and ground-source cooling.
- Case Study 3: The Technical University Campus in greater Copenhagen, which has established an infrastructure for heating and cooling in symbiosis with 33 MW gas-fired combined cycle (CC) CHP, 136.49 MMBtu/h (40 MW) electric boiler, and combined heating and cooling.
- Case Study 4: A typical district heating system or a campus supplied by a gas-fuelled CHP plant, an electric boiler, a large heat pump, large-scale solar heating, and a heat storage facility that offers demand response to the power system for efficient integration of fluctuating wind and solar energy.

In this paper we will briefly describe the Danish legal framework for the heating sector and how it is administrated by local communities with the aim to meet the objectives in the most cost-effective way. The four case studies illustrate how the policy has been implemented to the benefit of the society and the consumers. The tradition of cooperation, consumer empowerment, and commitment from the cities has developed the district heating and cooling infrastructure in such a way that it is almost as if Denmark is one single campus.

Winfield, E.C., Rader, R.J., Zhivov, A.M., Adams, T.A., Dyrelund, A., Fredeen, C., Gudmundsson, O. and Goering, B. 2021. *Best Practices for HVAC, Plumbing, and Heat Supply in Arctic Climates*. ASHRAE Winter Conference 2021, Virtual, 9-11 February 2021.

Abstract: Arctic climates provide unique challenges for designers of heating, ventilating, and air-conditioning (HVAC), plumbing, and thermal energy systems. The importance of considering outdoor air temperatures, system reliability, and building resiliency cannot be understated. This paper describes best practice examples of robust and reliable systems with the emphasis on their redundancy, durability, and functionality. The paper also discusses the most common heating system and ventilation system approaches used in Arctic climate and emphasizes the importance of a maintenance program that allows building operators to successfully troubleshoot and maintain buildings in the Arctic. Concepts are illustrated by several best practice examples (e .g., U.S. military bases in Alaska and Søndre Strømfjord, the international airport of Greenland that previously was used as a U.S. military base).

The paper results from experts' discussions during the Thermal Energy Systems Resilience in Cold/Arctic Climates (ERDC 2020) consultation forum and research conducted under the International Energy Agency's Energy in Buildings and Communities (IEA EBC) Program Annex 73, the Environmental Security Technology Certification Program (ESTCP) Project "Technologies Integration to Achieve Resilient, Low-Energy Military Installations," and U.S. Army Program Project 633734T1500 under Military Engineering Technology Demonstration. The paper is complementary to the ASHRAE Cold-Climate Design Guide (ASHRAE 2015) with a focus on resilience of thermal energy systems.

Cold Climate HVAC and Energy 2021 (REHVA), Virtual, 20-21 April

Winfield, E.C., Rader, R.J., Zhivov, A.M., Dyrelund, A., Fredeen, C., Gudmundsson, O. and Goering, B. 2021. *HVAC Best Practices in Arctic Climates*. Cold Climate HVAC and Energy 2021, Virtual, 20-21 April 2021.

Abstract: Arctic climates provide unique challenges for designers of HVAC, plumbing, and thermal energy systems. The importance of considering the operation outside air temperatures, system reliability, and building resiliency cannot be understated. The paper describes best practice examples of robust and reliable systems with the emphasis on their redundancy, durability, and functionality. The paper also discusses the most common heating and ventilation system approaches used in arctic climate with the emphasis on the importance of a maintenance program that allows building operators to successfully troubleshoot and maintain buildings in the arctic. More detailed discussion of concepts presented in this paper can be found in the Guide [1] where these concepts are illustrated by best practice examples from U.S. military bases in Alaska and Søndre Strømfjord, the international airport of Greenland that previously was used as a U.S. military base. The paper results from experts' discussions during the Consultation Forum "Thermal Energy Systems Resilience in Cold/Arctic Climates" [2] and research conducted under the IEA EBC Annex 73, the Environmental Security Technology Certification Program (ESTCP) Project "Technologies Integration to Achieve Resilient, Low-Energy Military Installations" and U.S. Army Program project 633734T1500 under Military Engineering Technology Demonstration. The paper is complementary to the ASHRAE Cold Climate Design Guide [3] with a focus on resilience of thermal energy systems.

5.8 Reports

Several reports were finalized in the project, but most findings were compiled into one main report, corresponding to number 1 in the list below. Number 4 in the list is a database in an Excel spreadsheet.

1. Energy Master Planning for Net-Zero Energy Resilient Public Communities – Main report
2. Energy Master Planning for Net-Zero Energy Resilient Public Communities – Summary report
3. Energy Resilience of Interacting Networks (E^2RIN) Tool - User Guide
4. Annex 73 Technologies Database
5. Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates
6. Guide for Resilient Thermal Energy Systems Design in Hot and Humid Climates
7. Energy Master Planning for Resilient Public Communities – Case Studies

5.9 Trade journal articles

The Danish team has written an article for HVAC Magasinet, January 2022 – in Danish:

Dyrelund, A., Thomsen, S.M., Gudmundsson, O., Sandemand, J.P., Andersen, A. Rose, J. and Thomsen, K.E. 2022. *Energirenovering på Distriktsniveau Giver Bedre Muligheder for Optimering og Udnyttelse af Ressourcer*, HVAC-Magasinet, January 2022.

https://ipaper.ipapercms.dk/TechMedia/HVACMagasinet/2022/1/?page=30

All deliverables are available at the project website: https://annex73.iea-ebc.org/

5.10 Activities in the extension of the project (64018-05489)

The supplementary application concerned the participation of EMD International A/S in Annex 73.

EMD International is a software and consulting company that provides software and consulting services worldwide within design, planning and documentation of renewable energy projects with a focus on wind energy, cogeneration, trigeneration, biomass and biogas.

At the first international meeting in Annex 73 in April 2018 in Frankfurt, EMD gave a presentation on their energy system analysis tool energyPRO, which is used by advisors worldwide for simulation of campus facilities and large energy systems. During the debate after the presentation, it emerged that projects calculated in the Master Planning Computer Tool developed in Annex 73 should subsequently be recalculated in a more dedicated energy system analysis tool, for e.g., more precisely to calculate the value of participation in electricity markets and the establishment of energy storage (heating and cooling storage as well as electric batteries).

EMD International A/S has primarily been involved in Subtask B, where they have contributed to several of the Danish case studies, e.g., Air Base Skrydstrup and Nymindegab Military Camp, with energy system analysis, Subtask C, where they have contributed to the best-practice examples on energy systems architecture and Subtask E, where they have contributed with reference cases from energyPRO that were used for validation of the E^2RIN tool developed in Annex 73.

6. Utilisation of project results

The project involves participation in the IEA project, so there is no apparent technology added value for users. The project has generated some of the necessary knowledge to help Denmark to meet stringent national energy policy objectives on energy planning on a district level. Thereby, Denmark can help meet individual and joint international demands for extensive reductions in CO_2 emissions.

The purpose of the project was to secure Danish participation in an IEA project and did not have the purpose to develop commercial products as such. However, the E^2RIN tool (planning resilience in districts) developed during the project is available and can be combined with other tools and possibly commercialized at a later stage and the technology database is also available for possible implementation in other tools.

The Danish participation did not involve PhD-students.

7. Project conclusion and perspective

The main purpose of the IEA EBC Annex 73 was to develop guidelines and tools that support the planning of Net Zero Energy Public Communities. The knowledge gained through the project will help shift the focus from individual buildings towards groups or clusters of buildings, districts, or cities, which will create synergies with the existing energy system infrastructure and enhance the possibilities for a low carbon transition.

All primary project objectives have been fulfilled, e.g., assessing existing case studies with regard to technical solutions, costs and performance data, developing a database of energy utilization indexes (EUI) of relevant building types and communities, developing energy targets, summarizing, developing and cataloguing representative building models by building use type, summarizing, developing and cataloguing representative energy supply and energy efficiency scenarios, developing guidance for Net Zero Energy Master Planning (NZEMP), developing a functional modelling tool to facilitate the Net Zero Energy Master Planning Process, which can enhance currently used building modelling tools to also address resiliency, collecting and describing relevant business and financial aspects and legal requirements and constraints and finally providing dissemination and training in participating countries.

Several reports and conference papers have been produced. Eleven Danish case studies have been produced, describing best-practice examples of energy master planning from Denmark. Furthermore, the Danish team has led the work of establishing and compiling a very comprehensive technology database that includes all the relevant technologies needed for energy system simulation, including best-practice examples on energy systems architecture. The library of energy system architecture templates comprises more than 50 examples for different use cases.

Annex 73 was organised as an international network project, expecting to encourage greater international cooperation concerning research and knowledge related to energy master planning for low or zero energy districts/communities. The project could help pave the way for a wider perspective on energy renovation where the synergies for clusters of buildings and a more holistic approach is clearly beneficial. At a national level this could result in increased energy savings, through the avoidance of suboptimization.

The three main results from the project are the guide for energy master planning, the E^2RIN tool for determining energy resilience and the technologies database. The guide can be used for planning low or zero energy/emission districts/communities and the tool and database can be combined with other tools for detailed analysis for the design process, determining the KPIs for baseline, base case, and energy system alternatives. This way, the results of the project can help reduce gross energy consumption in the existing Danish building mass, so that overall energy policy goals can be obtained.

8. Appendices

List of IEA EBC Annex 73 participants (main contributors)

Country	Organisation
Australia	University of Melbourne Ministry of Defense
Austria	AEE - Institut für Nachhaltige Technologien B.I.G. – Bundesimmobiliengesellschaft (LOI)
Denmark	Aalborg University Ramboll Ministry of Defense Ministry of Foreign Affairs Danfoss EMD International
Finland	VTT Technical Research Centre of Finland
Germany	KEA Klimaschutz- und Energieagentur Baden-Württemberg GEF Engineering IREES - Institute for Resource Efficiency and Energy Strategies University of Applied Sciences Stuttgart
Norway	Norwegian University of Science and Technology SINTEF
UK	Ministry of Defense
USA	U.S. Army Engineer Research and Development Center Construction Engineering Research Laboratory U.S. Army Corps of Engineers, Protective Design – Mandatory Center of Expertise U.S. Army Corps of Engineers, Power Reliability Enhancement Program Fort Leonard Wood Sandia National Laboratories National Renewable Energy Laboratory SC-B Consulting Big Ladder Software The Holmes Engineering Group International District Anergy Association William B. Rose & Associates Oak Ridge National Laboratory AECOM ESG Energy Systems Group NAESCO - National Association of Energy Service Companies CDC- National Institute for Occupational Safety and Health