ZEN

Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

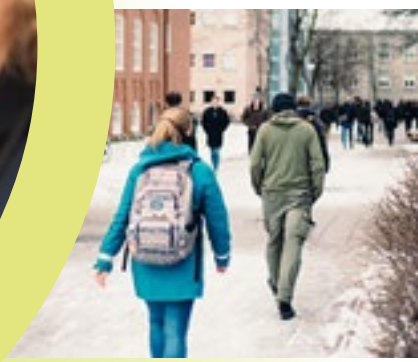
FINAL REPORT












ANNE-LISE AAKERVIK, ANN KRISTIN KVELLHEIM,
ARILD GUSTAVSEN

"We will enable the transition to a low carbon society by developing sustainable neighbourhoods with zero greenhouse gas emissions"

Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

ZEN REPORT No. 74
Editorial board: Anne-Lise Aakervik (NTNU), Ann Kristin Kvellheim (SINTEF/NTNU), Arild Gustavsen (NTNU)

Final Report
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CONTENTS

1. BUILDINGS AND NEIGHBOURHOODS ARE KEY TO A SUCCESSFUL SUSTAINABLE TRANSITION

Ann Kristin Kvellheim
Director ZEN Research Centre

The Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Research Centre) has developed key elements necessary to reach climate targets and improve energy security.

Together with 28 user partners, NTNU and SINTEF have developed solutions that are vital for the necessary energy- and climate transition ahead. Building upon the previous Zero Emission Buildings Research Centre, the system boundary was expanded to include more buildings and hence also infrastructure and spatial planning (mobility and area qualities) and research has spanned from the elements in a building and up to the energy system in large. The ZEN Research Centre is interdisciplinary due to the wide span in research areas, which has been challenging, but also received praise (e.g. the Mid-term evaluation) and brought research very close to the societal challenges research is set to solve. I am proud of what we have achieved over the project period. We have had national as well as international impact, being recognised and referred to in as well academic as in practical contexts.

This is the final report from the ZEN Research Centre, highlighting key lessons learned. It also gives the reader an overview of activities and results, hopefully as an inspiration for further action. It is necessary to continue the efforts to solve some of our times most complex challenges: the climate crises and the issue of energy security.

After ZEN, there is a lack of a "driving force" (i.e. a research centre with long-term funding) in research on buildings, neighbourhoods, and cities that can align societal goals with the need for comfortable, health-promoting, sustainable, and inclusive buildings and neighbourhoods. The potential is far from being fully utilized, and there is still a significant need for research to develop new solutions, as well as to further develop and implement the solutions we already have. A national project of considerable size is needed to have the power to build national teams and change the industry, and my hope is that a new research centre can be funded in 1–2 years to continue the work of the ZEN Research Centre.

Enjoy reading!

> It is necessary to continue the efforts to solve some of our times most complex challenges

PIONEERING ZERO EMISSION SOLUTIONS

Sara Brinch
Dean at Faculty of Architecture and Design, NTNU

The ZEN Research Centre has been a great success in terms of creating solutions for zero emission buildings and neighborhoods. The transition to a greener, and more energy efficient society is of critical importance, and what has been researched, tested out and run as pilot projects during the ZEN Research Centre's lifetime, will be pivotal in inspiring and guiding the future developments of zero emission solutions for a built environment.

The ZEN Research Centre's joining of researchers from NTNU and from SINTEF with expertise in energy efficiency, energy systems, architecture and planning, pairing them with stake-holders in Norwegian municipalities, public administration and industry, have produced not only new knowledge and insight on how to conduct collaborative and transdisciplinary projects, but also in outstanding activities in test areas across most of Norway. It has been a truly joint adventure, innovating not only technical solutions, but also the ways inhabitants living in houses and neighborhoods are interacting with and engaging in initiatives designed to save energy, optimize the energy flow, or to lower carbon footprints.

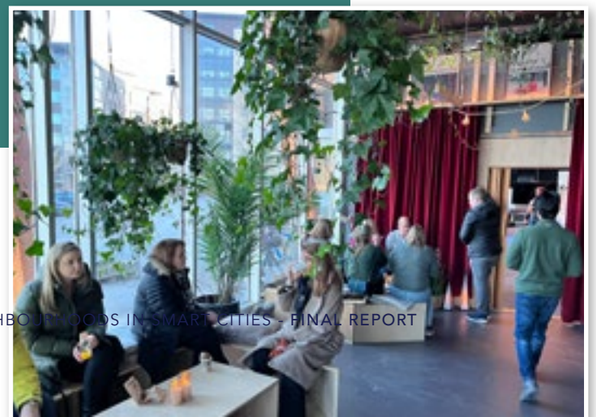
The results of the ZEN Research Centre have been made possible by the efforts by all the great people involved, and I am truly grateful for everyone's contribution to this success. The center was built on a strong professional environment, which over the years has only grown in strength. Senior researchers led the way, and by collaborations and the additional contributions made by post doctors, PhDs and master students, the ZEN Research Centre has become a vibrant arena for addressing the zero-emission society. The agenda for future initiatives will be set by researchers and societal stakeholders in collaboration, and I am convinced that the legacy from the centre will be recognizable in numerous projects and policy briefs to come.

> The transition to a greener and more energy efficient society is of critical importance

2. SUMMARY

1) THE CENTRE'S CONTRIBUTION TO THE FME SCHEME'S PRINCIPAL GOALS

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities was established on the foundation of the former Research Centre on Zero Emission Buildings (ZEB). The research and activities at the centre have significantly contributed to the FME scheme's goals of value creation and innovation by developing zero-emission solutions for buildings and neighbourhoods. The centre's interdisciplinary approach and collaboration have addressed key challenges in the energy and construction sectors. The work has focused both on longer term research and on applied research and innovation promoting sustainable practices and technologies to reduce greenhouse gas emissions and improve energy efficiency. The ZEN Research Centre has developed and demonstrated novel solutions and knowledge for improved energy security and reduced greenhouse gas emissions by utilizing the potential in the built environment. Research results show that the total energy delivered to buildings can be reduced by 13 TWh (15%) between 2020 and 2030, and by 40 TWh (48%) between 2020 and 2050, through ambitious energy efficiency measures and local renewable energy initiatives. The centre has also provided advice to politicians and other decision-makers through meetings, participation in Arendalsuka, at European conferences, through various policy documents, etc.



2) RESEARCH RESULTS

Research and development have taken place within six thematic areas: WP1 Analytical Framework for Design and Planning of ZEN, WP2 Policy Measures, Innovation and Business Models, WP3 Responsive and Energy-Flexible Buildings, WP4 Energy Flexible Neighbourhoods, WP5 Local Energy Optimization within a Larger System, and WP6 Pilot Projects and Living Labs. The centre has produced more than 275 high-quality scientific publications, contributing to the global knowledge base on sustainable building and urban development.

Both our research and the ZEB Laboratory have received praise and awards. Awards include the "Crown Prince Haakon's Research Award" for indoor ventilation and air quality, the Discovery Innovation Scholarship for carbon footprint calculations, and NTNU's award for research and art. The ZEB Laboratory is a national research infrastructure that can be utilized for decades to come.

The centre has developed an analytical framework for zero-emission neighbourhoods. As part of the ZEN framework, a set of key performance indicators (KPIs) has been developed and tested throughout the project period.

3) INDUSTRIAL AND/OR ADMINISTRATIVE RESULTS AND UTILITY

The ZEN Research Centre has facilitated the development and implementation of innovative solutions through pilot projects and living labs. These initiatives have provided valuable data and insights, contributing to the fine-tuning and scaling of sustainable solutions. The centre's work has also influenced regulatory frameworks and instruments, promoting the adoption of zero-emission technologies and practices in the energy and construction industries, both nationally and internationally. Through collaboration with user partners and involvement in the development of guidelines, sustainability frameworks, and standards, the ZEN Research Centre has ensured a widespread dissemination of its research and knowledge.

4) RESEARCH EDUCATION AND MASTER'S EDUCATION

Research results from the centre have been incorporated into NTNU's educational programs, especially the MSc program in Sustainable Architecture. This integration has kept the program up-to-date and popular, even in the face of the introduction of tuition fees. The centre has also contributed to the training of researchers, particularly PhD candidates.

5) INTERNATIONAL COOPERATION

The ZEN Research Centre has established itself as a leader in sustainable building and urban development beyond Norway's borders. The centre's international collaboration and contributions to European sustainability projects, have strengthened NTNU's and SINTEF's reputation and research impact. Key international projects include the EU-funded projects syn.ikia on sustainable plus-energy neighborhoods, and the EU Green Deal ARV project on climate-positive circular communities and the +CityxChange project on positive energy districts.

6) ADDED VALUE OF BEING A CENTRE

The ZEN Research Centre has promoted interdisciplinary collaboration across various fields, including architecture, engineering, and social sciences, while connecting researchers with industry and public authorities, making knowledge transfer and mutual learning easier. By building world-leading national expertise, the centre has addressed complex sustainability challenges, particularly in the construction and energy sectors. The centre's breadth and interdisciplinary approach have been praised for their ability to contribute to solving complex problems. Over time, the centre has positioned the partners as leaders in sustainable building and neighborhood research. For NTNU and SINTEF, it has influenced research strategies, and enabled collaboration with leading actors in the field. Through pilot projects and living labs, the centre has tested research and innovation in practice, ensuring the long-term relevance and applicability of the research findings.

SAMMENDRAG

1) SENTERETS BIDRAG TIL FME-ORDNINGENS OVERORDNEDE MÅL

Forskningssenteret for nullutslippsområder (ZEN) ble etablert med utgangspunkt i det tidligere Forskningssenteret for nullutslippsbygg (ZEB). Forskningen og aktivitetene i senteret har bidratt betydelig til FME-ordningens mål om verdiskaping og innovasjon gjennom å utvikle nullutslippsløsninger for bygninger og områder. Senterets tverrfaglige tilnærming og samarbeid har adressert sentrale utfordringer innen energi- og byggsektoren. Arbeidet har fokusert på langsiktig så vel som anvendt forskning og innovasjon, fremmet en mer bærekraftig praksis, forbedret energieffektiviteten, og utviklet teknologier som reduserer klimagassutslipp. ZEN-senterets forskning har resultert i løsninger og kunnskap for bedret energisikkerhet og reduserte klimagassutslipp ved å utnytte potensialet i bygninger og områder. Forskningsresultater viser at den totale energien levert til bygninger kan reduseres med 13 TWh (15%) mellom 2020 og 2030, og med 40 TWh (48%) mellom 2020 og 2050, ved ambisiøse energieffektiviseringstiltak og lokale fornybare energitiltak. Senteret har også levert råd til politikere og andre beslutningstakere blant annet gjennom møter, deltakelse på Arendalsuka, på konferanser i EU, samt gjennom ulike policy-dokumenter.

2) FORSKNINGSRESULTATER

Forskning og utvikling har funnet sted innen seks tematiske områder: WP1 Analytisk rammeverk for design og planlegging av ZEN, WP2 Politiske tiltak, innovasjon og forretningsmodeller, WP3 Fleksible- og energieffektive bygninger, WP4 Energifleksible områder, WP5 Lokal energioptimalisering innenfor et større system og WP6 Pilotprosjekter og levende laboratorier. Senteret har publisert mer enn 275 vitenskapelige publikasjoner av høy kvalitet, som bidrar til den globale kunnskapsbasen om bærekraftig bygging og byutvikling.

Både forskningen vår og ZEB-laboratoriet har mottatt ros og priser. Priser inkluderer "Kronprins Haakons forskningspris" for innendørs ventilasjon og luftkvalitet, Discovery Innovation Scholarship for karbonfotavtrykksberegninger, og NTNUs pris for forskning og kunst. ZEB-laboratoriet er en nasjonal forskningsinfrastruktur som kan utnyttes i flere tiår fremover.

I senteret er det utviklet et analytisk rammeverk for nullutslippsområder. Som en del av ZEN-rammeverket er et sett med nøkkelindikatorer (KPIer) utviklet og testet gjennom prosjektperioden.

3) INDUSTRIELLE OG/ELLER ADMINISTRATIVE RESULTATER OG NYTTE

Forskningssenteret ZEN har tilrettelagt for utvikling og implementering av innovative løsninger gjennom pilotprosjekter og levende laboratorier. Disse initiativene har gitt verdifulle data og innsikt som bidrar til å finjustere og skalere bærekraftige løsninger. Senterets arbeid har også påvirket regulatoriske rammeverk og virkemidler, fremmet opptak av nullutslippsteknologier og praksiser i energi- og byggenæringen, både nasjonalt og internasjonalt. Gjennom samarbeid med brukerpartnere og ved å være involvert i utviklingen av retningslinjer, miljøsertifiseringer og standarder, har ZEN-forskningssenteret sikret en god spredning av sin forskning og kunnskap.

4) FORSKERUTDANNING OG MASTERUTDANNING

Forskningsresultater fra senteret er tatt inn i NTNUs utdanningsprogrammer, spesielt MSc-programmet i bærekraftig arkitektur. Integrasjonen har holdt dette programmet oppdatert og populært, selv i møte med innføring av studieavgifter. Senteret har også bidratt til opplæring av forskere, spesielt PhD-kandidater.

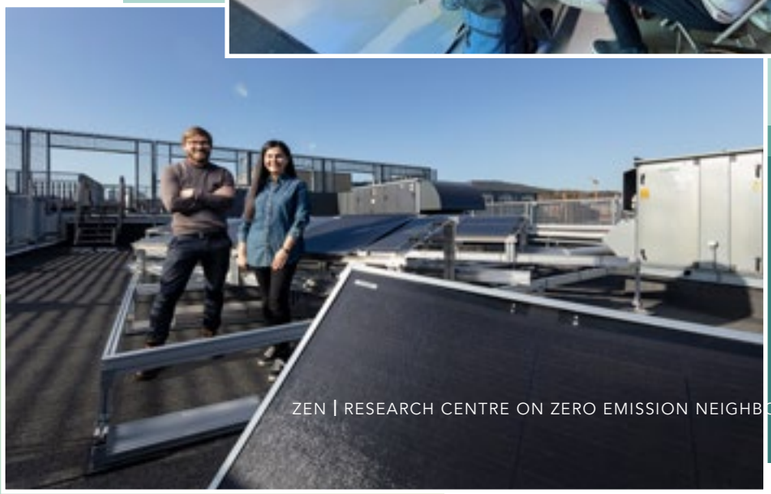
5) INTERNASJONALT SAMARBEID

Forskningssenteret ZEN har etablert seg som førende innen bærekraftig bygging og byutvikling også utenfor Norges grenser. Senterets internasjonale samarbeid og bidrag til europeiske bærekraftsprosjekter har styrket NTNUs og SINTEFs omdømme og forskningsinnvirkning. Viktige internasjonale prosjekter inkluderer de EU-finansierte prosjektene syn.ikia om bærekraftige plussenerginabolag og EU Green Deal ARV-prosjektet om klimapositive sirkulære samfunn samt +CityxChange om energipositive kvartal.

6) MERVERDI AV Å VÆRE ET SENTER

Forskningssenteret ZEN har fremmet tverrfaglig samarbeid på tvers av ulike felt, inkludert arkitektur, ingeniørfag og samfunnsvitenskap, samtidig som det kobler forskere med industri og offentlige myndigheter som gjør kunnskapsoverføring og gjensidig læring enklere. Ved å bygge verdensledende nasjonal ekspertise har senteret adressert komplekse bærekraftsutfordringer, spesielt innen bygg- og energisektorene. Senterets bredde og tverrfaglige tilnærming har mottatt ros for å bidra til å løse komplekse problemer.

Over tid har senteret posisjonert partnere i senteret som ledere innen bærekraftig bygg- og områdeforskning. For NTNU og SINTEF har senteret påvirket forskningsstrategier og gitt mulighet for samarbeid med de fremste aktørene på tematikken. Gjennom pilotprosjekter og levende laboratorier har senteret testet forskning og innovasjon i praksis, og sikret den langsiktige relevansen og anvendeligheten av forskningsfunnene.



3. VISION AND GOALS

Arild Gustavsen
Professor NTNU, Director ZEN Research Centre, 2016–2022

The vision of the ZEN Research Centre has been to enable the transition to a low carbon society by developing sustainable neighbourhoods with net-zero greenhouse gas emissions.

The main goals have been to:

- Develop neighbourhood design and planning instruments, integrating science-based knowledge on greenhouse gas emissions.
- Create new business models, roles and services that address the lack of flexibility towards markets and catalyse the development of innovations for broader public use.
- Create cost effective, resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies.
- Develop technologies and solutions for design and operation of energy flexible neighbourhoods.
- Develop a decision-support tool for optimization of local energy systems and their interaction with the larger system.
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and testing grounds for the solutions developed in the centre.

> Eleven ZEN pilot projects are now in different phases of realization and are in this way contributing to knowledge generation, evaluation, and visualization of innovations and solutions developed

The ZEN Research Centre has worked continuously from 2016-2024 to achieve the goals set at the start in 2016 and has also largely achieved the goals. A detailed ZEN definition and framework has been developed, with supporting tools and solutions such as the ZEN guideline and the ZEN key performance indicator (KPI) tool for planning and evaluation of environmental performance. Energy solutions and flexibility has been explored both on the building and neighbourhood levels, and towards the energy market, and software has been developed. Life-cycle design strategies have been applied both on the building and neighborhood scale to find more environmental-friendly solutions.

Eleven ZEN pilot projects have been developed, evaluated, and used as living labs. They are now in different stages of realization and are in this way contributing to knowledge generation, evaluation, and visualization of innovations and solutions developed. Work, however, still remains to bring about a large-scale transformation of existing buildings and neighborhoods towards the zero-emission ambition level.

Concrete examples of the knowledge, tools and innovations developed are shown in this report.

4. EFFECTS OF CENTRE FOR THE OVERARCHING GOAL OF THE FME-PROGRAMME

This section provides a description of how energy research within buildings and neighbourhoods has contributed, or can contribute, to achieving the goals set forth in Norwegian energy, climate and environmental policy. It is an edited version of an impact-study which is undertaken by all the FME-centres on behalf of the Research Council of Norway.

The research conducted by the ZEN Research Centre, the previous ZEB Research Centre and FlexBuild (a knowledge-building project for the industry), has made significant contributions to Norway's energy, climate, and environmental policy goals, particularly for 2030 and 2050. This work has focused on reducing greenhouse gas emissions, improving energy efficiency, enabling building energy flexibility and advancing the use of renewable energy in buildings and urban areas. In doing so, it has also demonstrated that buildings and neighbourhoods contribute to improved energy security.

REDUCTION OF GREENHOUSE GAS EMISSIONS

Cities are responsible for two-thirds of global energy use, and more than 70% of the world's global energy-related greenhouse gas emissions, with transport and buildings being among the largest contributors. The greenhouse gas emissions in Norway are less, since the energy system primarily is based on hydropower, but the potential for savings is still large. The central goal of the ZEB and ZEN Research Centres was to develop solutions for zero-emission buildings and neighbourhoods in smart cities. The ZEB method for planning and evaluating buildings aims to minimize the climate impact by optimizing material and energy use, ensuring that buildings produce enough renewable energy to offset their emissions over their lifespan. Research show that emissions related to material use can be reduced by 35% without increased costs. In particular, material emissions from technical installations of buildings can be reduced by 20–40% through better material choices, reuse, and recycling. Buildings already using this methodology can further achieve about 50% reduction in greenhouse gas emissions compared to standard regulations. Expanding this to entire areas, ZEN aims for net-zero emissions over 50 years by addressing emissions from buildings, infrastructure and mobility. Emissions related to energy use and mobility can be reduced by 60% by 2050, compared to 2020.

ENERGY EFFICIENCY

Research in the ZEB and ZEN Research Centres highlights the critical role of improving energy efficiency in buildings and neigbourhoods. Studies show that by implementing energy efficiency measures, rehabilitating existing buildings, adopting more energy-efficient heating technologies, and utilizing local renewable energy sources, the total energy delivered to buildings could be reduced by up to 13 TWh (15%) by 2030 and 40 TWh (48%) by 2050. Additionally, the amount of electricity purchased from the grid could be decreased by 13 TWh (19%) by 2030 and 42 TWh (60%) by 2050.

NEW RENEWABLE ENERGY: SOLAR POWER

The integration of zero-emission buildings will lead to a significant increase in local solar energy generation. Solar power generation is projected to reach 4 TWh by 2030 and 12.5 TWh by 2050, with around 80% of this energy being used within the buildings themselves. Research also indicates that end-user flexibility can accelerate solar panel adoption, particularly in single-family homes.

ENERGY FLEXIBILITY AND REDUCTION OF POWER DEMAND

Energy flexibility is vital for managing the increasing share of variable renewable energy, like solar and wind power. Also, it can level out power peaks and avoid or delay the need for grid investments. Advanced control systems and tools (e.g. MPC – Model Predictive Control) have been developed to optimize energy use in buildings. These systems

can enable up to 80% of energy use to be shifted away from peak periods in individual buildings and about 10-20% across entire building stocks (FlexBuild project). This strategy could prevent the need for large-scale power production and transmission capacity expansion, helping to keep overall system costs low.

USE OF DISTRICT HEATING

Increased use of district heating can reduce electricity consumption, especially during peak demand periods. By combining district heating with energy efficiency measures and heat pumps, significant reductions in both total electricity and peak load demand can be achieved. This strategy can also lower overall system costs and environmental impacts, ensuring that energy production and distribution remain efficient and sustainable. Combining energy efficiency measures with the use of district heating in urban areas and heat pumps in rural areas could reduce electricity demand by 12% by 2030 and 26% by 2050, with peak load demand reduced by 17% and 35%, respectively.

MOBILITY AND GREEN TRANSPORT

Early planning for mobility patterns ensures that projects are designed to minimize transportation emissions and promote sustainable alternatives. The research emphasizes reducing travel distances through denser development, local amenities, and better integration of transportation systems. Life Cycle Assessment (LCA) within the ZEN framework integrates mobility to identify key emission sources and enables targeted reduction measures.

CONCLUSION

The energy research in buildings and neigborhoods includes research from several projects such as ZEB, FlexBuild and ZEN. It has provided crucial methodologies and technological advancements to support Norway's climate goals for 2030 and 2050. The work demonstrates how significant reductions in greenhouse gas emissions can be achieved through energy efficiency, renewable energy adoption, and smart control. By focusing on material and energy efficiency, energy flexibility, district heating, and sustainable mobility, ZEN aligns with national climate objectives while offering practical solutions for zero-emission buildings and neighborhoods. Collaboration between academia and the construction and energy industries is key to translating these research findings into real-world applications, ensuring that energy research within buildings and neighbourhoods help shape Norway's sustainable future.

5. BASIC FACTS ABOUT THE ZEN RESEARCH CENTRE

MAIN ORGANIZATION OF THE CENTRE

The daily operation of the Centre was managed by the Centre director, assisted by the leader group formed by work package leaders, a coordinator, and a communication officer. The research and innovation activities were organized in six work packages and three crossover activities.

The Centre had a General Assembly and an Executive Board. The General Assembly included all partners and gave guidance to the Board. The Board was responsible for the quality and progress of the research activities required by the Research Council of Norway and for the allocation of funds. The board consisted of six members from our user partners in addition to one from the host organization, NTNU, and one from SINTEF. The Board members at the conclusion of the center's activities are listed below. The following individuals/companies previously held positions as board members: Daniel Bjarmann-Simonsen (Bodø kommune), Synnøve Lyssand Sandberg (Statsbygg), Rune Stene (Skanska), Therese Troset Engan (NTE – Nord-Trøndelag Energiverk), Svein Olav Munkeby (NTE – Nord-Trøndelag Energiverk), Thomas Løkken (Hunton), Fredrik Shetelig (NTNU), Marianne Skjulhaug (NTNU), Rakel Hunstad (Bodø kommune), Partow Henriksen (SINTEF), and Jo Mortensen (Skanska). Torfinn Lysfjord (GK), Knut Helge Sandli (DiBK), Ane Torvanger Brunvoll (NVE), Kim Robert Lisø (GK), and Jon Erling Fonneløp (Fornybar Norge) have been deputy members of the board.

A Scientific Advisory Board of international experts was appointed to give scientific and strategic advice. Further, an innovation committee has been instrumental in the Centre's innovation work. The overall management structure is illustrated below, and further key academic personnel is listed in the appendix.

FME ZEN MANAGEMENT TEAM 2024.
From left: Judith Thomsen, Anne-Lise Aakervik, Brynjar F. Svarva, Helge Brattebø, Laurent Georges, Ann Kristin Kvellheim, David Collins, Hanne Kauko and Stian Backe.

HOST:

The Norwegian University of Science and Technology (NTNU)

RESEARCH PARTNER:

SINTEF

THE BOARD

Tonje Frydenlund, Snøhetta (Chair of the board)

Anders Fylling, Statsbygg

Anna-Thekla Tonjer, Elverum Tomteselskap

Jørgen Nordahl, Statkraft Varme

Leif Øie, GK

Sigrid Strand-Hanssen, Asplan Viak

Sara Brinch, NTNU

Siri Hunnes Blakstad, SINTEF

SCIENTIFIC ADVISORY BOARD:

Eva Heiskanen, University of Helsinki, Finland

Kristina Mjörnell, RISE, Sweden

Lieve Helsen, KU Leuven, Belgium

Stephen Selkowitz, Lawrence Berkley National Laboratory, USA

CENTRE MANAGEMENT

CENTRE DIRECTOR

Ann Kristin Kvellheim, senior advisor, SINTEF / Adjunct associate professor, NTNU, 2021 (substitute) and 2023–2024

Thomas K. Thiis, professor, NTNU, 2022–2023

Arild Gustavsen, professor, NTNU, 2016–2022

INDUSTRY LIAISON

Terje Jacobsen, Vice President, Research, SINTEF, 2016–2022

WORK PACKAGE LEADERS

WP 1

Helge Brattebø, professor, NTNU, 2018–2024

Annemie Wyckmans, professor, NTNU, 2016–2018

WP 2

Stian Backe, researcher, SINTEF / Adjunct associate professor, NTNU, 2023-2024

Ann Kristin Kvellheim, senior advisor SINTEF, 2019–2023

Asgeir Tomasgard, professor, NTNU, 2016–2019

WP 3

Laurent Georges, professor, NTNU, 2021–2024

Hans Martin Mathisen, professor emeritus, NTNU, 2019–2021

Judith Thomsen, research manager, SINTEF, 2016–2018

WP 4

Igor Sartori, senior researcher, SINTEF

WP 5

Hanne Kauko, senior researcher, SINTEF, 2020–2024

Ove Wolfgang, researcher, SINTEF, 2016–2020

WP 6

Judith Thomsen, research manager, SINTEF, 2019–2024

Inger Andresen, professor, NTNU, 2016–2019

EXTENDED MANAGEMENT GROUP

International and cross-activity coordination

Niki Gaitani, International coordinator, Associate professor, NTNU

Edgar Hertwich, leader LCA Coordination, professor, NTNU

John Krogstie, leader ICT and Tools Coordination, professor, NTNU

Thomas Berker, leader User Coordination, professor, NTNU

Anne Grete Hestnes, scientific advisor, professor emerita, NTNU

Administration and Communication

Anne-Lise Aakervik, communication officer, NTNU, 2022-2024

David Collins, innovation manager, NTNU, 2023-2024

Brynjar F. Svarva, coordinator, NTNU, 2021-2024

Sunniva Moum Danielsen, communication officer, NTNU, 2020-2021

Katinka Sætersdal Remøe, communication officer, NTNU, 2019-2022

Annika Bremvåg, coordinator & communication officer, NTNU, 2017-2018

Hanne Kristin Skjevik, financial officer, SINTEF, 2016-2024

Yana Bezdudna, financial officer, NTNU, 2021-2024

International resources

Eva Heinen, professor ETH Zurich / adjunct professor, NTNU

Henrik Madsen, professor DTU / adjunct professor, NTNU

Tobias Nordström, Vice VD Spacescape, researcher, NTNU

OUR USER PARTNERS:

The ZEN Research Centre's user partners cover the entire value chain and include representatives from municipal and regional governments, property owners, developers, consultants and architects, ICT companies, contractors, energy companies, manufacturers of materials and products and governmental organisations.

COMPANY PARTNERS:

AFRY, asplan viak, ByBo, CIVITAS, ELVERUM VEKST, Formybar Norge, FUTURE BUILT, Multiconsult, Heidelberg Materials, nfv Norsk Fjernvarme, NTE, SKANSKA, smart grid services cluster, Snøhetta, GK, TOBB

SWECO	HUNTON	Moelven	Caverion	NUMASCALE
2016–2022	2016–2022	2016–2022	2016–2019	2016

MUNICIPALITIES AND REGIONAL GOVERNMENTS:

BERGEN KOMMUNE, bodø KOMMUNE, BÆRUM KOMMUNE, ELVERUM KOMMUNE, Oslo, Steinkjer kommune, TRONDHEIM KOMMUNE, Trøndelag fylkeskommune

GOVERNMENTAL ORGANISATIONS :

NORWEGIAN BUILDING AUTHORITY, NVE, STATSBYGG, Statkraft

An innovation committee has been instrumental in considering the need, relevance and impact of research and development for further exploitation. The committee has been led by a representative from the user partners. Listed below are the representatives at the conclusion of the centre. Additionally, the following individuals/companies have previously participated: Svein Olav Munkeby (NTE – Nord-Trøndelag Energiverk), Rakel Hunstad (Bodø Municipality), Zdena Cervenka (Statsbygg), Anne Nujten (innovation manager, NTNU) and Shannon Truloff (innovation manager, NTNU).

INNOVATION COMMITTEE:

Jørgen Nordahl, Statkraft Varme (Chair)

Kjell Skjeggerud, Heidelberg Materials

Stein Stoknes, FutureBuilt

Morten Dybesland/Vitalis Pavlovas, Statsbygg

Heidi Erikstad, Elverum Vekst

Ann Kristin Kvellheim, SINTEF / centre director, ZEN Research Centre

David Collins, NTNU / ZEN Research Centre

Elsebeth Holmen, NTNU

COOPERATION WITHIN THE CENTRE

The ZEN Centre's research was conducted according to annual and semi-annual work plans based on the project description in the ZEN Centre application, previous work, and input from and discussions with our partners.

The research in the Centre was mostly carried out by NTNU (PhD candidates, postdocs, researchers, and professors) and SINTEF (scientists / personnel).

The main contribution from the user partners has been to guide the direction of the research, contribute to the pilot projects, and to be active in the implementation of the technologies and solutions developed. In addition, they have contributed actively and participated in ZEN Cases, being smaller and more short-term research and innovation actions.

The Centre's research team has primarily been located at the NTNU Gløshaugen Campus in Trondheim; first in Sentralbygg 1, and later in the ZEB Laboratory that is built as a zero emission office building and living laboratory. Some research staff has also been located in Oslo (SINTEF Community).

6. FINANCING THROUGH THE LIFE OF THE CENTRE

The table below shows the financing of the activities of the ZEN Research Centre, divided among the various partner categories. The table shows a considerable in-kind contribution from all partner categories, and cash contribution that together trigger a support from the Research Council of 176 MNOK. This is in line with budgeted numbers.

2016–2024			MNOK
Contributor	**Cash**	**In-kind**	**Total**
Host		67,026	67,026
Research partners		48,344	48,344
Companies	20,753	33,884	54,637
Public partners	22,614	15,695	38,309
RCN	176,000		176,000
Sum	219,367	164,950	384,316

7. RESULTS – KEY FIGURES

	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total
Scientific publications (peer reviewed)	2	10	17	70	60*	61	36*	20*	27	303
Dissemination measures for users	1*	96*	53*	92*	26	29	29*	35*	38	386
Dissemination measures for the general public	3*	13*	46*	50*	41*	41	6	9*	9	218
Research Innovations	-	2	2	7	8	6	6	-	-	31
Number of new/improved methods/ models/prototypes finalised	-	-	-	2	8	1	-	4	-	15
Number of new/improved products/ processes/services finalised	-	-	-	1	6	4	1	1	3	16
PhD-degrees completed	-	-	-	-	1	2	7	1*	2	13
Master degrees	-	-	-	14	4*	9*	13	7*	9	56

The table is aligned with the last numbers from Cristin. Some numbers are changed as a result of this, these are marked with *

Numbers are partly from the reporting system Cristin, and partly from previous progress and innovation reports, as well as updates for 2024. Publication activity has been high throughout the full period of the centre.

The ZEN research centre has worked continuously with innovation developments. Focusing on the two categories in the table, a total of 31 research innovations have been developed. The number of new/improved methods/models/prototypes finalised refers to the total count of new or significantly improved theoretical frameworks, analytical models, methodologies, or physical/digital prototypes that have reached a stage where they are fully developed and ready for application, testing, or demonstration. The number of new/improved products/processes/services finalised refers to the total count of new or significantly enhanced tangible products, operational processes, or services that have been fully developed and are ready for implementation, commercialisation, or practical use. These should go beyond conceptual models and have clear, real-world applicability.

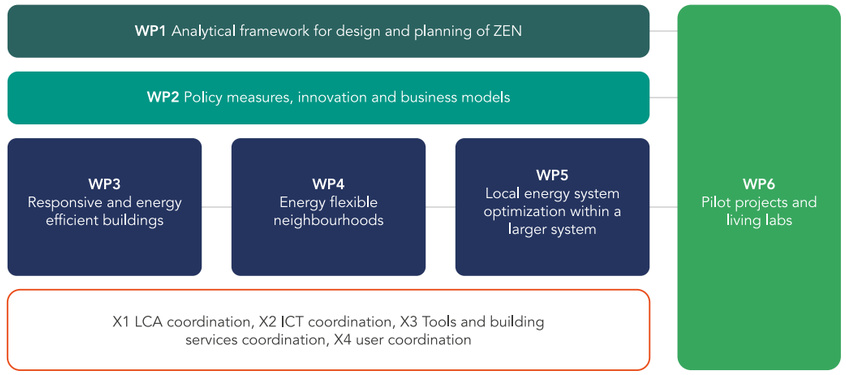
27 PhD candidates are partly or fully funded by the ZEN Research Centre. At the end of 2024, 13 had successfully defended their thesis. In addition, the Centre has funded nine postdoctoral fellows, and 56 master students have been connected to the centre.

8. OUR RESEARCH

Ann Kristin Kvellheim
Director
ZEN Research Centre

Anne-Lise Aakervik
Senior advisor communication
FME ZEN, NTNU

The ZEN Research Centre had a swift start, building upon a lot of experience from the previous Research Centre on Zero Emission Buildings (ZEB Research Centre). The first research plan (for 2017) was primarily based on to the project proposal, structured according to the main work packages and tasks.



Organisation of the centre's research activities

8.1 ORIGINAL RESEARCH PLAN AND DEVELOPMENT UNDER THE PROJECT PERIOD

WP1 Analytical framework for design and planning of ZEN, should deliver an analytical framework for design and planning of ZEN, integrating science-based knowledge on GHG emissions into practice-based instruments for design and planning of sustainable neighbourhoods, and supporting ZEN partners in identifying low carbon, high quality solutions and exploring and reducing uncertainty. The WP included three tasks, Task 1.1 Definitions, metrics, data management and monitoring, Task 1.2 Life cycle analysis, and Task 1.3 User-centered architectural and urban toolbox.

WP2 Policy measures, innovation and business models, should evaluate possible transition pathways towards ZEN consisting of integrated studies of policy measures, different forms of public private collaboration, different financial and business models and instruments as well as improved innovation processes. WP2 had the following main tasks: Task 2.1 Development of transition strategies in their contexts, Task 2.2 Public private collaboration and business models, and Task 2.3 The innovation system for zero emission neighbourhoods. Since 2021, WP2 had one additional Task 2.4 Regulatory challenges.

WP3 Responsive and energy efficient buildings, should create cost effective, responsive, resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies. This WP had the following tasks: Task 3.1 Resource efficient materials and construction systems, Task 3.2 Low emission building services, and Task 3.3 Architecture and building design procedures.

From the opening av the new school in pilot Ydalir, Elverum Municipality. Photo: Elverum Vekst.

In WP4 Energy flexible neighbourhoods, the aim was to develop knowledge, technologies and solutions for design and operation of energy flexible neighbourhoods, with several tools developed. WP4 had the following tasks: Task 4.1 Local thermal grids, generation and storage, Task 4.2 Local electrical generation and storage, and Task 4.3 Energy flexible operation.

WP5 Local energy system optimization within a larger system, the aim was to develop and apply methodologies that identify the socio-economic optimal operation and expansion of energy systems within demarked areas. Several of these results have been integrated in a software tool for optimal operation and investment in local energy systems with multiple energy carriers. The main tasks have been Task 5.1 ZEN-modules and algorithms, Task 5.2 KPIs and ZEN constraints, and Task 5.3 Energy system impacts.

WP6 Pilot projects and living labs, the goal was to realize at least seven pilot projects for ZEN concepts in Norway. These should serve as: innovation hubs for co-creation between researchers and building professionals, property developers, municipalities, energy companies, building owners, and users; living labs to verify, document and optimize the real-life performance of the solutions developed in the ZEN Centre; and lighthouse projects to learn, inspire, and disseminate ZEN-related knowledge. WP6 had the following tasks: Task 6.1 Planning, Task 6.2 Concept design, Task 6.3 Prototype design and testing, and Task 6.4 Innovation design and evaluation.

In addition to the work packages, we have allocated resources to cross-cutting and key research topics of particular importance for the ZEN Research Centre. These are LCA Coordination to ensure a consistent use of LCA-methods across WPs, ICT and Tools Coordination to coordinate tools development, and User Coordination to ensure that users not being partners in the centre (e.g. end users) also are considered when proposing new solutions.

After the initial workplan, being only for one year, the next plans were developed for two years to allow for some more continuity in the planning of the research activities. With every revision, the ZEN Centre user partners were invited to give input and contribute to the work plan development. Further, during the first centre years the ZEN Board also proposed to establish ZEN Cases, to address user-partner-initiatives coming up during a work plan period.

The Mid-term evaluation gave very positive feedback overall, stating that FME ZEN "is a well-structured and successful Centre". Our broad scope and interdisciplinary approach were praised for its ability to tackle the interconnected challenges of developing zero-emission neighbourhoods. The evaluation highlighted that the research output was of high quality, both in terms of the significant volume of scientific publications, but also for being in the forefront of international efforts to transition towards low-carbon settlements and societies. Furthermore, the evaluation found that the ZEN Research Centre has built a critical mass of expertise and will remain relevant in the long term not least because of our work with pilot projects and living labs. These are highlighted as a key strength, that has allowed for practical testing and implementation of research findings. The evaluation also provided suggestions for improvement:

- Focus on practical implementation, testing, and dissemination of tools and strategies in real-world settings.
- Develop a formal process to manage diverse topics within zero-emission neighbourhoods.
- Facilitate knowledge transfer between academia and industry.
- Enhance communication efforts to reach the general public.

The suggested improvements were broadly discussed and measures for improvement were incorporated in the workplan whereupon actions were taken. In particular ZEN has focused on testing and dissemination of tools and key performance indicators to follow up on this feedback. A process to handle diverse topics within zero-emission neighbourhoods has materialized in the ZEN-definition. And in the last three years of the centre period, ZEN had a communication advisor in a 90% position which has enabled us to reach out to the public and be more effective in our research communication.

The vision and goals have been discussed under the development of the research centre, but have largely been kept as they were originally formulated.

8.2 RESEARCH ACHIEVEMENTS

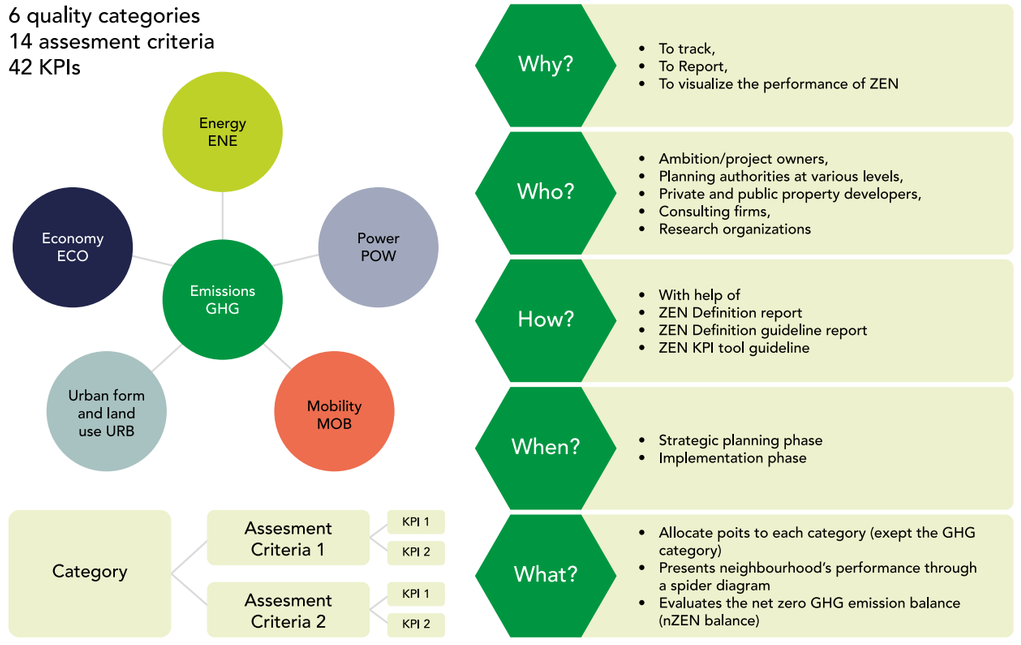
WP1 – ANALYTICAL FRAMEWORK FOR DESIGN AND PLANNING OF ZEN

The most important task of Work Package 1 in the ZEN Centre has been to develop a well-working analytical framework, with its associated methods and tools, for evaluating the performance of a project with net zero emission ambitions. The ZEN Definition is the formal description of what is meant with the term "zero emission neighbourhood", pointing not only to the ambition of net zero emission of greenhouse gases (GHGs) during a 50-year time horizon for a project, but also to a set of wider quality categories where a ZEN project is expected to perform: energy, power, mobility, urban form and economy. For each of these categories, we have developed performance criteria and KPIs, paying attention to the needs of project planners, designers and developers. Basically, this means that KPIs should be applicable in practice, allowing for access to project specific information and input data of sufficient quality, and giving output data and results that are useful for decision-making when applied to a given project.

Work Package 1 also developed models based on life cycle assessment (LCA) methodology, which were successfully applied to explore and verify the emission of greenhouse gases and other environmental impact profiles at several ZEN pilot projects. A novel method for scenario analysis of the dynamic changes in the building stock the neigbourhood level was applied to ZEN pilot Kunnskapsaksen, demonstrating the ability to evaluate how ZEN policies may impact long-term changes in building energy use.

WP2 – POLICY MEASURES, INNOVATION AND BUSINESS MODELS

This work package has been focused on analyses of business models and costs related to ZEN from a system perspective, what is needed to realize ZEN, and how to make it profitable. We have shown that a large-scale adoption of ZENs in Europe could decrease total system costs of meeting European climate targets (ZEN report no 30), and that energy efficiency measures can reduce total delivered energy to the Norwegian building stock by 48% between 2020 and 2050 at an additional cost of 18 billion NOK per year (ZEN report no 50). Research on process innovation has revealed that well-prepared processes with a focus on collaboration across public and private stakeholders can create conditions that increase the chances of realizing ZEN. Tensions between building developers and district heating companies have been an increasingly relevant topic throughout FME ZEN. We found that tensions stem from misaligned climate strategies and cost concerns, and that developers and district heating companies



Structure and use of quality categories, performance criteria and key performance indicators (KPIs) in line with the ZEN Definition and the KPI-Tool.

ought to work together on regulatory adjustments to achieve balanced environmental and economic sustainability. We have explored the drivers and barriers to ZENs in Norway, focusing on technological, market, and societal aspects. Advancements in energy technologies at the building level, particularly photovoltaics and battery technology have been discussed and analysed as key solutions to enable ZEN. We have found that profitability of photovoltaics in the building stock depends largely on the electricity spot price and the design of grid tariffs, and that batteries are currently too expensive to be economically profitable (ZEN Report no 55). To facilitate the development of ZEN, we have the following recommendations for owners, developers, infrastructure providers (ZEN Report no 22):

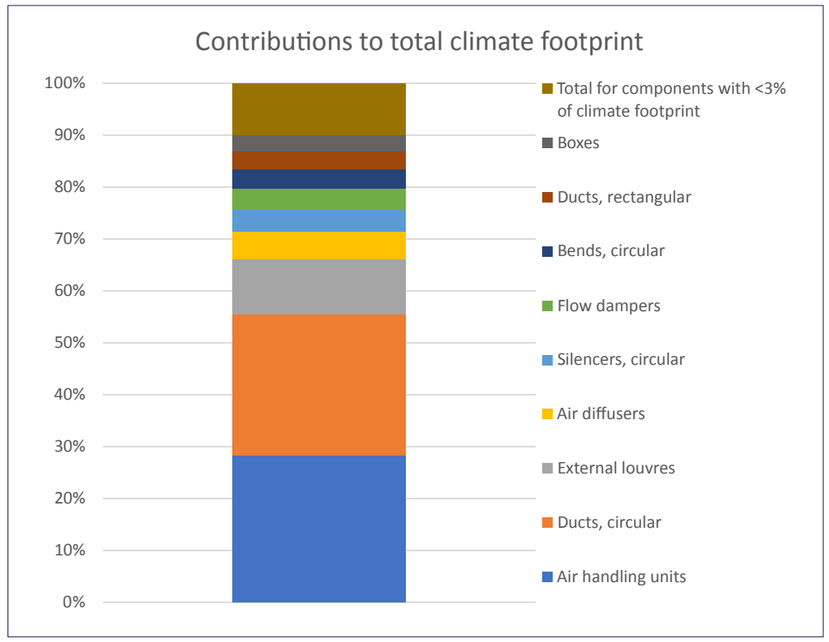
- Owners and Developers: Set ambitious goals, innovate business models, create demand for ZEN solutions, engage users, and support smart technology.
- Supply and Infrastructure: Innovate business models, leverage technology and digitalization, and form new partnerships across energy and building sectors.
- Society and Policy: Engage citizens, evaluate regulations, support research, and promote best practice projects.

In exploring the costs of ZEN projects, the Nidarvoll development in Trondheim, Norway, serves as a case study, showing that ZENs can be profitable with some investment support from Enova. ZEN report 59 quantifies additional short-term costs in ZEN, which are linked to reducing heat loss, producing renewable energy, and distributing energy. Compared to the current building code (TEK17), the Nidarvoll project reduced electricity needs by 50% and district heating by 91%. Despite challenges such as limited area for solar panels, and unsuitable ground conditions, the project achieved a 30% reduction in greenhouse gas emissions over its lifespan.

WP3 – RESPONSIVE AND ENERGY EFFICIENT BUILDINGS

This work package has been focused on research on smart buildings and the building envelope to enhance the efficiency, comfort and safety of the building environment. It has been shown that CO_2 emissions connected to technical equipment in buildings, including ventilation, are not negligible compared to emissions related to the building operation. Hence, ventilation design and practices should be adapted to minimize embodied emissions while maintaining high indoor air quality (IAQ) and energy efficiency. The research quantified embodied emissions of typical mechanical ventilation systems and identified the ventilation components that have the largest influence on these emissions.

It is necessary to ventilate buildings to have good indoor air quality, for improved health, comfort, and productivity. Demand-controlled ventilation (DCV), adapts the amount of supply air entering the building as a function of the current pollutant load inside the building, typically the number of occupants. We have undertaken research to maximize the efficiency of the heat exchanger to obtain high indoor quality and high energy efficiency at the same time.



Climate footprint for the ventilation system in a test case office building

WP3 also investigated responsive building envelopes. A definition and roadmap for implementation has been introduced. In addition, the robustness of responsive building envelope designs has been assessed using a decision-support methodology developed in in the workpackage. The robustness is considered to account for the uncertainties on real and future operating conditions of the building that may differ from the main design scenario.

WP4 – ENERGY FLEXIBLE NEIGHBOURHOODS

A key achievement has been the development and application of Model Predictive Control (MPC) systems to harness the energy flexibility of buildings. These systems optimize energy use by leveraging predictive algorithms that account for external factors such as weather, user behavior, and energy prices. MPC enables significant flexibility in heating systems, shifting 50–90% of energy consumption away from peak hours in simulations without compromising indoor comfort. Testing MPC in several pilot projects demonstrated its effectiveness, achieving up to 80% reduction in peak-hour consumption. The advancements in data acquisition and processing ensure that MPC systems respond efficiently to real-time signals, optimizing energy use while maintaining user comfort.

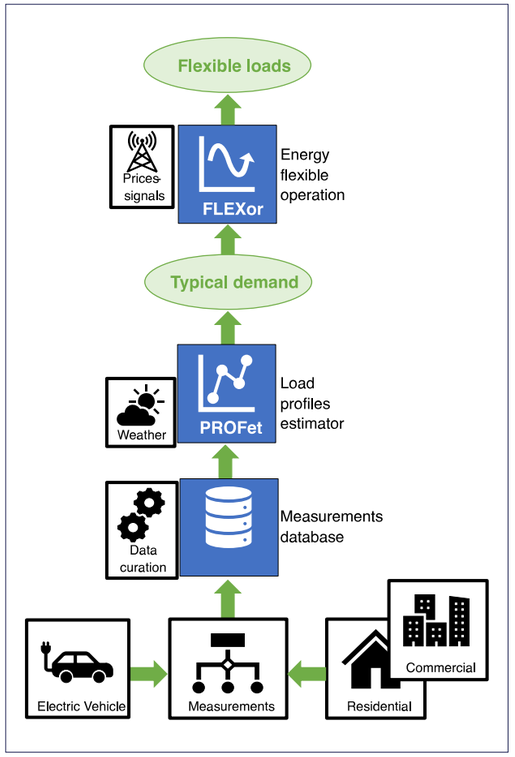
WP4 has developed innovative tools like PROFet and FLEXor to facilitate energy planning and optimal system control. PROFet creates accurate load profiles using real measurement data, ensuring precise planning for electricity and thermal energy demand. FLEXor optimizes building energy flexibility by controlling indoor temperature, water heaters, and EV charging in response to price signals, reducing energy costs and peak demand. These tools combine statistical modeling, software development, and energy system engineering, promoting solar installations and reducing environmental impacts. Both tools are available via a Web App and Application Programming Interface (API) for advanced users.

The rapid adoption of electric vehicles (EVs) presents both challenges and opportunities for energy systems. WP4's research into EV charging habits revealed that EVs are connected to chargers for an average of 12 hours, though actual charging takes less than 3 hours, offering a window to shift charging to off-peak hours. This flexibility can reduce grid stress and energy costs, balancing energy loads and ensuring grid reliability while accommodating the growing number of EVs.

WP5 – LOCAL ENERGY SYSTEM OPTIMIZATION WITHIN A LARGER SYSTEM

WP5 developed an accessible operational model called Integrate for optimization of local energy systems with multiple energy carriers. The tool was applied in numerous case studies during the centre period, assisting the user partners in critical decisions concerning the energy system development at a local level in different parts of the country. The Integrate -tool was the starting point for a newly developed, broader modelling framework, EnergyModelsX, for modelling and optimization of integrated energy systems at different geographical scales.

Understanding the impact of zero emission neighbourhoods in the energy system on a larger scale was one focus area in WP5. A stochastic capacity expansion model (EMPIRE) has been used to understand the impact of ZEN on the development of the European power market towards 2050. Findings include that wide-scale implementation of ZENs can lower the costs of meeting the European climate targets. In addition, the impact of energy flexibility from the Norwegian building stock on the future power market has been analysed. A key take-away is that Norwegian hydropower will adapt its production profile based



Schematic representation of the collection, preparation, and calculation of typical energy demand and flexible load profiles using PROFet and FLEXor.

on the electricity use in the Norwegian building stock to stabilize Norway's role in the European power market towards 2040.

Regulatory challenges that arise when expanding the system from single buildings to neighbourhoods and influences of different grid pricing structures on multi-stakeholder decisions have also been studied. The research finds that current tariffs do not always incentivize efficient energy use or coordination between buildings. However, expanding the regulatory framework to include local market mechanisms show promise in enhancing energy coordination and reducing overall system costs. The main conclusion is that carefully designed pricing mechanisms can optimize the deployment and operation of energy resources at the neighbourhood level, helping to reduce the need for grid upgrades and support a sustainable, carbon-neutral energy system.

WP6 – PILOT PROJECTS AND LIVING LABS

During the lifespan of the ZEN Research Centre, we have worked with a total of 11 pilot areas. The pilot areas are owned by the centre's partners, primarily municipalities. The ZEN pilot projects include both new and established areas that are to be upgraded and developed further.

The involvement of end users has been organised in living labs in five of the pilot projects. The target group for the living lab activities were people impacted by the suggested changes implied by ZEN within the geographically defined area of the pilot.

Towards the end of the ZEN Research Centre a goal has been to summarize challenges and learnings from implementing Zero Emission Neighbourhoods (ZEN) pilot projects from the perspective of the involved stakeholders. This sums up a multi-stakeholder perspective and highlights key points that are important learning for future work with ZEN neighbourhoods, summarized in a final report. Key points are presented in chapter 13 under "success stories".

CROSS CUTTING ACTIVITIES

LCA coordination

Given the need to document net-zero emissions and target reduction efforts to the largest emissions, Life Cycle Assessments (LCA) was central to ZEN. The main task of this activity was to coordinate the use of LCA across the center with respect to calculation rules, use of allocation methods, data, and tools. The coordination was achieved mainly through dialogue with and contributions to the Working committee (Arbeidsutvalget) for the ZEN definition. Main activities focused on the creation of a set of rules, led by WP1 and WP5, but involving several other parts of the center. There was a special focus on the emissions intensity of electricity used and supplied by a neighbourhood, and on the allocation of emissions from waste incineration to district heat. In addition, there was activity around a life cycle inventory database.

The cross-cutting activities have resulted in contributions to, in particular, the 1: ZEN definition (co-produced by WP 1), 2: Calculation rules for electricity (co-produced by WP 5), and 3: Calculation rules for district heat (co-produced by WPs 1) and 4: Work on transport and settlements integrated, consideration of transport infrastructure and effect of settlement pattern on transport demand.

ICT and tools coordination

Information and Communication Technology (ICT) harmonization and coordination throughout the centre period was an essential task to maximize the results of ICT use in the different work packages, which also depended on the harmonization of modelling methods (also with the other resource coordinators). The focus was on the collection of data that would be aggregated and visualized for different types of stakeholders (e.g., politicians, planners and citizens), that would contribute to decisions on a small and large scale. In this cross-cutting activity, there was a special focus on aspects such as data flows and the use of data across ICT tools.

In the ZEN Research Centre, we have further developed several tools / models / software, that can be categorized according to the figure on the next page. A separate activity has been on how to collaborate in the developments of the various tools. The key tools and their contact person are noted in the table on next page.

User coordination

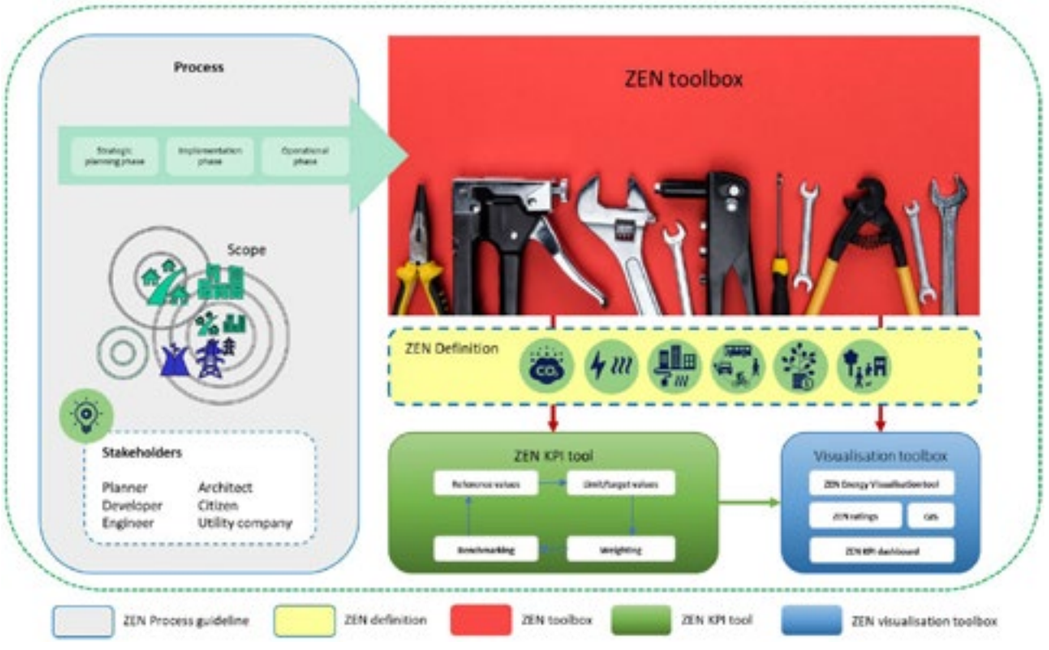
This cross-cutting activity focused on users that were not directly represented as partners in the centre. The most important group were end-users, i.e. occupants that are – potentially and maybe only indirectly – affected by the transition to zero emission neighbourhoods. In addition, local facilities managers were included into the work because of their central role in implementation and operation of buildings and neighbourhoods.

While the work done during the centre's lifetime produced a wealth of insights into user-related aspects of the implementation of zero emission neighbourhoods, three findings stand out: (a) the difficulty of involving users in zero emission infrastructure development, (b) tensions between universal solutions and local interventions, and (c) the importance of the demographic and economic context.

Key tools and their contact persons

Group	Name of tool	Contact person	Short description
Decision support	ZEN KPI Tool	Marianne Kjendseth Wiik	Evaluation of KPIs of a ZEN
Design support	ZEN ventilation design tool	Luis Caetano	Optimization of ventilation ductwork for total emissions
Database	ZEN LCA ventilation database	Håvard Bergsdal	Generic LCI database for ventilation components
Decision support	Robustness methodology (T-Robust)	Shabnam Homaei, Mohamed Hamdy	Holistic methodology to select robust design
Design support, Decision support, Investment planning	PROFet	Igor Sartori	Typical load profiles (per energy service)
Design support, Decision support, Investment planning	FLEXor	Igor Sartori	Flexible load profiles (per energy carrier) in response to a price signal
Decision support, investment planning	INTEGRATE	Magnus Askeland	Energy system planning and optimization
Spatial scales/ decision support	ZENIT	Dimitri Pinel	A model for creating a cost-optimal energy system for zero emissions neighbourhoods
Spatial scales/ decision support	EMPIRE	Stian Backe	A digital energy and power system model that analyzes the effects of variable power supply on investments in the power system
Guideline, process support	ZEN Enabler (Z.En)	Giulia Vergerio	Iterative guideline to ensure ZEN ambitions are realized as planned

ZEN KPI conseptual framework



8.3 HIGHLIGHTS FROM SCIENTIFIC RESEARCH

This sub-chapter presents a selection of much cited articles as well as interviews with some of the researchers behind the articles. Articles can be read through the links in the titles.

SCIENTIFIC RESULTS – A SELECTION OF MUCH CITED ARTICLES

Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock

The study analyzes the material flows and greenhouse gas emissions (GEEs) of a neighborhood building stock over 60 years. It finds that 52% of GEEs come from initial construction, while 48% are due to material replacements over time. The study highlights the importance of material efficiency (ME) strategies, such as using fewer materials, extending building lifetimes, and improving material production. Implementing these strategies can reduce GEEs by up to 44%. The study emphasizes the need for early planning to incorporate ME strategies and maintain buildings well to extend their lifetimes. Overall, a combination of ME strategies at different times can best mitigate GEEs in neighborhood projects.

Large potentials for energy saving and greenhouse gas emission reductions from large-scale deployment of zero emission building technologies in a national building stock

The study explores the potential energy and greenhouse gas (GHG) emission savings from large-scale deployment of zero emission building (ZEB) technologies in Norway's national building stock by 2050. Using the RE-BUILDS 2.0 model, the study compares a Baseline scenario with two ZEB scenarios, showing significant potential for energy and GHG emission reductions. The results indicate that ambitious ZEB policies could reduce energy demand by up to 56% and GHG emissions by up to 93% compared to 2020 levels. The study emphasizes the urgency of implementing ZEB policies to avoid lock-in effects and achieve climate targets. It also highlights the importance of energy-efficient renovations and the role of local renewable energy generation. Overall, the findings suggest that ZEB technologies can play a crucial role in mitigating climate change and reducing energy consumption in the building sector.

Global scenarios of resource and emission savings from material efficiency in residential buildings and cars

This article explores how improving material efficiency in residential buildings and cars can significantly reduce global greenhouse gas (GHG) emissions. It examines strategies like using materials more efficiently, extending the lifespan of products, and increasing recycling. These strategies could reduce GHG emissions by 20–52 gigatons for buildings and 13–26 gigatons for cars by 2050. The study highlights that alongside energy efficiency and low-carbon energy sources, material efficiency is crucial for deep decarbonization. For buildings, using wood and reducing floor space are effective strategies, while for cars, ride sharing and car sharing have the highest potential. The findings suggest that material efficiency can help achieve climate goals and reduce reliance on costly carbon-removal technologies.

Stakeholder collaboration in sustainable neighbourhood projects

The article reviews how different stakeholders work together on sustainable neighborhood projects. It highlights that these projects are important for reducing energy use and carbon emissions in urban areas. However, collaboration is more complex due to the diverse interests and priorities of stakeholders. The review identifies 20 key themes that affect collaboration, such as community involvement, stakeholder diversity, and policy support. It also suggests that understanding these themes can help improve collaboration and lead to better sustainability outcomes. Finally, the article proposes future research directions to further explore and enhance stakeholder collaboration in sustainable neighborhood projects.

Impact of energy communities on the European electricity and heating system decarbonization pathway

The article explores how energy communities (ECs) can help Europe reduce its electricity and heating system costs while meeting climate goals. ECs are defined as groups of buildings that generate, store, and share renewable energy locally. The study compares the impact of ECs on the European energy system with and without their development. Results show that ECs can lower overall system costs and reduce the need for new generation and storage capacity. However, there is a conflict between optimizing ECs for local benefits versus broader European benefits. The article suggests that better coordination and price signals are needed to align local and global energy goals.

Predictive rule-based control to activate the energy flexibility of Norwegian residential buildings: Case of an air-source heat pump and direct electric heating

The study examines the energy flexibility of a Norwegian single-family house using different heating systems and control strategies. It compares air-source heat pumps and direct electric heating, focusing on reducing energy costs, CO_2 emissions, and peak-hour energy use. The results show that price-based control does not save costs due to low daily price fluctuations in Norway. Similarly, carbon-based control does not significantly reduce emissions because of limited fluctuations in CO_2 intensity. However, controlling energy use during peak hours is very effective, especially for direct electric heating. The study highlights the importance of detailed modelling for accurate assessment of energy flexibility in buildings.

Responsive building envelope concepts in zero emission neighborhoods and smart cities - A roadmap to implementation

This study analyses the potential and requirements associated with using Responsive Building Envelopes (RBEs) to manage complex interactions between buildings, clusters of buildings, and utility grids. RBEs are useful for optimizing the balance between various energy flows at both single- and multi-building scales. They actively manage on-site renewable and purchased energy, while also enhancing user experience and indoor comfort by providing an interactive interface with the outdoors.

A six-step pathway for implementing RBEs in ZEN-like projects is proposed. These steps involve identifying the purpose of response, scale and interdependency, functionality, triggers and controls, interactions, and technical solutions. The proposed process emphasizes the importance of defining specific information such as responsive goal hierarchies, the scale of responses in relation to their purpose, and the significance of aesthetic expression to foster a positive user experience.

A cake closed the deal between academia, municipality and industry about developing the energy system at Nyhavna. A future ZEN in Trondheim.

Assessing the potential of seasonal thermal storage for local energy systems

The study evaluates the potential of seasonal thermal energy storage (STES) for a residential area in Oslo, Norway, using excess heat from a waste incineration plant. It compares low-temperature district heating (DH) with STES to high-temperature DH and direct electric heating. The results show that while STES is not the most cost-effective option under the applied energy prices, it contributes to reduced peak heating demand and emissions for DH production. The study highlights that higher electricity prices in winter and reduced grid capacity could make STES more competitive. Additionally, DH alone can alleviate pressure on the power grid, reducing peak power demand by 28%. Overall, STES and DH can play a crucial role in reducing grid investments and managing energy price volatility.

Flexibility through power-to-heat in local integrated energy systems with renewable electricity generation and seasonal thermal energy storage

The study evaluates different scenarios for the development of the energy system in Nyhavna, a future ZEN in Trondheim. The focus is on the thermal energy system, which includes a local heating network, heat pumps and seasonal thermal energy storage, and its interaction with the power grid and availability of locally produced electricity. The study evaluates different supply temperatures in the local heating network and the resulting demand for energy imports. The study highlights the importance of sector coupling between power and heat, and the ability to share locally produced electricity between different users at a neighbourhood level to gain full benefits of local energy and flexibility resources.

Approaches to Social Innovation in Positive Energy Districts (PEDs)—A Comparison of Norwegian Projects

While the energy transition is mainly focusing on technical innovations, social innovation is crucial to guarantee the uptake and deployment of concepts such as ZEN and Positive Energi Districts. The article describes the respective approaches and learnings for social innovation of the three research projects, ZEN, +CityxChange and syn.ikia, in a multiple case study approach. Through the comparison of these projects, the work identifies social innovation approaches with different scopes regarding citizen involvement, stakeholder interaction and capacity building. These insights are also expected to contribute to further planning and design of PED projects within local and regional networks (PEDs in Nordic countries) and contribute to international PED concept development.

RESEARCHER INTERVIEWS

JAN SANDSTAD NÆSS
Associate professor at Institute for architecture and technology, NTNU and researcher at FME ZEN

Jan Sandstad Næss has high hopes for the future. He experiences that the work he and his colleagues in work package one has been doing is creating engagement. There are many people who are highly dedicated to save our climate and reducing emissions. – And that makes me very excited, he says.

"I work with environmental analysis, circularity, and climate change mitigation. This includes many different topics such as resource efficiency and circular economy in the built environment, waste incineration with energy recovery, mobility, carbon capture and storage, sustainable land use, and land-based negative emission technologies such as bioenergy with carbon capture and storage and afforestation."

What do you think is the most important task to manage our climate ambitions?

As a society we need to quickly upscale environmentally friendly solutions, get rid of our dependency of fossil energy carriers and reduce the pressure on nature and biodiversity.

"We researchers have a responsibility to create a solid knowledge base that can be used for sustainable decision-making at all levels. We need robust methods that can be applied at the project level to make environmentally efficient investment decisions that contribute to the achievement of global sustainability goals. We also need political guidelines both locally, nationally, and internationally that are based on scientific insight, particularly regarding how human activities affect both climate and environment, as well as our ability to mitigate environmental impacts. Individual efforts to live more environmentally friendly are also important." And speaking for myself; I don't have a car and use public transport when I can in daily life. In general, I try to reduce my carbon footprint.

Jan S. Næss has also been appointed to NTNUs Outstanding Academic Fellows Programme 2024 – 2028.

STIAN BACKE
Researcher SINTEF Energy and work package leader in FME ZEN.

I work in both WP2 and WP5 to understand the interaction between technologies in ZEN and the economic framework associated with energy resources. This includes analyzing energy systems with mathematical optimization models to calculate the technical-economic impact of ZEN on the surrounding energy system, as well as how different market opportunities and price signals affect the profitability of energy resources in ZEN.

My research shows a great theoretical potential associated with flexible adaptation of heating and EV charging in ZEN on the road to a zero-emission society. At the same time, research on poor profitability indicates flexibility for individual players in ZEN. Therefore, it is particularly exciting to do more research on how the markets can better facilitate that flexibility deliveries from ZEN become more economically attractive, so that ZEN can contribute to more efficient development of the entire energy system.

What is the most important thing society, researchers, and others must do to achieve the ambitions that the world has set for itself?

If we are to succeed, everyone must be willing to adapt to sustainable solutions. We need society to understand the positive side of ambitions. I believe our most important task as researchers is to communicate the benefits and opportunities

of achieving our ambitions. We must also give actionable advice and guidelines for concrete actions that can be taken in neighbourhoods to accelerate the transition to a zero-emission society.

MARIANNE KJENDSETH WIIK
Researcher SINTEF Community and FME ZEN.

Marianne Wiik has been central in the development of one of the main results from FME ZEN, the ZEN Definitions and KPI's.

"I have worked on and developed the ZEN definition report, the ZEN definition guideline report, and the ZEN KPI tool and manual. My work has also involved testing and verifying the ZEN KPI's in the various ZEN pilot areas.

The ZEN KPI's are: GHG emissions, Energy, Power, Mobility, Urban form, and Economy. One highlight has been working on a Standard Norge Technical Specification (so called NSPEK) that details the framework for Zero Emission Neighbourhoods in terms of definition, process, method, and GHG emission requirements.

During my research, I have identified tasks to help reduce GHG emissions from the whole value chain, from planning, implementation and use of an area. One example is zero emission construction sites, where it is possible to use electric construction machinery and heavy-duty vehicles to reduce GHG emissions during the construction phase.

To reach our goals we need to start cutting our GHG emissions right away. There are just a few years left until 2030, and we have a long way to go if we are going to fulfill Norway's ambitions of at least a 55% reduction in our GHG emissions.

8.4 Awards

Researchers, PhD's and even the ZEB Laboratory itself, has received several awards during the FME ZEN timespan.

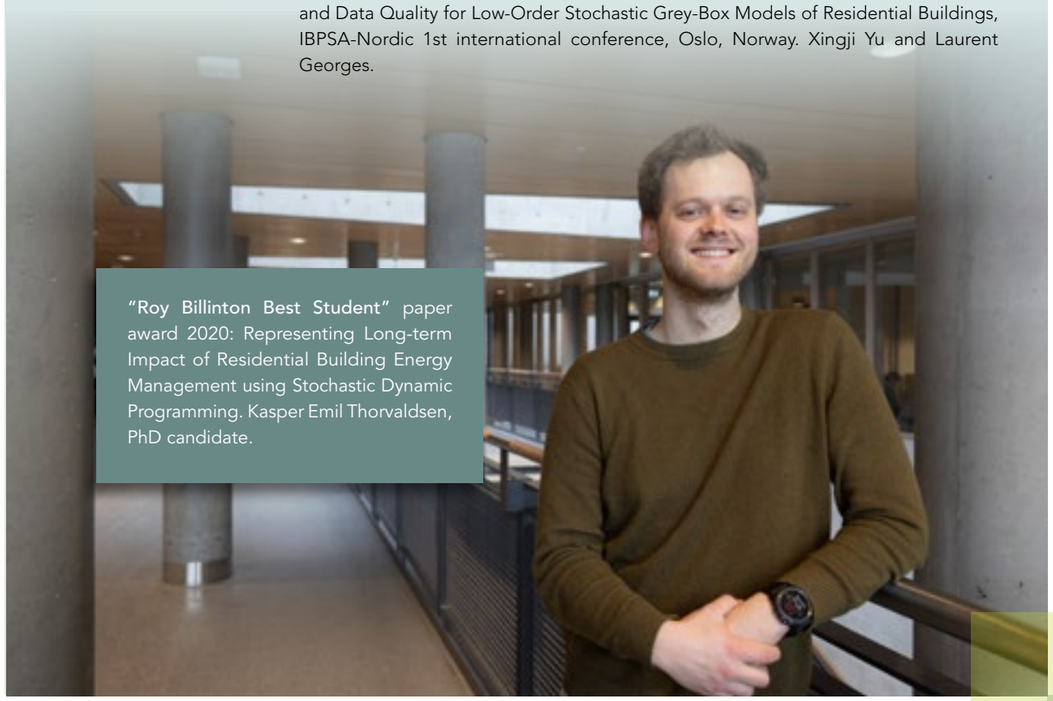
BEST PAPERS

Best paper in the Journal of Building Performance Simulation 2021–2022: *Building optimization testing framework (BOPTEST) for simulation-based benchmarking of control strategies in buildings.* **David Blum, Javier Arroyo, Sen Huang, Ján Drgoňa, Filip Jorissen, Harald Taxt Walnum, Yan Chen, Kyle Benne, Draguna Vrabie, Michael Wetter and Lieve Helsen**.

Best paper award EEM20 2nd price: Peer-to-peer trading under subscribed capacity tariffs – an equilibrium approach | IEEE Conference Publication | IEEE Xplore. Sigurd Bjarghov, Stian Backe, Magnus Askeland. (2020)

Best paper award PMAPS 2020: Representing Long-term Impact of Residential Building Energy Management using Stochastic Dynamic Programming, International Conference on Probabilistic Methods applied to the power system (PMAPS), Kasper Emil Thorvaldsen, Sigurd Bjarghov, Hossein Farahmand

Best paper award BuildSim-Nordic 2020: Influence of Data Pre-Processing Techniques and Data Quality for Low-Order Stochastic Grey-Box Models of Residential Buildings, IBPSA-Nordic 1st international conference, Oslo, Norway. Xingji Yu and Laurent Georges.



"Roy Billinton Best Student" paper award 2020: Representing Long-term Impact of Residential Building Energy Management using Stochastic Dynamic Programming. Kasper Emil Thorvaldsen, PhD candidate.

AWARDS

Maria Justo Alonso won "Kronprins Haakons research award" from Astma og Allergi association for her PhD research om indoor ventilation and air quality. (2023)

PhD candidate **Eirik Resch** won the Discovery Innovation Scholarship for his software for carbon footprint calculations in the construction sector. (2020)

Annemie Wyckmans was elected "Mission Innovation Champion" (2020)

Edgar Hertwich is the award winner of NTNU's Price for Research and Art (2023).
He was also appointed member of European Scientific Advisory Board on Climate Change (2022)

PhD candidates **Kristian Stenerud Skeie** and **Elena Catto Lucchino** won "Climathon in Trondheim" with their solar energy sharing model Nabosol. (2019)

Outstanding Academic Fellows Programme 2017–2024, NTNU:

Francesco Goia 2017–2021
Natasa Nord 2017–2021
Jan Sandstad Næss 2024–2028

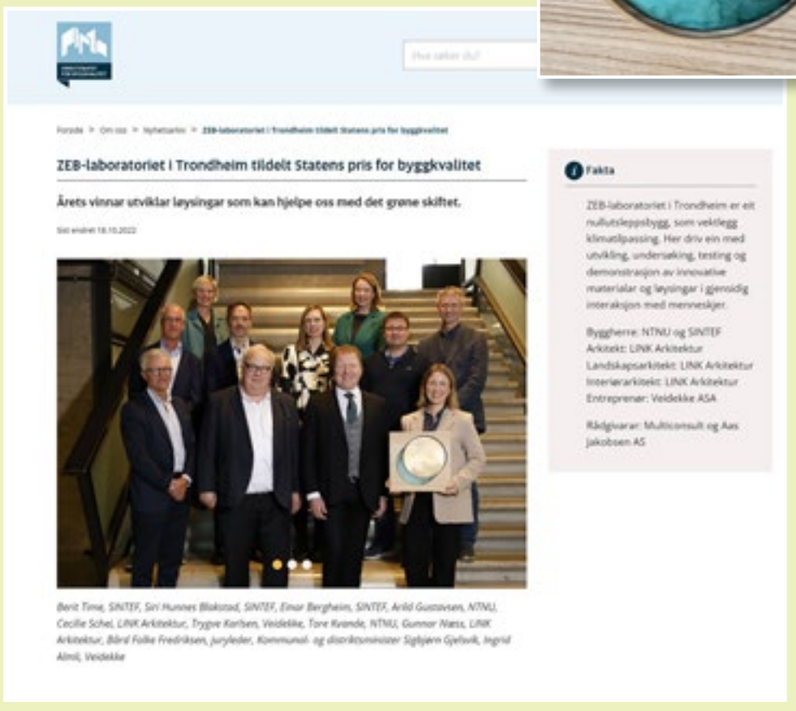
The programme facilitates academic development and merit by concentrating on research to qualify some of our foremost young research talents for internationally leading research careers.

The Onsager Fellowship Programme at NTNU

Jan Sandstad Næss, at the Faculty of Architecture and Design was elected the second-generation Onsager Fellows. The Onsager Fellowship is designed to attract talented early-career scholars with documented excellent supervised work, ready to work independently and with the potential to become a research leader.

ZEB LABORATORY

The ZEB-laboratory, finalized in 2021, is based on the research activities in the ZEB and ZEN Research Centres. The building itself has received several awards. In 2022 it won **The Norwegian Government's prize for building quality**, from The Norwegian Building Authority (DiBK), and **Betonghammeren for best practise**, given by Bygg21.



ZEB-laboratoriet i Trondheim tildelt Statens pris for byggkvalitet

Årets vinnar utviklar løysingar som kan hjelpe oss med det grøne skiftet.

Sist endret 18.10.2022

Berit Time, SINTEF, Siri Hunnes Blakstad, SINTEF, Einar Bergheim, SINTEF, Arild Gustavsen, NTNU, Cecilie Schei, LINK Arkitektur, Trygve Korben, Veidekke, Tore Kvande, NTNU, Gunnar Næss, LINK Arkitektur, Bård Folke Fredriksen, juryleder, Kommunal- og distriktsminister Sigbjørn Gjelsvik, Ingrid Almli, Veidekke

Fakta

ZEB-laboratoriet i Trondheim er eit nullutsleppsbygg, som vektlegg klimatilpassing. Her driv ein med utvikling, undersøking, testing og demonstrasjon av innovative materialar og løysingar i gjensidig interaksjon med menneskjer.

Byggherre: NTNU og SINTEF
Arkitekt: LINK Arkitektur
Landskapsarkitekt: LINK Arkitektur
Interiørarkitekt: LINK Arkitektur
Entreprenør: Veidekke ASA

Rådgivarar: Multiconsult og Aas Jakobsen AS

9. INTERNATIONAL COOPERATION

The Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Research Centre) has actively engaged in international collaborations to advance sustainable building and urban development.

NIKI GAITANI
International Research Co-ordinator, Associate Professor, NTNU

Notable partnerships include three EU projects that are coordinated and led by NTNU. Syn.ikia and ARV builds upon research from the ZEN Research Centre.

EUROPEAN UNION PROJECTS

- **syn.ikia Project:** Coordinated by NTNU, this project involves 13 partners from six countries, aiming to increase the proportion of sustainable neighbourhoods with surplus renewable energy across Europe. The initiative focuses on developing solutions adaptable to various climates and markets.

- **ARV Project:** NTNU leads this collaborative effort with 35 European partners representing the entire building and energy sector value chains. Funded by the EU's Green Deal initiative, ARV focuses on creating climate-positive circular communities through six large-scale demonstration projects in cities across Europe, including Oslo, Sønderborg, Karvina, Utrecht, Palma, and Trento.

- **+CityxChange Project:** The project led by NTNU, was an EU-funded initiative (2018–2023) focused on developing Positive Energy Districts (PEDs) in European cities. It involved 32 partners from 11 countries, working on sustainable urban energy solutions through digital innovation, local energy trading, and community engagement. The project tested smart city solutions in seven cities to support the EU's climate goals.

These collaborations underscore the ZEN Centre's commitment to fostering international leading partnerships that drive innovation and progress in zero-emission neighbourhoods and smart city initiatives.

INTERNATIONAL RESEARCH NETWORKS

- **European Energy Research Alliance (EERA):** NTNU has coordinated the Joint Programme on Smart Cities within EERA, facilitating collaboration among European research institutions to promote sustainable urban development.
- **International Energy Agency (IEA) Involvement:** NTNU and SINTEF researchers have contributed to IEA projects, such as Annex 83 on Positive Energy Districts (PEDs), focusing on energy-positive urban areas. This involvement facilitates knowledge exchange and the development of best practices in sustainable urban energy systems. NTNU and SINTEF researchers have also been involved in Annex 81 on Data-Driven Smart Buildings.

NTNU'S CONTRIBUTIONS

- **Course Offerings:** In NTNU's International MSc programme on Sustainable Architecture courses are offered on topics such as "Zero Emission Neighbourhoods," reflecting the interdisciplinary nature of designing and planning sustainable communities. These courses provide knowledge and skills relevant to ZEN-related topics.
- **International Summer School:** Over several years the ZEN Centre co-organized a summer school course in time series analysis, with a focus on modelling and forecasting in energy systems. Henrik Madsen, adjunct professor at ZEN/NTNU and professor at DTU, was responsible for the course together with Peder Bacher, DTU.

EXPANDED RESEARCH HORIZONS

The international collaboration has significantly enhanced the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN) in several key areas. It has expanded research horizons by engaging with global partners which has allowed the ZEN Research Centre to incorporate diverse perspectives and expertise, enriching its research scope. Collaborations with institutions like the European Energy Research Alliance (EERA) have facilitated the exchange of knowledge and best practices in sustainable urban development.

Participation in international projects has provided ZEN partners with access to substantial funding and resources. For instance, leading the ARV project under the EU's Green Deal initiative has enabled ZEN to work on large-scale demonstration projects across Europe, focusing on climate-positive circular communities. Collaborations have accelerated the development and implementation of innovative solutions.

International partnerships have elevated ZEN Centre's profile in the global research community, positioning it as a leader in zero-emission neighbourhood research. This has opened doors for further collaborations and opportunities to influence policy and practice in sustainable urban development. International cooperation within the ZEN framework has also enabled NTNU and SINTEF to facilitate knowledge exchange and capacity building with academic and non-academic partners, including industry players, municipal governments, and policymakers. This enhances the ability to influence policy and practice on a global scale by providing evidence-based solutions and demonstrating the feasibility of zero-emission urban development through pilot projects.

Building International Relationships: The ZEN Research Centre has fostered long-term international relationships that extend beyond research projects. These collaborations build trust and deepen engagement between NTNU and international institutions, contributing to future cooperation in emerging areas such as smart city technologies, circular economies, and social sustainability.

In many cases, partnerships formed under ZEN have led to collaborative ventures with private sector companies, local governments, and NGOs, ensuring that sustainable solutions are not just theoretical but also applicable and scalable globally.

10. TRAINING OF RESEARCHERS

THOMAS BERKER
Professor NTNU

HENRIK MADSEN
Adjunct Professor NTNU
Professor DTU

Training of young researchers in the ZEN Research Centre was primarily conducted through a dedicated PhD course, which was offered to ZEN doctoral/PhD candidates but was also open to other doctoral candidates.

The course, which ran four times during the center's funding period, had one major goal: helping young researchers contextualize their work. To achieve this, two main approaches were used:

First, the center's interdisciplinary approach was discussed in relation to the PhDs' projects. Work package leaders presented their understanding of their contributions and discussed with course participants what a ZEN approach could be and how it differed from other approaches.

Second, the PhD candidates were encouraged to reflect on the societal context of their work through lessons taught by experts in urban planning, responsible research and innovation (RRI), and history. According to course evaluations, PhD students particularly benefited from the field trips organized as part of the courses, where the group visited ZEN pilot projects at Tempe and Evenstad and spoke with local representatives. Another positive outcome was that the courses helped ZEN PhD students develop a stronger sense of belonging to both the center and a group of young researchers with a specific ZEN identity.

Several of the PhD candidates also followed the international summer school on Time series analysis, with focus on modelling and forecasting in energy systems. The course was co-organized by the ZEN Research Centre, DTU, and the International Energy Agency (IEA) Energy in Buildings and Community (EBC); Annex 71 Building Energy Performance Assessment Based on In-situ Measurements, and Annex 81 Data-Driven Smart Buildings. The course contained several examples on the use of the methodologies for energy systems, smart buildings and cities.

Key learning outcomes for students included:

- to formulate and apply models for short-term forecasting in energy systems, e.g. for heat load in buildings and electrical power from PV and wind systems.
- to formulate and apply grey-box models – model identification-tests for model order and model validation, and advanced non-linear models.
- to achieve an understanding of model predictive control (MPC) and flexibility functions and indices using data-driven methods.

PhD candidates were further encouraged to participate at international conferences and to stay with international partners to connect to relevant leading international research groups and to broaden their network. Several of the candidates have also participated in international working groups, e.g. through the International Energy Agency (e.g. IEA EBC Annex 81 on data-driven smart buildings and Annex 83 on positive energy districts).

Master students were invited to participate in the research activities by posting ZEN topics on student and master thesis websites. Many students were also connected to the research activities by key researchers working in the center, as many of these also teach at the host institution, NTNU.

Recruitment. All postdoctoral and doctoral positions were announced openly through national and international job posting sites. Good MSc-candidates were encouraged to apply for the doctoral positions. Open positions were also announced through the researcher's network, i.e. though IEA annexes.

Employment of PhD-candidates. The ZEN Research Centre has 13 PhD candidates that have been hired after they completed their PhD degrees, as shown in the table below. Additionally, 4 candidates were hired before completing their PhD degrees (noted in parentheses). At the time of writing this report (January 2025), 14 candidates are still in the process of completing their PhD theses and are not yet employed elsewhere. Many of these are expected to complete their theses by mid/end of 2025.

Employment of PhD-candidates (number)							
By centre company	By other companies	By public organisations	By university	By research institute	Outside Norway	Other	Total
(1)	1		1	9 (3)	2		13 (4)

FROM A PHD STUDENT'S PERSPECTIVE

ANNE-LISE AAKERVIK, Communication Advisor FME ZEN

Energy efficient building design; care for people and environment

All the way from bachelor to master, and now to PhD, David Bjelland has focused on energy efficient buildings, architecture and sustainable design. For his PhD heritage buildings specifically have become part of the picture.

"My academic journey began in Germany, where I pursued a bachelor's degree in energy efficient design / building engineering, a field that bridges traditional architecture and sustainable engineering. This interdisciplinary approach suited my broad interests. I then specialized in facade design during my master's, focusing on both technical and non-technical aspects of indoor well-being."

His master's studies included collaborations with an industry partner and the work gained international exposure, which eventually led him to consider research opportunities abroad.

"My master's supervisor suggested Norway, and having visited Trondheim before, it felt like a natural choice

"I was born and raised in Augsburg, a large city in southern Germany. However, I have strong family connections to Norway, particularly on the West Coast. Growing up, I frequently visited Norway for vacations."

The fact that his father is Norwegian, made the move to Norway and work at NTNU feel natural to him. And then he found an interesting PhD position at NTNU, where he started focusing on retrofitting heritage buildings.

Why did you choose this field of study?

"I've always been interested in a wide range of topics, which is why I chose a field that combines technical and social aspects. Facade design, particularly the impact of daylight and indoor environmental quality on well-being, intrigued me. I wanted to explore how building design and building retrofitting can enhance the quality of life for occupants, balancing technical efficiency with human well-being."

What are you writing about in your thesis and why?

"My PhD research focuses on retrofitting heritage buildings, specifically the central building block on the NTNU campus in Trondheim. These buildings are protected due to their historical and cultural value, which adds complexity to the retrofitting process. My goal is to develop strategies that balance energy efficiency with heritage preservation", he says.

This involves creating digital models of the buildings, testing various retrofitting measures, and collaborating with heritage protection bureaus. The importance of this research lies in the need to include protected buildings in our energy reduction goals. Excluding them would ignore their great potential and lower our capability to meet current energy reduction targets.

Any thoughts about the future?

"Looking ahead, I see multiple paths. I could continue in academia, where there are interesting research positions, or move into industry or municipal roles where I can implement my ideas. My broad interest in energy design, simulations, and optimizations opens various opportunities. Regardless the path, I aim to contribute to sustainable building practices and energy efficiency."

Sustainable development: finding ways of using less materials and cut emissions

Lola Sylvie Annie Rousseau, originally from Nice, France, moved to Norway in Trondheim when she found that NTNU had a topic that really matches her growing interest in environmental impacts.

She was studying engineering and was looking for opportunities to further studies.

"And I came across a double degree program that allowed me to pursue a master's degree abroad. Norway caught my interest because of its strong programs in industrial ecology, which aligned perfectly with my growing interest in environmental issues and sustainable development. My partner's mother had lived in Norway, which also piqued our interest in the Nordic countries. We left our families behind in the south of France, and settled in Trondheim, where I completed my master's degree in industrial ecology."

Why did you choose this field of study?

"My interest in industrial ecology stemmed from a curiosity about how our society is built, the materials we use, and the resulting waste and pollution that often comes with it. The program at NTNU seemed like a perfect fit for these interests. It allowed me to explore these topics in depth and understand the environmental impacts of our built environment."

What are you writing about in your thesis and why?

"My PhD research focuses on the built environment, specifically looking at buildings, infrastructure, and mobility. I study the materials used in these sectors, their accumulation, and the associated greenhouse gas emissions. One of my studies involved mapping the global stock of road materials, collaborating with colleagues from the University of Toronto and MIT. Another study focused on the greater Oslo area, estimating material stocks in residential buildings, infrastructure, and vehicles, and projecting future material use and emissions scenarios. The goal is to identify strategies to reduce material use and emissions, such as improving material efficiency and decarbonizing production processes."

Lola really likes to study in Trondheim, and the town itself. "It is perfectly located when it comes to outdoor activities. I love hiking, and here it is easy to decide in the afternoon and soon you are out in the woods. We often go for overnight hikes, just bringing a tent and a sleeping bag. That is very easy from city center. As for my studies, I feel fortunate to have a group of fellow PhDs around me. We often do something social at work, having breakfast or lunch together, and there is always someone to ask. We are all in the same boat."

Any thoughts about the future?

"I plan to submit my thesis in early 2025 and hope to defend it later that year. Looking ahead, I am open to continuing in research, either in my current field or exploring new areas to gain additional skills and knowledge. Ideally, I would like to stay in Trondheim, but I am open to opportunities that come my way. I believe in taking life as it comes and being open to new possibilities, even if it can be a bit stressful at times. But first I need to finish my PhD," she says.

Solar neighborhood planning

With the aim of widening his horizons and improving his language skills, Matteo Formolli sought for a university outside Italy. The focus had to be architecture, technology and sustainability.

Matteo Formolli began his academic journey with a bachelor's degree in architectural design at Politecnico di Milano, a technical university that blends artistic and technical aspects of architecture. Realizing his strengths lay more in the technical realm, he decided to pursue a master's degree specializing in architectural technology and sustainability. His quest for broader horizons and enhanced English proficiency led him to explore international programs. "Among these, the Master's in Sustainable Architecture at NTNU in Norway stood out, not only for its academic rigor but also due to his fascination with Nordic countries" he recalls.

Originally from the Lombardy region in northern Italy, Matteo has always been surrounded by high mountains and a culture rich in skiing and hiking. His homeplace, Valtellina, is famous for its excellent hiking qualities and winter sports, something he also appreciate with Norway, and Trondheim.

Choosing the Field of Sustainable Architecture

Matteo's decision to specialize in sustainable architecture was driven by the growing importance of sustainability in the modern world. The international master's program in Sustainable Architecture at NTNU provided him with deep insights into life-cycle assessment, daylight, energy efficiency, and strategies for lowering the environmental impact of buildings. This focus on sustainability aligned perfectly with his interests and the global shift towards greener construction methods.

Solar Accessibility in Urban Areas

"During the master's program we got many insights into the Norwegian climate, the Norwegian building practice, and the principles of zero-emission buildings and neighborhoods. By the time I graduated, I felt I had acquired a lot of knowledge that would be highly valuable in the job market."

Matteo's interest in continuing his education in Norway stemmed from his desire to delve deeper into some of these topics. His master's thesis, which focused on daylight and solar energy production, laid the foundation for his PhD research.

His doctoral research investigates solar accessibility at the neighborhood level, a topic that combines his interests in solar energy and urban planning. He examines three urban spatial domains: outdoor spaces, building envelopes, and indoor environments. One of Matteo's primary goals is to develop an indicator that evaluates the solar readiness of neighborhoods, particularly in high-latitude regions like Scandinavia.

Looking Ahead

As Matteo approaches the completion of his PhD, he is also gaining practical experience working at a consultancy firm.

"I think that this dual engagement enriches my research with real-world insights and prepares me for future challenges in the industry".

Looking forward, Matteo envisions continuing his career in Norway, appreciating the country's nature and the professional opportunities it offers.

Exploring Sustainability and economic evaluation

Sara Sharbaf is a dedicated researcher with a passion for sustainability and architecture. Originally from Iran, Sara moved to Norway for PhD studies.

Sara completed her bachelor's in architectural engineering and Master's in Sustainable Architecture in her home country, Iran.

"During my master's degree, I was encouraged to continue my education by pursuing a PhD because I was among the top of the class. But, at that time, I really felt that I needed real-world experience. And that was the reason I spent a few years in industry, working as a sustainability advisor, which has enriched my understanding of sustainable architecture"

Wanted international experience

Her decision to pursue a PhD abroad was finally driven by a desire to experience an international academic environment.

"I wanted to go abroad to broaden my horizons, as it was really important for me to see how others think and approach their education outside my country."

Norway, with its strong focus on sustainability and innovative energy approaches, was a natural choice. Sara was particularly intrigued by how Norway manages its oil and gas resources sustainably, a stark contrast to the practices in her home country.

"And when I saw this PhD position, which combined sustainable practices and economic evaluation, I realized that it fits perfectly with my passion for sustainable efforts. It had a combination of all my passions in one position. And I still have this strong passion for economic evaluations because it's deeply connected to real-world challenges."

Her PhD research within the ZEN-center focuses on the intersection of building economics and renovation measures. Her work aims to highlight the uncertainties and ambiguities in economic calculations that often hinder sustainable practices in building design. By combining her industry experience with academic research, Sara seeks to investigate solutions that are both economically viable and environmentally friendly. Her thesis focuses on developing a framework for cost-benefit analysis of renovation measures in existing buildings, with a specific emphasis on achieving net-zero emission objectives. Her research also investigates the impacts of macroeconomic, microeconomic, and temporal parameters on the profitability of upgrading projects.

Balancing academic life and private life

"One thing that was really fascinating for me when I came here is the work-life balance. It was interesting to see how Norwegians respect quality time with their family, ensure they have spare time for personal activities, and how they concentrate on work during working hours. And it was also amazing to me that, at NTNU and in Norway, PhD candidates are treated as employees/regular staff in university, rather than students, as is common in other countries!"

Future Prospects

Sara will finish her PhD this spring and she is now contemplating her next steps. "I am open to opportunities in both academia and industry, valuing the unique experiences each sector offers. My goal is to contribute to a more sustainable future, whether through research, teaching, or practical application in the industry".

11. COMMUNICATION AND DISSEMINATION

ANNE-LISE AAKERVIK, Communication Advisor FME ZEN

Dissemination of research results beyond the confines of the research environment is important.

A communication strategy has guided our work in the ZEN Centre for the whole project period. It has been updated regularly, and our goal has been to reach out to authorities at all levels, neighborhoods, academics, construction companies and others that may take interest in our research. We have had an increased focus on communication in the last years of the centre. Since august 2022 a communication advisor was employed in a 90% position. Before that, communication was covered with an advisor working 30% with communication and dissemination.

From day one, we established a strategy for disseminating knowledge in various media forms. This has been e.g. through the website fmezen.no, which was created as a platform for presenting news, research/reports, ongoing projects, and interviews with key personnel. The website was first published in early 2018 in English only but got a makeover and a Norwegian translation in 2020. In 2022 we did a new makeover, making the Norwegian site the primary one.

The ZEN Centre has had three different social media channels over the years. Facebook, Twitter (X) and LinkedIn. We have used Facebook and LinkedIn for sharing stories, news and research results. After 2022 we decided to not prioritize Twitter/X since we had little time to use it properly and had little feedback.

Throughout the centre duration we have worked closely with the communication department at SINTEF Community, e.g. to increase capacity.

For our internal communication we have focused on lunch lectures from the start, where PhD candidates, researchers and partners have shared findings, publications and success stories. In June 2023 we arranged a "ZEN-day" with nearly all employees in Trondheim, planning the last year of the center.

We have arranged two communication courses for ZEN personnel, and three writing seminars for article writing and how to write debate posts.

As for partner meetings, we have had two meetings each year, one in May/June and one in October (except for the last two years where there was one yearly meeting). The partner meetings have been important to ensure a close dialogue about results and plans ahead.


Bodø 2022


Breakfast meeting at Asplan Viak16. February 2023

COMMUNICATING OUTSIDE THE RESEARCH COMMUNITIES

We have from the very start published a (almost) monthly newsletter to those who has signed up, internal and external. By 2024 we have approximately 400 subscribers.

For media features and popular articles, we have distributed press releases and provided media outlets with news and research findings. We have a service by Retriever that picks up the words FME ZEN and targeted names.

We have further pushed and encouraged researchers and PhDs to engage in the public debate and participate in e.g. podcasts. We have also arranged breakfast seminars together with our partners. From 2019 the Lunch Lectures have been open for everyone, announced through our webpage and by e-mail invitations.

We have participated three times at the "EUs Sustainable Energy Week" (EUSEW) in Brussels. The first time (in June 2018), we organized a seminar at the European Parliament, titled Accelerating the clean energy transition: The strategic contribution of zero emission buildings and neighborhoods. The second time, in 2022, we gave a speech and a presentation of the ZEN Centre. The third time in 2024 we arranged a workshop together with the related projects Syn.ikia and ARV as well as the Green Digital Finance Alliance. The topic was financial policy recommendations to speed up zero emission neighbourhoods across Europe. The workshop resulted in a joint publication.

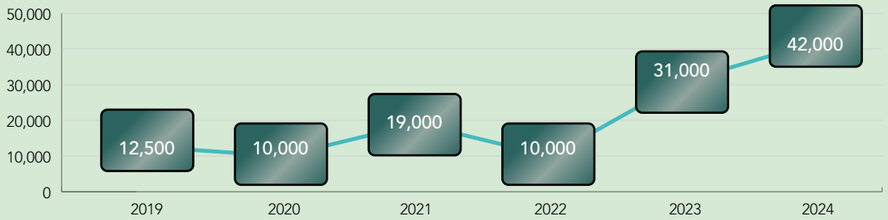
In March 2024 we were co-organizers of the first FME-conference "The FMEs as enablers in mitigating climate and energy challenges". We held a session together with FME HighEFF on the topic *Energy efficiency first! ... and how does it matter and give impact?*

We have arranged three ZEN-conferences over the years, the first in 2018, the second in 2021. In September 2024 the ZEN Centre arranged the third and final conference. 125 persons joined us at Scandic Fornebu and the conference was opened by the Minister of Local Government and Regional Development. The program gave highlights from the full length of the research period, and we also launched our four Policy Briefs. Key information about our outreach activities is noted below.

NUMBERS:

År	Partner workshops /seminars	Newsletter	Media features/ popular scientific articles (Retriever)	Lunch Lectures
2017:	16	10	10	
2018	19	29	96	19
2019	18	8	87	16
2020	4	11	40	10
2021	4 + 25 partnermøter	11	56	13
2022	11	23	33	8
2023	10	11	58	17
2024	8 (incl. Final Conference /breakfast- meetings)	10	44	13

PAGE VISITS OF FMEZEN.NO




13 TWh i 2030!
42 TWh i 2050!


BYGGFAKTA nyheter
VVS
Kategorier
Rapporter
Jobbmarkedet
eBlad
Aktuelt
– Det er viktig at forbrukerne får klare og gode anbefalinger til gode energiløsninger
9 april 2024


Byggenæringen ønsker å bli sirkulær, men har en vei å gå
Ire scenarioer for fremtiden


NemsTek 100 år
VENTILASJON
Nye anbefalinger for lavutslippsventilasjon i bygg


TU
Gi fem milliarder i året til energieffektivisering i bygg

12. EFFECTS OF THE CENTRE FOR THE HOST INSTITUTION AND RESEARCH PARTNERS

ARILD GUSTAVSEN
Professor NTNU

SIRI HUNNES BLAKSTAD
Executive Vice President
SINTEF Community

The research partners in the ZEN Research Centre have been The Norwegian University of Science and Technology (NTNU) and SINTEF. NTNU has participated with five faculties (Architecture and design, Engineering, Economics and management, Information technology and electrical engineering, and Humanities) and SINTEF with two institutes (SINTEF Community and SINTEF Energy).

By spanning across NTNU faculties, SINTEF institutes, and sector borders (e.g. building and energy), the ZEN Research Centre has contributed to building bridges and enabling inter- and multi-disciplinary research activities not possible without the Centre.

This collaboration has enabled taking on the ambition of developing zero emission neighbourhoods in smart cities, including the research areas needed in that endeavor. By applying an inter- and multi-disciplinary approach, the ZEN Research Centre has significantly contributed both to NTNU's and SINTEF's research strategies, e.g. by:

- Performing innovative research: ZEN Research Centre has spearheaded numerous innovative research projects focused on developing zero-emission solutions for buildings and neighborhoods. These projects align with goals of advancing sustainable technologies and practices.
- Interdisciplinary collaboration: As noted, the centre has fostered collaboration across various disciplines, including architecture, engineering, and social sciences. It has also connected new disciplines, like researchers addressing the energy sector with architects and building engineers. This interdisciplinary approach has enriched the research environment and promoted comprehensive solutions to sustainability challenges.
- Contributed to pilot projects and living labs: The ZEN Research Centre has implemented pilot projects and living labs that serve as real-world testing grounds for new technologies and strategies. These initiatives provide valuable data and insights, helping to refine and scale sustainable solutions, as well as connect academia with industry and public authorities.
- Developed global impact and partnerships: The ZEN Research Centre's work has positioned the research partners as leaders in sustainable building and urban development on the global stage. The centre's international collaborations and contributions to European sustainability projects have enhanced NTNU's and SINTEF's reputation and research impact.

In addition, NTNU has utilized research results in education programmes:

- Research results are integrated in e.g. the MSc program on Sustainable Architecture and has kept this study program up-to-date and popular even when tuition fees have been implemented in Norway, and other international programs have been forced to reduce their activity or end.

Overall, the ZEN Research Centre has played a crucial role in advancing NTNU's and SINTEF's research strategies by driving innovation, fostering interdisciplinary collaboration, and contributing to global sustainability efforts. The ZEN Research Centre has also contributed to lasting connections between research partners that will continue to work together also after the project has ended.

13. EFFECTS OF THE CENTRE FOR THE USER PARTNERS AND SOCIETY AT LARGE

ANN KRISTIN KVELLHEIM, Director ZEN Research Centre, Senior advisor, SINTEF
ANNE-LISE AAKERVIK, Communication advisor ZEN Research Centre

13.1 THE POTENTIAL FOR INNOVATION AND VALUE CREATION

Value creation from the innovations in ZEN can be achieved in various ways, as illustrated in the table below. For instance, innovations can be applied and further developed scientifically by various master's or doctoral students refining a tool. For society, it is important to put knowledge into use, which can be done e.g. by developing various courses and seminars, or new textbooks and studies. Furthermore, standardization and harmonization, for example by transforming the ZEN definition and guidelines into building design guidelines or a national standard, are important for dissemination and application of results. Research can also result in innovations that are significant for shaping new policies in the field. Commercial exploitation of innovations can include startups or products where rights are secured, for example through licensing agreements.

We have examples from all the different pathways in the ZEN Research Centre. In total, we have reported 31 research innovations in this report, but the total number of innovations are higher. In particular since there are examples that the ZEN Research Centre partners are further developing innovation ideas and results within their respective organisations.

NON-COMMERCIAL	VALUE CREATION
1. Further research and publishing • Masters, PhD & Post Doc positions • Scientific articles and books • Conference contributions • Reports • Repository (database, data, coding) • Open-source software (copy left) • Prototypes & demonstrations	Scientific
2. Education and transference of knowledge • Courses • Seminars/training/workshop (including industry /public sector) • Handbooks and textbooks • Other educational efforts & material	Societal
3. Standardisation & harmonizing • Evidence-based decision-making • Contribute to evolving ZEN definitions and KPIs • Contribution to respective research networks focused on ZENs	Technological + scientific
4. Policy making • Contribute to public policy making	Policy
COMMERCIAL	
5. Marketing an innovation • Spin off/start-up • Technology transfer • Licensing • Patent	Economic + technological
6. Consultancy service for further research • Use of results to solve specific client challenges	Economic + science

Exploitation pathways

13.2 INNOVATION AND VALUE CREATION

This is a short review of what is considered as some of the most important effects for the user partners and society

The ZEN definition and framework

The ZEN Definition is the formal description of what is meant with the term "zero emission neirbourhood", pointing not only to the ambition of net zero emission of greenhouse gases (GHGs) during a 50-year time horizon for a project, but also to a set of wider quality categories where a ZEN project is expected to perform: energy, power, mobility, urban form and economy. For each of these categories, we have developed performance criteria and Key Performance Indicators (KPIs), paying attention to the needs of project planners, designers and developers. Basically, this means that KPIs should be applicable in practice, allowing for access to project specific information and input data of sufficient quality, and giving output data and results that are useful for decision-making when applied to a given project. The ZEN Definition is a prerequisite for the realization of any neighbourhood project in reality, if its aim is net zero GHG emissions in parallel to becoming attractive also in terms of efficient and flexible energy use, avoiding high power peaks, ensuring attractive mobility and urban form qualities for users, at acceptable life cycle costs (see ZEN Report 62 on Zero Emission Neighbourhoods in Smart Cities - Definition, Key Performance Indicators and Assessment Criteria: Version 5.0).

In addition there are other definitions of highly ambitious building and neighbourhood frameworks. To ensure compatibility and a further outreach of our research, ZEN researchers have worked closely with ZEN partner FutureBuilt, to help develop their FutureBuilt ZERO criteria as well as their Circularity Index, which is assumed to highly influence the sustainability transition process for Norwegian buildings.

Using real-life projects to find the best solutions

In the ZEN Research Centre, we have used living laboratories (pilot projects) as a research method. In this way, research gets access to and are implemented in actual neighbourhoods, and partners and society can more easily take part in the research. Researchers will then also get feedback on the research more quickly. To begin with, it was unknown what the zero-emission ambition actually meant for a neighbourhood and the road has been formed along the way, gradually testing, evaluating and improving over and over again. The collaboration between the research and user-partners, as well as the results from this approach have been of significant importance. Towards the end of the centre period, we made a final evaluation report in which you can read more about the learnings from the pilot projects, where the key points are repeated here:

1. The importance of Stakeholder Coordination: Managing diverse stakeholders over long-term projects is complex, requiring skilled facilitation and conscious process design. Conflicting interests, especially in multi-owner projects, can pose challenges to aligning ZEN principles.
2. The Role of the ZEN Research Centre: Participation in a research centre such as the ZEN Centre helped the involved partners to establish ambitious project goals and be supported by early-stage planning, despite initial confusion over the evolving ZEN methodology. While the KPIs were helpful, practitioners expressed a need for national, unified guidelines for GHG calculations and assessment systems.
3. Collaboration and Learning: The ZEN Research Centre facilitated mutual learning between researchers and practitioners through a variety of arenas. Pilot projects were planned to be test arenas for new technologies. Researchers experienced that complex neighbourhood projects faced greater challenges to implement solutions, due to the number of people involved and changing requirements over time. The collaboration helped integrate ZEN principles into practice. From a partner's perspective there was sometimes a desire for even quicker application of research outcomes.
4. Technology and Market: The rapid pace of technological development sometimes posed challenges, as technologies sometimes become outdated during lengthy neighbourhood developments. Partners also highlighted the need for better financial planning and incentives to support the adoption of innovative, often costly, solutions.
5 Regulatory Challenges: Achieving ZEN ambitions was in several cases hindered by regulatory barriers, especially when it comes to renewable energy sharing. Changes to regulations are slow, and that it is currently necessary to work outside existing frameworks to demonstrate solutions was mentioned by partners.
6. Political and Financial Support: Strong leadership, political will, financial incentives, and skills of involved personnel, were emphasised as essential for maintaining ambitious ZEN goals in long-term planning. Interviewees called for

clearer regulatory frameworks and political courage to drive change in the building sector.

7. Community Engagement: Effective communication and community involvement are crucial for fostering acceptance and participation. The Living lab activities found that people were often not sufficiently involved in the changes planned in their neighbourhood and did not fully understand the goals of the ZEN framework. Some partners stated that activities and educational tools like games helped raise awareness of ZEN principles, and pilot projects served as inspiration for broader market adoption.
8. High Costs and Economic Challenges: Costs were named as a major challenge to choosing ZEN solutions. Better incentives and business models were emphasized as necessary to support innovation and secure long-term commitment to solutions such as ZEN.

The energy-saving potential of the Norwegian building stock

Throughout the lifetime of the ZEN Research Centre there have been several studies exploring the energy-saving potential of the Norwegian building stock. Even though the methodology has varied slightly, the various studies have shown substantial energy saving potentials towards 2030 and 2050. In the most recent study we analyzed two scenarios: The Baseline and Ultra Green scenarios. The Ultra Green scenario shows significant energy savings with ambitious measures, including efficient heating technologies and solar power. The Baseline scenario shows that a continuation of the current trends leads to total added energy increasing by 2 TWh from 2020 to 2030 and by 4 TWh from 2020 to 2050. The Ultra green scenario shows that total delivered energy is reduced by 13 TWh (15%) from 2020 to 2030 and by 40 TWh (48%) from 2020 to 2050. In the same periods, purchased electricity is reduced by 13 TWh (19%) and 42 TWh (60%). However, the difference between the two scenarios shows that the potential will not be realized by a continuation of current trends. The report recommends clear goals, financial incentives, green loans, and regulatory alignment to achieve these targets. It also suggests additional measures for long-term energy efficiency improvements. The study was presented at Arendalsuka 2023.

Energy system transformation and energy flexibility

The Norwegian power system faces significant challenges in the transition to a fossil-free society, driven by the electrification of transport and industry. To meet the growing need for renewable energy and transmission capacity, energy efficiency and increased use of energy flexibility of buildings and neighbourhoods, heat pumps, and district heating, can be crucial. These topics have received continuous attention during the eight-year-duration of the ZEN Research Centre.

Energy flexibility refers to the ability of a building or neighborhood to activate its local sources of flexibility (building thermal mass, thermal storage tanks, batteries, electric

vehicle charging), while meeting the needs and comfort of its users. The ZEN Research Centre has demonstrated practical implementation of advanced control systems, such as model predictive control (MPC), in various real buildings. This includes the ZEB Living Lab (experimental house in Trondheim), the ZEB laboratory (office building in Trondheim), a school in Trondheim, a school in Ydalir, and office buildings in Evenstad and Oslo. The experiments showed how the thermal mass of buildings can act as a "thermal battery" to reduce power load and contribute to consumer flexibility. Up to 80% of energy use could be shifted away from peak load periods in the electricity grid, while maintaining user satisfaction. Furthermore, experiences from the ZEB laboratory have been documented in preparing building automation systems for energy flexible operations. Such preparation in building automation is crucial for large-scale use of MPC. By leveraging the flexibility of existing systems and integrating new data technologies, buildings can become active participants in energy markets.

One study shows that increased use of district heating can reduce total electricity consumption and especially peak load demand. Without these measures, electricity demand will increase by 3% by 2030 and 7% by 2050. Maximum use of district heating can keep electricity demand stable at 2020 levels, with a reduction in peak load demand of 1% by 2030 and 5% by 2050. Combining maximum use of district heating in urban areas with ambitious energy efficiency and heat pumps in the district, total electricity demand can be reduced by 12% by 2030 and 26% by 2050, while peak load demand can be reduced by 17% and 35%, respectively. The results are important for all actors in the energy system, as they show that investments in energy efficiency can reduce the need for new power generation and transmission capacity, while saving nature from unnecessary interventions.

13.3 POLICY BRIEFS FROM ZEN

Towards the end of ZENs project period, we identified core areas where we have a particularly strong foundation in our research to make well-funded, solid recommendations.

The core areas identified were: 1) How to use GHG calculations to affect regulations, politics, standards and area planning? 2) From pilotprojects to common property: Implementation and upscaling of zero emission neighbourhoods. 3) How to exploit the energy efficiency potential of buildings and neighbourhoods? 4) Smart ventilation with low emissions that gives comfortable and healthy buildings.

These core areas have been developed into policy briefs that have been presented broadly at events and in media. The findings can be summarized as such:

1. *GHG-calculations:* This policy brief from FME ZEN emphasizes the importance of integrating greenhouse gas (GHG) calculations into regulations, policies, and planning to achieve Norway's climate goals for 2030 and 2050. It highlights the need for stricter GHG requirements in building regulations, improved methodologies for GHG calculations, and better use of these calculations in area projects. The brief identifies current challenges, such as weak incentives in existing regulations and inconsistencies in calculation methods. It recommends specific actions, including revising technical regulations to include more building types, establishing a national GHG database, and developing a national roadmap for energy use and emissions in buildings. The brief also stresses the importance of early-phase planning and clear communication of GHG calculation results to various stakeholders.

HELGE BRATTEBØ
Professor NTNU

2. *Implementation and upscaling:* The policy brief "From pilot-projects to common property" emphasizes the urgent need to reduce energy use, greenhouse gas emissions, and improve energy security through the development of zero-emission neighborhoods (ZEN). It highlights the potential to save 40 TWh of energy in Norway's building sector by 2050, which can be redirected to other sectors. The brief identifies barriers such as lack of knowledge, high costs, conservative regulations, and insufficient leadership. Recommendations include creating a clear regulatory framework, providing financial support, enhancing education and training, and fostering innovation. The brief also stresses the importance of integrating buildings with energy systems to reduce peak loads and improve resource efficiency.

INGER ANDRESEN
Professor NTNU

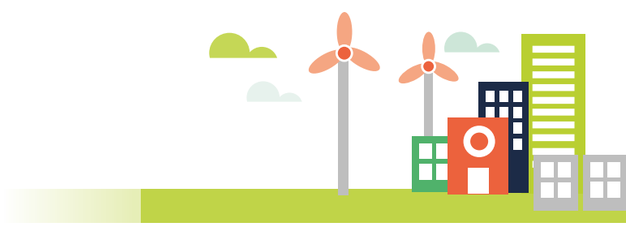
3. *Energy-flexibility in buildings and neighbourhoods:* This policy brief from FME ZEN emphasizes the importance of flexible energy use in buildings and areas to support a renewable energy system. It highlights the need for buildings to adjust their energy consumption to match the availability of renewable energy sources like wind and solar power. Recommendations include adopting current and new control solutions for energy flexibility, improving energy efficiency, and using district heating. The brief also suggests providing clear price signals to consumers and coordinating flexibility solutions at the neighbourhood and city levels. It stresses the role of technology providers, policymakers, and energy companies in facilitating these changes. The goal is to enhance energy flexibility to reduce emissions, improve energy security, and support the transition to a sustainable energy system.

ÅSE SØRENSEN
Senior scientist,
SINTEF

4. *Smart ventilation with low GHG emissions:* The policy brief from FME ZEN emphasizes the importance of smart ventilation systems with low carbon footprints to ensure healthy and comfortable buildings. It highlights the need to reduce CO_2 emissions from ventilation materials and improve energy efficiency through digital transformation. Recommendations include integrating material emissions into ventilation design, using advanced sensor technology, and adopting AI for better air quality management. The brief calls for regulatory changes to support innovation and the development of low-emission ventilation products. It also stresses the importance of coordinated efforts at the European level and the need for more research and pilot projects to optimize ventilation systems for both energy efficiency and indoor air quality.

LAURENT GEORGES
Professor NTNU

The policy briefs can be read in full (Norwegian only) on the project website: https://fmezen.no/policy-brief/



13.4 SUCCESS STORIES FROM THE PARTNERS IN FME ZEN

On a general note, our partners have found the partnership in the ZEN Research Centre useful, and networking has been highlighted as a particular advantage (both between user partners and user partners and researchers). Ambitious actors that do not normally meet and talk, have found an arena for this through the ZEN Research Centre. This is of pivotal importance when we are going to solve the complex challenges we are facing. Many partners are focused on commercial developments that the partnership can lead to, but innovation has many forms. You can read what user partners say about innovation and important effects in selected interviews below.

PARTICIPATION HAS PROVIDED VALUABLE INSIGHTS AND RESULTS

Norsk Fjernvarme has been a partner since 2018 and sums up the time in FME ZEN as fruitful and result oriented.

"It is important for the district heating industry to have research communities backing them to clarify the opportunities and challenges to central authorities and decision-makers. It is precisely the breadth and discussions that give the results greater value – and through that we will be able to contribute to real change Norsk Fjernvarme has important work ahead to highlight district heating as an energy carrier Norway cannot do without. In the work towards politicians, we need facts that support the importance of changes around framework conditions.", says ODA THERESE GIPLING, general manager Norsk Fjernvarme.

Important and necessary to be part of FME ZEN

Participation has provided valuable insights and results, especially through the shorter case research courses. It is incredibly important that an eight-year FME can extract research results along the way – and examine very specific relationships. For example, the research report on the power and power saving potential of the existing building stock by replacing direct electric heating with hydronic solutions was particularly valuable.

In many ways, it was absolutely necessary for us to be part of FME ZEN, as the development in energy and power use in the country's building stock is central for urban energy players like our members. The challenges of energy use in buildings are not only solved in the individual building, but also through interaction with other buildings, the surroundings and the energy systems, where the whole is central.

Buildings play an important role in relieving the power grid

The building sector's increasing concern with power challenges has obviously contributed to FME ZEN. This must be built upon. Own production of energy is important – but perhaps even more important is that the production actually meets the need when it arises, whether it is one's own need or the system's needs.

Buildings can play a key role in relieving a strained power grid by shaving their own power peaks and utilizing renewable energy other than electricity. This is also a key point in the public debate. This can be done either in the building or through connection to city systems.

Reuse of energy

The message of using the right energy at the right time is easy to link to our climate goals. When we have neither enough power production nor enough grid capacity for the necessary electrification of the large share of fossil energy that society still uses, it is absolutely crucial that we also reuse energy and utilize renewable energy other than electricity. The indirect fossil phase-out this contributes to is essential for us to achieve more of everything, but faster, as the Energy Commission requested.

This is an edited version of the interview published in FME ZEN's annual report for 2023.

DEMAND FOR HIGHER ENVIRONMENTAL REQUIREMENTS

FME ZEN helps to make it easier to translate research into practice, says LEIF ØIE, Division Director at GK. He wants more bold builders who test new solutions, and authorities who set stricter environmental requirements.

"FME ZEN is an example of something we need more of; a close collaboration between academia and the construction industry in order to quickly use research and new knowledge," says Leif Øie.

GK has broad expertise in ventilation, electrical, plumbing and energy technology. They work with everything from consulting and design to installation, operation and service.

How is the innovation competence in your organization?

"Interest and commitment are high. We experience some frustration because it is demanding to gain acceptance for the most sustainable solutions with customers. We would like to see the builders be a little bolder and dare to apply new knowledge earlier. In addition, the authorities could set stricter environmental requirements, and the market would adapt accordingly". He thinks the bureaucracy is too unambitious when it comes to the willingness to make changes that make a difference.

Calculator for CO_2 footprint

Øie is concerned with finding solutions to a well-known challenge, translating research into practical knowledge. There are several barriers here.

"It may be that the researchers have not focused on the problem correctly, or that the language is so academic that it is difficult to understand for those who are not researchers themselves. FME ZEN is helping to correct this. The case scheme is one of the things I would like to highlight that works best."

GK received good help from the scheme in connection with calculating the CO_2 footprint of a planned new building. "We had a researcher with us who worked with our people. In a short time, we made the calculator and put it into use".

Wants to be a role model on climate

Øie says that being a partner has also given them access to good ideas and inspiration that they can benefit from in already existing projects. GK has the ambition to be a role model for climate in the industry. They have been inspired by FME ZEN to create alternative, more climate-friendly offers for the builders.

"One way to do this is to use the calculator to find out what the project means for the CO_2 footprint. When we have to deliver a quote to a builder with a price and description, we also make an alternative offer that is more sustainable. We are used to thinking about money and progress, but not used to dimensioning the CO_2 footprint, it is still immature in the industry".

This is an edited version of the interview that was published in our 2023 Innovation report.

INFLUENCING FRAMEWORK CONDITONS

One of the best things about FME ZEN has been the ability to quickly put new solutions into commercial operation, says SVEIN OLAV MUNKEBY at NTE.

"For our part, it's about the opportunity to quickly translate research into commercial solutions for our customers. It has been a great value for us to participate in FME ZEN, and we have tried to contribute with the energy expertise we have so that others can benefit from it," says Munkeby.

NTE's ambition is to make Trøndelag climate-neutral and digital, and produces, distributes and sells renewable energy in addition to building fiber infrastructure with associated content services.

FME ZEN has influenced framework conditions in the industry

Munkeby has been on the board of FME ZEN, and has also been chair of the innovation committee in the centre.

"When you enter a research center, there are always many pilot projects. This is important, but the most important thing is that the knowledge from the pilots is applied. I think we can move much faster from research to realization of good and sustainable solutions for our customers; who, after all, are the ones who will contribute to us reaching a zero-emission society".

He believes that the collaboration in FME ZEN has helped to influence the framework conditions in the industry. A positive change is that it is now possible to share energy between buildings. Those who have paved the way here are customers and partners of FME ZEN, and not political authorities.

The world's first zero-emission area

NTE has participated in one of the national pilots that deals with the zero-emission farm at Mære agricultural school together with Trøndelag County Municipality. This has provided useful knowledge on how to design and implement energy efficiency measures in an area with many existing buildings.

According to Munkeby one of the best things about being a partner in FME ZEN is the experiences you share with other partners and the networking. The collaboration can also be taken out of FME ZEN, as they have done in an exciting innovation project with Skanska (also a partner in ZEN).

"Together with Skanska, we are in the process of realizing what will be the world's first zero-emission area. There is a new residential area in Trondheim where there will be 200 housing units that produce more energy than they use.

Also a lot of invisible innovation

Another partner from FME ZEN with whom they have started a collaboration is the housing cooperative TOBB.

"We have established a joint energy company with the housing builders' association TOBB where we will jointly assist housing companies in producing their own energy in combination with various energy efficiency measures. That would not have happened if we had not collaborated with FME ZEN. One should not forget that there is a lot of invisible innovation that has also come out of the centre".

This is an edited version of the interview that was published in our 2023 Innovation report.

SHARING KNOWLEDGE ABOUT ENERGY EFFICIENCY

NVE has benefited in several ways by participating in FME ZEN. "Sharing of knowledge around energy efficiency for example has been very important for our work", says HANNA TYSSELAND SKULSTAD, Senior Engineer, Section for Energy Use and European Framework Conditions, NVE.

"FME ZEN's sharing of knowledge in the energy field has helped to lift and nuance the public debate. Among other things, about energy efficiency, energy use in the building stock, the interaction between heat and power, and building-integrated solar cells. FME ZEN has presented exciting reports on potentials, barriers and costs. It has helped to increase society's interest in energy efficiency and has been a useful contribution to NVE's work to promote efficient use of energy. Knowledge that has been produced and shared in the centre is useful in NVE's work with regulatory formulation and analyses".

- What is the most important lesson you take away from FME ZEN?

Important knowledge about opportunities to trigger energy efficiency and consumer flexibility, with associated barriers. The collaboration with the + city exchange project and other user cases has also provided knowledge about practical and regulatory challenges in energy sharing. It is also an important lesson that those who take the lead in the development of zero-emission areas encounter challenges at many levels, from regulations and interpretation of regulations to practical implementation in the construction phase and technical challenges.

We will also highlight good professional discussions on model development with participants in FME ZEN, and the use of power profiles for district heating from Profet, among other things.

- What would you highlight as the most important success factors through the partnership in FME ZEN?

FME ZEN has been an important meeting place for committed actors who want to contribute to more efficient use of energy, and reduced greenhouse gas emissions. Regular workshops, lunch seminars and newsletters have been useful for making contacts and keeping up to date with the latest research. The physical meeting points have been important for discussions and knowledge sharing.

Up-to-date professional knowledge is important for the work we do at NVE. We regularly invite research groups and others to present new research or provide professional input. Participation in FME ZEN has made it easier to pick up new exciting research that is relevant to NVE. A short distance to the research communities and the industry makes it easier to get in touch with relevant actors and subject experts if needed.

SKANSKA: WE ARE ON THE RIGHT TRACK WITH ZERO EMISSION NEIGHBOURHOODS

Being part of FME ZEN has been instructive and confirms that Skanska is on the right course when it comes to the development and construction of buildings with low greenhouse gas emission.

The breadth of the research work that FME ZEN is obliged to cover, means that we as a project developer and contractor have made some strategic choices about where we believe we can contribute in the best possible way. We have therefore chosen to focus on energy supply and solar power production with exchange within and out of an area. A lot of good work has been done under the auspices of ZEN in these areas, which we have benefited from, says **TORE WIGENSTAD**, chief advisor for Skanska Teknikk.

For Skanska, it has also been important to highlight the importance of energy efficiency in the building stock and what this contribution can represent in terms of energy savings up to 2050. The energy saving potential is significant, but it will not be solved by itself. The authorities must dare to impose higher climate and environmental requirements on industry, for example in the form of national guidelines at regulatory level. At the same time, they must also offer incentives through good, targeted support schemes that make it more profitable to develop and build more climate smart.

What is the most important lesson you take away from FME ZEN?

It has been particularly interesting to gain increased knowledge and a better understanding of how the interaction between buildings within an area can function in a more climate-smart way.

And what would you highlight as the most important success factors through the partnership?

In general, networking is another aspect that is important to highlight. Although we at Skanska already have a close and good relationship with both SINTEF/NTNU and several of the partners, it is important to cultivate collaboration over time in projects like this. For Skanska, participation is first FME ZEB, then FME ZEN, important to highlight our sincere willingness to contribute to a more energy-efficient industry. Being part of FME ZEN has been instructive and confirms that Skanska is on the right course when it comes to the development and construction of buildings with low greenhouse gas emissions.

FME ZEN has a broad scope, but we have mainly concentrated on gaining experience and working on examples of the cost-benefit element for zero-emission areas in smart cities. We are now working to bring knowledge and lessons into our projects.

FME ZEN HAS THE IN-DEPTH EXPERTISE THAT COMPLEMENTS OUR KNOWLEDGE

The best practise projects in FutureBuilt must be innovative, socially and ecologically sustainable, and of high quality. With the help of FME ZEN, they have developed criteria that measure how sustainable and innovative they actually are.

"The fact that we are a partner in FME ZEN and have NTNU and SINTEF on the team gives us both credibility and knowledge," says **STEIN STOKNES**, program manager at FutureBuilt.

FutureBuilt is an innovation program for the most ambitious in the construction industry. So far, they have realized around 70 out of 100 best practice projects, both urban areas and individual buildings, that exceed the UN's sustainability goals and the Paris goals. They also require that greenhouse gas emissions must be 50 percent below what is normal.

Access to in-depth expertise

FutureBuilt is involved in several of the pilot projects in ZEN.

"Through FME ZEN, we gain access to in-depth expertise to develop methodologies and tools that can quantify and document what we are doing. It has been particularly useful in relation to developing our criteria," says Stoknes.

For FutureBuilt, it is crucial to focus on quality criteria that are central to the development of sustainable cities. The criteria indicate a level of ambition that is higher than what the usual Norwegian standard and statutory requirements indicate. An example of a criterion is FutureBuilt ZERO, which is about reducing greenhouse gas emissions from energy use and material use in buildings. Examples of other criteria are social sustainability and innovation.

FutureBuilt works with circular buildings, and Stoknes points out that they have also received assistance from ZEN to develop FutureBuilt Circular, a method that quantifies the degree of circularity in buildings.

Tightens requirements

The vision of FutureBuilt is to show that it is possible to develop a sustainable and attractive zero-emission city.

Has the partnership contributed to any innovations that have changed your way of working, or provided other benefits?

"We are an innovation program so innovation is something we think about all the way, but yes, it is a fruitful collaboration and a way to push innovation. Norwegian industry standards often lack innovation and forward-leaning and can also act as a hindrance by being updated too rarely. But by joining forces and showing that we take the climate and environmental goals seriously, it may be easier to be heard and the requirements to be tightened.

This is an edited version of the interview that was published in our 2023 Innovation report.

CONCRETE WITH CARBON CAPTURE – REALIZATION OF SORIA MORIA

After almost 20 years of research and development, Heidelberg Materials in Brevik will be the world's first cement factory to produce cement with carbon capture and storage (CCS) from 2025.

"We are proud to be the first to be able to produce cement with carbon capture and storage. The entire industry will benefit from this," says **VETLE HOUG**, Managing Director, Heidelberg Materials Sement Norway AS, which is also a partner in FME ZEN. "For our factory in Brevik, it means that we cut a significant part of our own emissions, approx. 400,000 tons a year, which accounts for close to 50 percent."

In what way has knowledge developed in FME ZEN benefited Heidelberg Materials?
"Heidelberg Materials has used the case scheme actively in FME ZEN and through several cases/projects we have received good value for being part of ZEN. We have explored different business models for financing and implementing CCS products. This has provided an important understanding of how Heidelberg should introduce the products to the market and find good financing models. In addition, two master's students from NTNU/FME ZEN have investigated the willingness to pay for the various cement products that Heidelberg Materials can offer."

What are the most important lessons you take away from FME ZEN?
"The most important lesson is the understanding of how to develop and introduce low-emission products into the market, as well as the importance of finding good financing models. The level of knowledge and network within the LCA environment in ZEN has also been very important for participation in the center."

What would you highlight as the most important success factors through the partnership in FME ZEN?
"The most important success factors include the collaboration with academia and industry, the development of business models for CCS products, and the broad contact with various partners in ZEN, especially on the client side in the public sector. It has been important for us to make contacts in a wider part of the market"

The Brevik cement production site

POWER OF CO-CREATION AND COLLABORATION

Close collaboration with different stakeholders is one of the success factors for partner Snøhetta in our work with FME ZEN, says TONJE VÆRDAL FRYDENLUND, Director of Operations, Snøhetta.

The ability to collaborate closely with a diverse range of stakeholders, including researchers, industry partners, and public authorities, has been crucial. This collaboration has facilitated the exchange of knowledge and expertise, leading to inspiring results and innovative solutions. Working with researchers and building industry partners has enabled the sharing of diverse perspectives and expertise, resulting in more comprehensive, realistic, and effective solutions. The power of leveraging in-depth knowledge fosters innovative thinking and opens up new possibilities.

Collaboration & building relations

Unfortunately, Snøhetta has not been directly involved in the development of the pilot projects as we were in our FME ZEB partnership. We had higher hopes and expectations when entering the research collaboration and have not achieved as much as we anticipated. We have, however, participated in case studies and tested the tools and definitions in other project involvements during the same period. Personally, as a board member through eight years, I have had the pleasure to follow the research center more closely which has provided valuable insights, learnings, and relationships that I will bring forward to future-proofing our upcoming projects.

Access to Cutting-Edge Research and knowledge sharing

Being part of FME ZEN has provided access to the latest research and technological advancements, enabling us to stay ahead in our respective fields and implement state-of-the-art solutions. Snøhetta are pioneers in developing carbon neutral projects with cutting-edge architecture and design. To maintain our leading position, we must engage with the best expertise, experience and knowledge to design innovative solutions.

Staying updated with the latest research has been crucial for maintaining our competitive edge over several years, ensuring that the solutions we design, and implement are based on the most current and effective technologies and methodologies. Continuous knowledge sharing has been a key aspect of our collaboration.

The support from FME ZEN in terms of professional advice, regular research updates, and the development of tools and methodologies has been integral. The knowledge transfer from these eight years of research excellence will continue to play an important role in the transition to a low-carbon society. Industry partners naturally have a greater sense of urgency than researchers, yet this dynamic accelerates the focus on finding realistic solutions that will influence the low-carbon transition. Testing and refining solutions in real-life settings through various case studies have provided more rapid insights and feedback, ensuring that the technologies and methodologies developed are practical and effective.

Takeaways

The ZEN Research Centre has been a beacon of interdisciplinary research, bringing together experts from NTNU, SINTEF, and 28 partners to address some of the most pressing energy and climate challenges of our time. Our collective efforts have resulted in groundbreaking solutions that optimize energy use, enhance living and working environments, and contribute to developing neighborhoods more resilient to climate change.

As we conclude eight years of research, the journey towards a sustainable future is far from over. We will bring the knowledge, tools, and methodology frameworks developed by the FME ZEN Research Centre into our future initiatives, ensuring that we achieve more advancements, than we would have been able to alone and without these insights.

Our takeaways from 16 years of partnership in FME Research Centers (ZEB and ZEN) are the value of common goals and ambitions, and the power of co-creation among transdisciplinary experts and diverse stakeholders to achieve these goals. We're stronger together!

13.5 FEEDBACK FROM OUR PILOT PROJECTS

Pilot projects in the ZEN research centre are real-life development projects. During the lifespan of the ZEN research centre, we have worked with a total of 11 pilot areas. The partners running these projects have committed to adopt ZEN as the ambition level of their project. In this section you can read how some of our pilots have experienced being a part of FME ZEN.

BODØ MUNICIPALITY:

IMPROVES COMPETENCE AND KNOWLEDGE REGARDING ZERO-EMISSION SOLUTIONS

EIRIK LERUM VIGERUST:
"Participation in FME ZEN has significantly increased our competency within the organization. We've learned a lot and managed to stay aligned with the project's goals due to the knowledge we've acquired. Many relevant departments within the municipality now understand what ZEN is, and the zero-emission ambition is well integrated into our environmental and climate plans. We've drawn inspiration and knowledge from ZEN in developing these plans."

KRISTOFFER SEIVÅG:
"The partnership with FME ZEN has been broadly positive, although it took some time to understand what ZEN could contribute and what we needed as a municipality. Initially, we didn't fully grasp the potential benefits. Over the years, we've engaged in many processes, and it hasn't always been easy to stay connected with the researchers' work. However, the ambition to define zero-emission neighbourhoods has helped us stay focused and integrate these concepts into all our plans, which has gained political support."

IMPORTANT RESULTS FOR BODØ KOMMUNE

New Processes, Products, and Services:

- Development of energy solutions for the new district through feasibility studies and real projects.
- Utilization of the "Into Zero" digital tool for area mapping in collaboration with Asplan Viak.
- Integration of zero-emission concepts into the municipality's environmental and climate plans.

Strengthened Networks and Collaborative Relationships:

- Increased collaboration with consulting companies and technology providers.
- Establishment of the Competence Forum (Kompetanseforum) a collaboration between the local construction and engineering industry, businesses, consultants, and politicians.
- Enhanced engagement with residents and end-users through open meetings and public involvement initiatives.

Other Positive Outcomes:

- Improved competency and knowledge within the municipality regarding zero-emission solutions.
- Greater societal benefits by preparing for future sustainability requirements.
- Better communication and understanding of climate and economic costs among politicians, leading to more informed decision-making.

BYBO AS:

BEING A PART OF FME ZEN HAS BEEN A SIGNIFICANT JOURNEY FOR US

THORBJØRN HAUG:
"We've been involved since the days of FME ZEB, and our focus has evolved from building-specific solutions to area-wide strategies. This shift has allowed us to develop a comprehensive sustainability strategy. The collaboration has provided us with valuable insights into energy solutions, production, and storage, which are crucial for our projects at Ådland and Dolvik."

KJETIL HELLAND:
"The complexity of the themes we tackled was much greater than we initially anticipated. Working with FME ZEN has taught us a lot about optimizing energy use and creating incentives for low energy consumption. The partnership has also helped us navigate regulatory challenges and develop new business models that could make sustainable housing economically viable. The legitimacy and support from FME ZEN have been instrumental in advancing our projects and ambitions."

IMPORTANT RESULTS FOR BYBO AS

New Processes, Products, and Services:

- Development of energy solutions for housing projects, including energy production and storage.
- Implementation of strategies to optimize energy use and reward low energy consumption.
- Creation of a sustainability strategy based on learnings from FME ZEN.

Strengthened Networks and Collaborative Relationships:

- Enhanced collaboration with energy companies like BKK.
- Participation in forums and partnerships with shared sustainability ambitions.
- Increased engagement with researchers and other stakeholders in the housing and energy sectors.

Other Positive Outcomes:

- Improved understanding of regulatory frameworks and how to navigate them.
- Greater legitimacy and support for sustainable housing projects.
- Valuable knowledge that has helped refine project planning and execution.

BÆRUM MUNICIPALITY:

THE CHALLENGE OF ORDERING AND IMPLEMENTING INNOVATIVE SOLUTIONS

KAREN GUNLEIKSRUD:

"Being a part of FME ZEN has been incredibly valuable for Bærum kommune. The ZEN goals were integrated from the very beginning, which significantly influenced our decisions in developing the Fornebu area. The interdisciplinary approach and access to updated research and professional knowledge have been important in our planning processes. For example, the Flytårnområdet pilot has benefited greatly from the insights and data provided by ZEN researchers."

CAMILLA BAKKEN TORP:

"Our first major project, the Oksenøya centre, has been a learning experience. While the technology we used was already established by 2016, the challenge was in ordering and implementing innovative solutions. The collaboration with ZEN has helped us understand the complexities of integrating advanced technical systems and has provided us with the expertise needed to maximize their potential. Additionally, the focus on reducing car usage and implementing green solutions has been a direct result of our partnership with ZEN."

IMPORTANT RESULTS FOR BÆRUM KOMMUNE

New Processes, Products, and Services:

- Installation of a large photovoltaic system at Oksenøya, enabling energy exchange between buildings.
- Implementation of green roofs, low-carbon concrete, and timber constructions.
- Conducting greenhouse gas calculations at a master planning level for the first time.

Strengthened Networks and Collaborative Relationships:

- Formation of an interdisciplinary group with a zero-emission mindset from the start.
- Collaboration with FutureBuilt, contributing to achieving sustainability goals.
- Engagement with ZEN researchers for professional input and data analysis.

Other Positive Outcomes:

- Increased focus on zero-emission goals in all planning processes.
- Preservation and integration of historical buildings, such as the fire station at Flytårnområdet.
- Enhanced ability to argue for and implement sustainable solutions, providing a driving force for future projects.

ELVERUM MUNICIPALITY:

GREATER AWARENESS AND INVOLVEMENT IN ENVIRONMENTALLY FRIENDLY URBAN DEVELOPMENT

ANNA-THEKLA TONJER, CEO of Elverum Tomteselskap AS

"Being part of FME ZEN has provided us with credibility, networks, and competency building. Although we didn't initially plan to join, the partnership has been crucial. It has allowed us to raise our ambitions for the Ydalir project and provided us with professional assistance to tackle the challenges we face. The collaboration has also increased awareness around zero-emission buildings and areas within the municipality."

HEIDI ERIKSTAD, Project manager, Elverum Vekst AS

"We initially thought the center would act as an advisor with ready answers, but we soon realized that it is a research centre, and there are no ready answers. The partnership has given us a stronger foundation for discussions with other professionals and has committed us to our goals and made us more confident in our mandate for Ydalir. It has also influenced the focus of the ZEN centre, bringing more attention to social values and the importance of people and surroundings in successful neighbourhoods."

IMPORTANT RESULTS FOR ELVERUM KOMMUNE

New Processes, Products, and Services:

- A focus shift from all technical solutions to focus on people in the development process.
- Implementation of zero-emission strategies in the Ydalir area, raising the project's ambitions.
- Utilization of ZEN's definition report and process tools for urban development.

Strengthened Networks and Collaborative Relationships:

- Building networks with other municipalities and stakeholders interested in zero-emission solutions.
- Increased collaboration with researchers and professionals in the field of sustainable urban development.
- Enhanced engagement with the community and visitors interested in learning about the Ydalir project.

Other Positive Outcomes:

- Greater awareness and involvement in environmentally friendly urban development.
- Improved competency and confidence in discussing and implementing zero-emission strategies.
- Influence on the ZEN centre's focus, incorporating more social values and human-centric approaches in urban planning.

TRØNDELAG COUNTY:

GAINED SIGNIFICANT INSIGHTS INTO ZERO-EMISSION AREAS AND SYSTEM BOUNDARIES

TOVE H. JYSTAD, Leader of Grønt Kompetansesenter Mære – Skjetlein
"Being a part of FME ZEN has been incredibly beneficial for Mære Agricultural school. We have gained significant insights into zero-emission areas and system boundaries, which are crucial for our goal of becoming a zero-emission farm. The collaboration has provided us with expert advice and research support, helping us understand complex concepts like life cycle analyses and energy consumption. This partnership has also allowed us to develop educational tools like the Climate Game 1.0, which give the farmer a tool to reduce greenhouse gas emissions."

TORGER MJØNES, Leader of sustainable building, Trøndelag fylkeskommune
"Trøndelag Fylkeskommune has greatly benefited from participating in FME ZEN. The knowledge and innovations emerging from this collaboration have substantial potential for further business development and application in various projects within the county. We have had a productive dialogue and have collectively set ambitious goals for the project. This partnership has been a valuable resource, providing us with crucial academic contacts and helping us stay at the forefront of environmentally friendly material use and net zero emission building operations."

IMPORTANT RESULTS FOR MÆRE AGRICULTURAL SCHOOL

New Processes, Products, and Services:

- Definition and development of a zero-emission farm concept.
- Creation of the Climate Game 1.0, a digital game aimed at reducing greenhouse gas emissions.
- Implementation of microgrid technology to manage energy consumption and production.

Strengthened Networks and Collaborative Relationships:

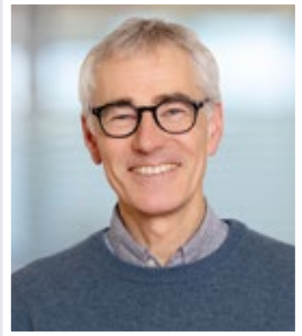
- Enhanced collaboration with researchers and academic institutions.
- Increased engagement with Trøndelag Fylkeskommune and other partners in FME ZEN.
- Development of a strong partnership with NTE for energy solutions.

Other Positive Outcomes:

- Improved understanding and awareness of zero-emission strategies among students and farmers.
- Educational impact, with over 600 people learning about ZEN in 2024 alone.
- Identification of key factors influencing energy consumption and emissions, leading to more informed decision-making.

STATSBYGG:

VALUABLE INSIGHTS AND INCREASED KNOWLEDGE ABOUT SUSTAINABLE PRACTICES



EIVIND SELVIG, consultant, Civitas:

"My role involved working on greenhouse gas calculations and method development, as well as the collaborative contracting at Evenstad. The partnership with FME ZEN has been demanding but rewarding. It required deep integration of knowledge within the project team and strong organizational support. The collaboration has led to significant advancements in our understanding and application of sustainable practices."

MARIUS ALEKSANDER KOLBY, Property representative at Evenstad:

"My experience has been about integrating and managing new technologies. We faced the challenge of implementing and living with technologies that had never been combined before. This was difficult because the technology was less mature than we anticipated. However, the project has been a testament to the importance of human factors and trust in technology."

IMPORTANT RESULTS FOR STATSBYGG AND CAMPUS EVENSTAD

New Processes, Products, and Services:

- Development and testing of a CHP (Combined Heat and Power) machine from Voltèr, which uses wood chips to produce heat and electricity.
- Implementation of a V2G (Vehicle to Grid) solution, allowing electric cars to both receive and supply power to the battery bank.
- Creation of a comprehensive energy management system to handle various energy supply solutions and control systems.

Strengthened Networks and Collaborative Relationships:

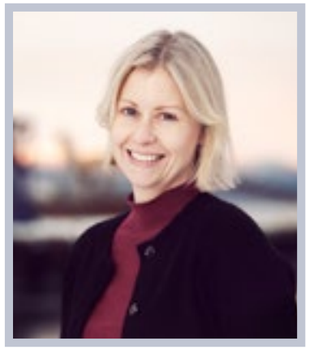
- Enhanced collaboration between researchers, property managers, and operational staff.
- Development of a strong partnership with technology providers and innovators.
- Increased engagement with the academic community and other stakeholders in the energy sector.

Other Positive Outcomes:

- Improved resilience and energy self-sufficiency at Campus Evenstad, particularly important due to frequent power outages in the region.
- Valuable insights into the integration of multiple energy technologies and their practical applications.
- Advancement of knowledge in managing energy peaks, energy flexibility, and supply security, which are critical for future energy systems.

NYHAVNA UTVIKLING:

INCREASED AWARENESS AND COMMITMENT TO ZERO-EMISSION GOALS



BIRGITTE KAHRS, Head of planning:

"Being a part of FME ZEN has been crucial for Nyhavna Utvikling AS. This collaboration has provided us with invaluable insights and support as we work on transforming Nyhavna into a sustainable city district with zero-emission ambitions. The partnership has helped us develop a comprehensive zero-emission strategy for the entire Nyhavna area, even for the plots we are not directly responsible for. This has been pioneering work, as there is no existing certification scheme for building such areas. The expertise and guidance from FME ZEN have been essential in navigating the complexities of this long-term project."

IMPORTANT RESULTS FOR NYHAVNA UTVIKLING AS

New Processes, Products, and Services:

- Development of zero-emission districts based upon the ZEN Definition.
- The zero-emission goals are anchored in the strategy for Nyhavna.

Strengthened Networks and Collaborative Relationships:

- Engagement of one person to lead the sustainable work, and to ensure holistic planning solutions.
- Collaboration with Statkraft Varme on the seasonal heat storage project.
- Establishment of partnerships with various stakeholders to support the zero-emission ambitions.

Other Positive Outcomes:

- Increased awareness and commitment to zero-emission goals within the organization.
- Enhanced ability to plan and implement sustainable urban development practices, setting a model for future projects.

TRONDHEIM MUNICIPALITY:

AN ENRICHING PARTNERSHIP THAT BOOSTS THE AWARENESS OF ZEN

MARIANNE LANGEDAL, Municipality's contact:

"Being a part of FME ZEN has been incredibly enriching for Trondheim kommune. As the coordinator, I've seen firsthand how the knowledge and expertise from the centre have been integrated into our projects. For instance, the experiences from Sluppen and Nyhavna have been invaluable. We've been able to apply the climate and energy insights from ZEN to our urban planning, ensuring that our developments are sustainable and forward-thinking."

JENS TØNNESEN, Energy and climate advisor:

"From the beginning, my role has involved providing input to the work plans at FME ZEN. The centre has generated a wealth of socially beneficial knowledge that we've been able to use in various municipal projects. Personally, I've focused on energy analysis, which has been crucial for our city-wide energy planning. The collaboration has also led to the development of new working methods and improved data collection tools like PROFet, which benefit both the municipality and the research community."

CAMILLA CHARLOTTE STENSTAD, Project leader for Sluppen:

"As the project leader for the Sluppen area, I've worked closely with ZEN researchers to develop climate and quality of place indicators. This collaboration has not only enhanced our planning processes but also provided us with practical recommendations that we can apply to other areas. The knowledge we've gained has been shared with other municipalities, amplifying the impact of our work."

IMPORTANT RESULTS FOR TRONDHEIM KOMMUNE

New Processes, Products, and Services:

- Development of climate and quality of place indicators for urban planning.
- Creation of a climate norm for the Sluppen area, which has been shared with other municipalities.
- Enhanced energy analysis methods and tools, such as PROFet.

Strengthened Networks and Collaborative Relationships:

- Increased collaboration with researchers, other municipalities, and external developers.
- Participation in workshops and knowledge-sharing sessions, leading to a deeper understanding of sustainable urban development.
- Establishment of a strong partnership with NTNU and other academic institutions.

Other Positive Outcomes:

- Improved integration of climate considerations into urban planning.
- Enhanced ability to influence national policies and regulations through the knowledge and experiences gained from FME ZEN.
- Development of a comprehensive climate plan for the Nyhavna area, focusing on energy systems and seasonal heat storage.

14. ANALYSIS OF THE ROLE OF THE CENTRE

ARILD GUSTAVSEN
Professor NTNU

TERJE JACOBSEN
SINTEF

In 2016, at the start of the ZEN Research Centre, most of the environmental performance analysis frameworks were addressing individual buildings and technologies for these. Since then, we have seen a development towards more holistic frameworks, addressing a group of buildings, neighborhoods, and districts, to utilize resources more effectively compared to what is possible when addressing individual buildings.

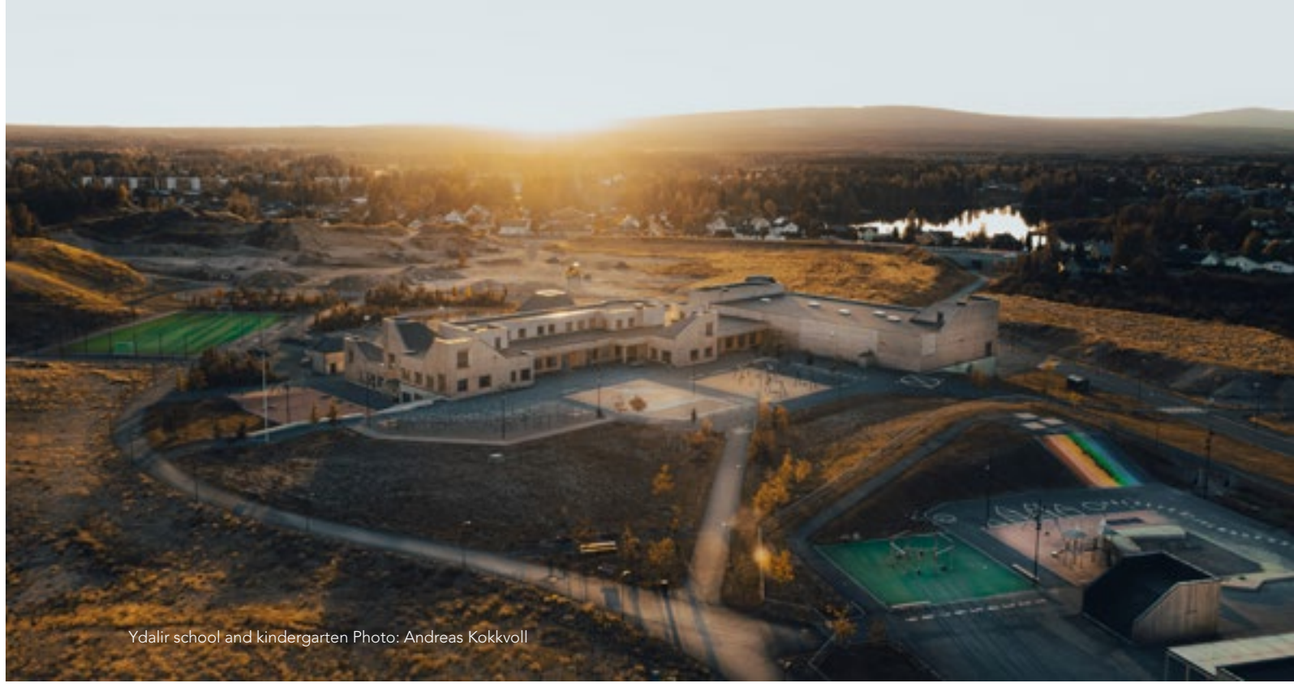
This includes e.g. use of renewable energy harvested on individual buildings and infrastructure and used by several buildings, taking down peak loads by exploring energy flexibility measures across several buildings, and by vehicle-to-grid solutions.

Addressing neighbourhoods in smart cities also allows for optimization of energy systems (e.g. including local/district heating systems), and the mobility system and location of services (e.g. bus stops, parks, shops) to reduce the need for non-sustainable transport options. The neighbourhood dimension also allows for engaging with the users in another way compared to addressing individual buildings, allowing for community engagement.

The zero-emission building and neighborhood concepts contribute to a strong focus on energy efficiency and reduction of greenhouse gas emissions in a life-cycle perspective. In addition, energy flexibility measures, sustainable mobility and behavior, and new local renewable energy are promoted. All these measures are key in addressing the climate crises as cities are responsible for two-thirds of global energy consumption and 70% of annual global carbon emissions (IEA), where transport and buildings are among the largest contributors. The Norwegian and European energy crises in 2022 have further strengthened the need for all these measures, and the recent ZEN Research Centre study has shown that there are large energy efficiency potentials in the Norwegian building stock towards 2030 and 2050.

While the construction sector in general is fragmented with many small companies and often is considered conservative, we see that several Norwegian building companies and municipalities are leading the way with regard to sustainability. This is especially true for many of the partners working in the ZEB and ZEN Research Centers. Here are some examples that highlight their efforts:

- Energy-positive buildings: Initiatives like the Powerhouse Alliance and the innovation program FutureBuilt are at the forefront of the development of environmentally friendly buildings. Powerhouses produce more energy than they consume over their lifetime. Realized buildings include ZEB Centre pilot buildings Powerhouse Kjørbo and Powerhouse Brattørkaia. The Powerhouse concept has been further developed to also focus on zero-emission buildings, i.e. a maximum and total CO_2 emission per square meter, which will require zero-emission construction sites in combination with climate-friendly materials, reuse and recycling.
- Zero-emission construction sites: Oslo Municipality has a goal that all construction and civil engineering activities in the municipality will be emission-free by 2030. This involves using electric machinery and innovative construction techniques.
- Sustainable building materials: Norway is pioneering the use of environmentally friendly materials like massive timber and low-carbon concrete. The ZEB Laboratory (an office living laboratory) is one example of a building with focus on reduction of embodied emission through innovative use of materials.
- Carbon capture and storage (CCS): Projects like Longship (where e.g. ZEN partner Heidelberg Materials is a central participant) are implementing CCS to reduce emissions from industrial processes, including cement production, and from waste-to-energy district heating systems.
- Public sector leadership: The Norwegian public sector (i.e. municipalities and governmental building developers), as a major construction client, sets stringent sustainability requirements for developers and contractors. This drives the adoption of green practices across the industry.



Ydalir school and kindergarten Photo: Andreas Kokkvoll

These efforts demonstrate Norway's commitment to greening the construction industry and reducing its environmental impact. We would however have liked to see more stringent regulations, guidelines and plans put forward by the Norwegian Government. These are still lagging behind the requirements of some of our European neighbours. Further research on how to scale up the transformation of the existing building stock to energy and climate positive buildings and neighbourhoods is also needed as the overall transformation is too slow.

NTNU and SINTEF have made significant contributions to creating a more sustainable built environment through various initiatives and projects:

- Research and innovation: NTNU and SINTEF collaborate on numerous research projects aimed at sustainability, where the ZEN Research Centre is one example.
- In the ZEN Research Centre, NTNU and SINTEF have brought the construction and energy sectors together in one common research initiative, making it possible to investigate, look for synergies, and develop the best solutions across both sectors.
- Sustainable building and urban development: NTNU's Sustainability program includes research on smart, sustainable cities and built environments. This involves planning for low-emission cities, integrating nature-based solutions, and enhancing resource efficiency.
- Testing and development of products and solutions together with the building industry in real living laboratories (see more information elsewhere in the report about the ZEN Pilot Projects) and in state-of-the-art laboratories (like the ZEB Living Lab and ZEB Laboratory).
- European projects: NTNU leads European sustainability projects, such as the Syn.ikia innovation project, which aims to increase the proportion of neighborhoods with surplus renewable energy.
- Development of building and neighbourhood sustainability frameworks (e.g. the ZEB and ZEN definitions and guidelines) together with the user partners, that are included in other frameworks and also referred to in EU strategy documents.

These efforts collectively contribute to advancing sustainable practices in architecture, engineering, urban planning, energy efficiency, and environmental impact reduction, and have in this way generated knowledge moving the nation closer to a sustainable low-carbon future.

15. FUTURE PROSPECTS

ARILD GUSTAVSEN, Professor NTNU
ANN KRISTIN KVELLHEIM, Director ZEN Research Centre, Senior advisor, SINTEF

NTNU has, together with SINTEF Community, been frontrunners in sustainable building research the last decades, with e.g. leading several research projects and participation in real demonstration projects going beyond the best practices at the time.

Our capacities were strengthened with the introduction of the research centers for environment-friendly energy (FME in Norwegian, appointed by the Research Council of Norway), where NTNU and SINTEF Community were awarded The Research Centre on Zero Emission Buildings (ZEB Research Centre) from 2009 to 2017. With the addition of research partner SINTEF Energy, we were funded for the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Research Centre) from 2016 to 2024. This has allowed NTNU and SINTEF to expand on our previous activities within building research and development and also take in other important aspects such as business models, energy system modeling, and digitalization.

As part of the FME scheme and also as part of additional projects, NTNU and SINTEF have developed research infrastructure, that up till now and also in the future will be important resources that we can build new industry and research projects around. These include the ZEB Living Lab (a residential dwelling/living laboratory), the ZEB Test Cell (a facility for testing building services systems and envelope systems towards a real climate), and the ZEB Laboratory (an office living laboratory). Together, these form unique research infrastructure that can be the basis for new applications and has the potential to be utilized in many projects in the future.

Furthermore, during the last decade, NTNU has contributed with extra funding to scale up the number of applications towards European research programs. Based on this the ZEN Research Centre was able to hire a project developer, who currently has contributed to NTNU leading two EU projects (syn.ikia on sustainable plus energy neighbourhoods and Green Deal ARV on climate positive circular communities) and participating in several others (e.g. towards the Driving Urban Transition initiative). These will continue for several years, and secure that NTNU, SINTEF and engaged user partners, continue to have high quality research activities within the area of sustainable built environments.

Within Norway, researchers in the ZEN Research Centre have contributed to several new applications. We did unfortunately not secure funding for a new FME, but have several new initiatives under preparation and evaluation, e.g. one application towards the call for Centres for Research-based Innovation (SFI in Norwegian) on energy- and climate-positive transformation of buildings and neighbourhoods. We are also working on the development of an innovation platform including the partners that participated in our third FME-application round.

We see that several of the user partners are part of new research projects, and some are also initiating new research and innovation projects themselves. ZEN user partners are also active in promoting sustainable building practices in own building and neighbourhood developments, promoting zero emission building and neighbourhood solutions and concepts.

All in all, the FME ZEN consortium is actively working on several initiatives to continue our efforts to decarbonize the built environment, as well as fully utilizing the energy potential in buildings and neighbourhoods.

16. CONCLUSIONS

ANN KRISTIN KVELLHEIM, Director ZEN Research Centre, Senior advisor, SINTEF
ARILD GUSTAVSEN, Professor NTNU, Director ZEN Research Centre 2016-2022

The ZEN Research Centre and its predecessor, the ZEB Research Centre, have both made a significant impact. Nationally, their long-term research has built strong capacities in the research partner communities, industry, and public partners. Internationally, both centres have delivered ground-breaking research which has influenced EU-directives and facilitated collaboration through EU-projects and beyond.

The ZEN Research Centre has brought together partners from different sectors, in particular the building- and the energy sectors. This has resulted in an increased understanding of the challenges we are facing and has given us a more far-reaching perspective. The arena for collaboration that a FME Centre represent is invaluable.

Building upon a previous FME Research Centre, the process for establishing a common strategy, organisation, and work plans was swifter than it would have been starting from scratch. The research topics in the ZEN Research Centre have brought together expertise from different fields, such as architecture, engineering, and social sciences. This interdisciplinary approach has resulted in solutions that are better adapted to the complexities of real-world situations.

The ZEN Research Centre has laid a strong foundation for a more sustainable future in the built environment. It has pioneered research and development of cutting-edge solutions for zero-emission neighbourhoods, positioning its partners at the forefront of sustainable building and energy innovation. Additionally, new research infrastructures, such as the ZEB Laboratory and the pilot projects, enable initiatives that drive the green energy transition.

17. APPENDIX 1: KEY ACADEMIC PERSONNEL

A large number of researchers have been involved in the ZEN Research Centre, in addition to the centre management team. Some examples are shown below (not an exhaustive overview). PhD and Postdoctoral researchers in the centre are shown in a separate table. Some of these have worked as key researchers in the centre after completing their studies.

KEY RESEARCHERS AND OTHER RESOURCES WORKING IN THE CENTRE

Name	Position	Role/workpackage
Daniela Baer	Senior researcher, SINTEF	WP 1
Håvard Bergsdal	Senior researcher, SINTEF	WP 3
Luitzen de Boer	Professor, NTNU	WP 2
August Brækken	Researcher, SINTEF	WP 5
Lars Arne Bø	Researcher, SINTEF	WP 2, 3 & 6
John Clauß	Senior researcher, SINTEF	WP 3 & 4
Benjamin Manrique Delgado	Research scientist, SINTEF	WP 4
Hossein Farahmand	Professor, NTNU	WP 4 & 5
Kristin Fjellheim	Research manager, SINTEF	WP 1
Francesco Goia	Professor, NTNU	WP 3, responsible laboratory activities
Lars Gullbrekken	Research manager, SINTEF	WP 3
Mohamed Hamdy	Associate professor, NTNU	WP 3
Bozena Dorota Hrynyszyn	Associate professor, NTNU	WP 3
Vegard Knotten	Research manager, SINTEF	WP 2
Magnus Korpås	Professor, NTNU	WP 4 & 5
Thomas E. Lassen	Research Engineer, SINTEF	WP 3 & 4
Synne Krekling Lien	Research scientist, SINTEF	WP 1 & 4
Anne Gunnarshaug Lien	Senior researcher, SINTEF	WP 1, 2 & 4
Bendik Manum	Professor, NTNU	WP 1 & 6
Roberta Moschetti	Senior researcher, SINTEF	WP 3
Tobias Nordström	Researcher, NTNU	WP 6
Sobah Abbas Petersen	Associate professor, NTNU	WP 1
Nina Holck Sandberg	Senior researcher, SINTEF	WP 1 & 2
Patricia Schneider-Marin	Associate professor, NTNU	WP 3
Christofer Skaar	Senior researcher, SINTEF	WP 1 & 3
Harald Taxt Walnum	Researcher, SINTEF	WP 4 & 6
Marianne Kjendseth Wiik	Senior researcher, SINTEF	WP 1 & 6

PHD CANDIDATES WITH FINANCIAL SUPPORT FROM THE CENTRE BUDGET

Surname	Name	Topic	Years in the centre
Askeland	Magnus	Regulatory and economical aspects related to ZEN within a larger energy system (WP5)	2018–2022
Backe	Stian	Transition pathways towards zero emission neighbourhoods (WP2)	2017–2021
Bagle	Marius	Model predictive control for optimal building energy use (WP4)	2021–2025
Bjelland	David	Sustainable solutions for retrofitting existing buildings towards zero emission neighbourhoods (ZEN) (WP3)	2021–2025
Brozovsky	Johannes	The climate dimension and the physical principles of zero emission neighbourhoods in Norway (WP1&6)	2018–2021
Favero	Matteo	Thermal comfort enabling thermal flexibility of buildings (WP4)	2018–2021
Formolli	Matteo	Solar neighbourhood planning (WP1)	2020–2023
Haaland	Petry Kristine Nøttum	Power markets and energy system planning (WP5)	2024–2025
Hamdan	Hasan Ahmed	Public private collaboration (WP2)	2018–2022
Henriksen	Hanne Marit	Representing zero-emission built environments (WP6)	2020–2025
Homaie	Shabnam	Optimal integrated building designs for resilient zero emission neighbourhoods (WP3)	2017–2021
Justo Alonso	Maria	Optimal combination of demand-controlled ventilation and heat recovery for ZEB (WP3)	2017–2022
Lausselet	Carine	LCA methods for zero emission neighbourhood concepts (WP1)	2017–2020
Mangion	Tanya	Migrating landscapes (WP6)	2023–2026
Pinel	Dimitri	Local energy system optimization within a larger system (WP5)	2017–2021
Rizzardi	Victor	Comparative studies of regulatory challenges related to thermal/power systems (WP2)	2020–2023
Rokseth	Lillian	CO2 emission and correlation to building form and spatial morphology at neighbourhood scale (WP6)	2017–2021
Rousseau	Lola Silvie Annie	Mitigation of greenhouse gas emissions in urban planning and development: resource efficiency as a tool for local climate action in Bærum (WP1)	2021–2025
Satoła	Daniel	Off-grid zero emission building concepts for warm climates (WP3)	2018–2022
Scheffler	Tanja	City planning and household emissions from travelling and energy use (WP1 & WP6)	2022–2025
Schön	Peter	Urban Form and Accessibility: Implications for Active Mobility, Modal Shares and GHG Emissions (WP1)	2021–2024
Sharbaf	Sara Aghasizadeh	Cost-benefit life cycle analysis of upgrading measures in existing non-residential buildings (WP3)	2022–2025
Skeie	Kristian	Building energy performance assessment through in-situ measurement (WP3)	2017–2022
Sørensen	Åse Lekang	Smart strategies for energy and power management in neighbourhoods (WP6)	2017–2023
Thorvaldsen	Kasper Emil	The value of buildings energy flexibility in power markets (WP4)	2018–2022
Yin	Hang	Building needs to talk in zero emission neighborhoods (WP3&4)	2022–2025
Yu	Xingji	Model predictive control to activate the building energy flexibility (WP4)	2018–2021

POSTDOCTORAL RESEARCHERS WITH FINANCIAL SUPPORT FROM THE CENTRE BUDGET

Surname	Name	Topic	Years in the centre
Akin	Sahin	Building performance assessments and architectural visualization (WP1)	2024–2025
Kandpal	Bakul	Economic consideration of the implementation of zero emission solutions (WP2)	2023–2024
Sandstad Næss	Jan	Modelling of urban mobility and the development of mitigation strategies for the transport sector (WP1)	2022–2024
Sinaeepourfard	Amir	Large-Scale IoT Networks of Smart Cities (WP1)	2018–2021
Stokke	Raymond	Innovation eco-system and green public procurement (WP2)	2019–2023
Tereshchenko	Tymofii	Energy planning of future district heating systems (WP4)	2017–2019
Vergerio	Giulia	Best practise to achive high ambitions (WP2)	2023–2024
Woods	Ruth	Living Labs - user involvement in practise (WP6)	2017–2022
Zaferanlouei	Salman	Value of building flexibility (WP5)	2022–2023

18. APPENDIX 2: PERSONNEL, FUNDING & COSTS AND LITTERATURE LIST

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ZEN

Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

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