HighEFF

Centre for an Energy Efficient and Competitive Industry for the Future

2021

Annual report

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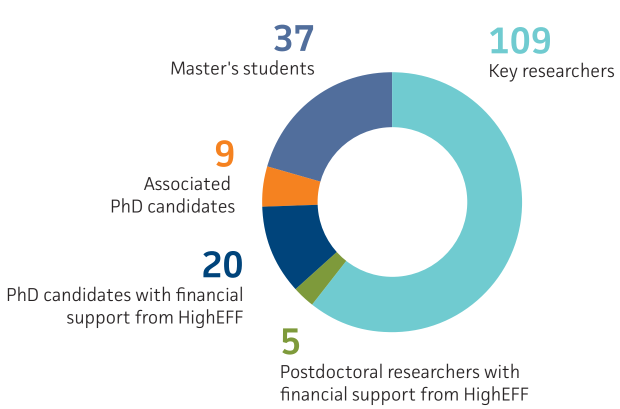
By numbers

42 PARTNERS

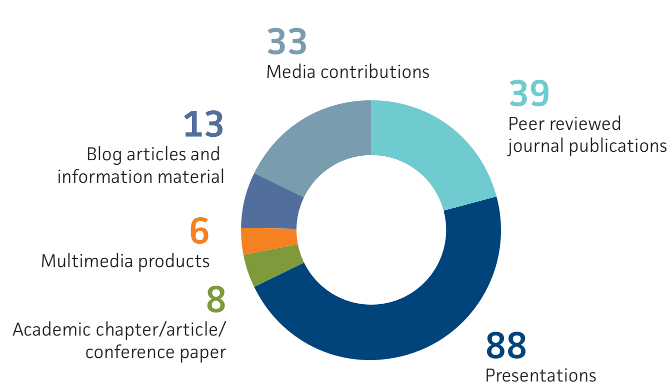
8 YEARS

400 MNOK

People



Communication and dissemination



HighEFF: Energy efficiency is a smart solution

The greenest kilowatt-hour is the one we do not need to produce. This is the short version of an important message from the International Energy Agency (IEA). Their premise is that as much as 37 percent of the emission cuts needed to meet the target of limiting global warming to a maximum of two degrees must be achieved through more efficient energy utilisation. Sustainability is a precondition to all activity during the ongoing green transition. For power-intensive industries, this means reducing energy use and using energy more efficiently.

The greenest kilowatt-hour is the one we do not need to produce.

A shift in policy – and vocabulary

In an effort to make a shift in the public debate, HighEFF has suggested changing our vocabulary when referring to industrial waste heat which gets released into the environment. All industrial processes have some level of energy loss, and in most cases, this energy is in the form of heat that does not get used as part of the industrial process. During a centre meeting, a suggestion was made that this heat, previously called waste heat, should from now on be on referred to as excess heat. This could make it easier to require such energy to be made available for other purposes.

Excess heat could be used as a resource for the development and increased efficiency of nearby industries. In this way, we can use the available energy as efficiently as possible and reduce the need for power grid upgrades. One of the concepts under study in HighEFF is to use excess heat from aluminum production to dry kelp and other seaweed. Once dried, the kelp could produce carbon-neutral reducing agents (biochar) for metal production or biofuels for the transport industry.

New, power-intensive industries like data centres and battery factories also produce large amounts of excess heat. HighEFF has stated that future energy-intensive industries should be positioned in such a way that nearby factories or communities can utilise their excess heat. This can be done by locating such industries in places with good grid capacity and access to district heating infrastructure, or in places where other industries can make use of the excess heat.

Successful midterm evaluation

In 2021, the Norwegian Research Council conducted a midterm evaluation of HighEFF which gave us an excellent review. The evaluation stated that the centre has demonstrated capacity to produce high-quality scientific and educational outputs through a structured and intentional approach to energy efficiency and optimisation interventions across all industries. While this is undeniably a grand challenge, the Centre has created a significant critical mass within a relatively short time with a number of excellent success stories at various stages of implementation.

All of the 25 PhDs and PostDoc fellows have been engaged and the centre has progressed well in establishing real case studies for the industry partners. These are cases where knowledge, technology and solutions developed within FME HighEFF can be applied in real industrial applications to increase efficiency and reduce emissions. This was noted in the midterm evaluation where the committee stated that the diversity of the students in the centre is commendable, and that the impact of the educational goals will undoubtedly continue to be felt throughout the global community into the future.

About HighEFF

HighEFF is a collaboration project between many national and international universities, research institutes and industry partners. In total, there are more than 40 partners from three continents. The industry partners represent all the largest industry sectors in Norway: Metal producing industries, oil, gas and energy companies, chemical industry and the food industry. HighEFF is led by SINTEF and NTNU.

Selected highlights from 2021

New Novel emerging concept funded

A new Novel emerging concept (NEC) obtained financing: **Biochar from Seaweed for Metal Production**. The project was awarded 1.5 MNOK to investigate the potential of sustainable farmed seaweed on the Norwegian coast, for: 1) biochar production; and 2) the production of relevant carbon products, by using industrial excess heat to process the seaweed.

Results used by partners

EPCON – STEAM PRODUCING HEAT PUMPS FOR INDUSTRIAL EXCESS HEAT RECOVERY

Steam producing heat pumps have a high fossil fuel replacement potential, and can reduce the primary energy consumption in electrified industrial applications. The development of the technology makes it possible to upgrade the excess heat over a wider temperature range, through multi-stage compression cycles.

REEL NORWAY – NEW GAS TREATMENT CONCEPT IN ALUMINIUM ELECTROLYSIS CELLS

The concept will be installed at Alcoa Mosjøen, in collaboration with IPN project AGATE. In the future, off-gas from aluminium electrolysis cells will have to be handled in a way that includes energy recovery and simple CO_2 capture. This will require solutions that increase the concentrations of the various components present in the off-gas without negatively impacting the working conditions and the equipment in the electrolysis hall. Of all the possible strategies to achieve this goal, the most promising is *Pot Gas Recycling (PGR)*. The solution being investigated combines the PGR with a CO-to-CO_2 catalyser, a heat exchanger, and a gas treatment centre to capture SO_2 and HF. With an added CO_2 capture unit, the system would give the industry the possibility to recover excess heat and capture CO_2 from its off-gas.

NOVEL EMERGING AND INNOVATIVE CONCEPTS

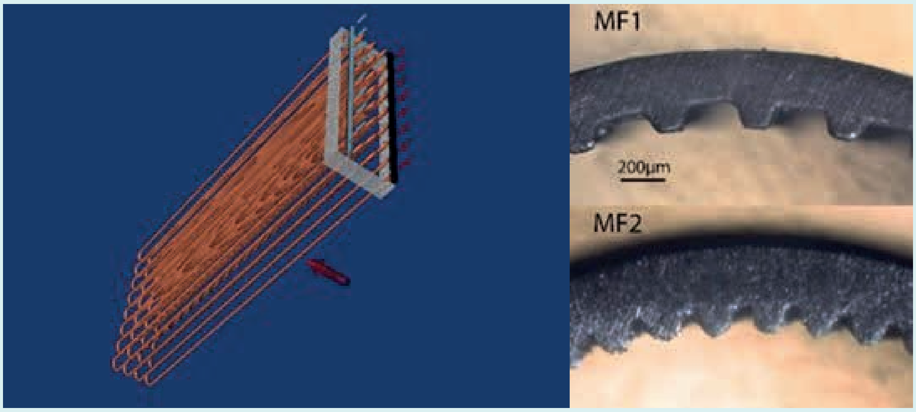
To further emphasise innovation and make room for new ideas, the centre has been yearly funding Novel Emerging Concepts (*NEC*). As of 2022, HighEFF will expand this programme to include the possibility to bring innovative concepts forward towards industrialising. The budget has been increased by use of previously unallocated funds. This new scheme will be called Novel Emerging and Innovative Concepts (*NEIC*). These will be projects directed at high value innovative concepts that can make a difference both in the short and long term. This activity will go beyond what is already planned or ongoing at the centre. One important criteria will be that NEIC must contribute directly to reaching the main goals of HighEFF with respect to increased energy efficiency and reduced emissions.

Selected PhDs completed in 2021

Ehsan Allymehr, PhD, NTNU

Investigation of Hydrocarbon Two-phase Flow for Charge Reduction in Heat Exchangers

Hydrocarbons offer an alternative to the HVAC industry as a natural working fluid with minimal environmental impact. The main challenge with hydrocarbons is flammability, which can be mitigated by reduction of charge. Internally enhanced tubes provide a powerful tool for designing more efficient heat exchangers leading to reductions in both volume and charge. Microfinned tubes are the most commonly used internally enhanced tubes that increase the heat transfer coefficient on the refrigerant side in heat exchangers. Due to higher heat transfer coefficients, the internal volume of the heat exchangers can be reduced. One of the main challenges for using microfinned tubes has been the design of heat exchangers due to lack of reliable predictive methods. In this context, this research provided experimental results for characteristics of two-phase flow of hydrocarbons. Propane, isobutane, and propylene were studied since they are commonly used in HVAC applications. Three tubes with an outer diameter of 5 mm were tested, one smooth and two microfinned. The two microfinned tubes differed in the number of fins and helix angle. One test rig was used to obtain both condensation and evaporation characteristics, which was possible due to the design of the rapidly interchangeable test sections. In evaporation tests, the effects of fluid properties, heat flux, mass flux and saturation temperature were studied in addition to the effect of internally enhanced tubes. Condensation tests were focused on fluid properties, mass flux and internal enhancement of tubes. Additionally, the data obtained for the heat transfer coefficient and pressure drop were compared against predictive methods to find the most reliable correlations. Finally, the data was used for numerical simulation of fin-and-tube heat exchangers in different environmental conditions to compare the charge with other types of heat exchangers.

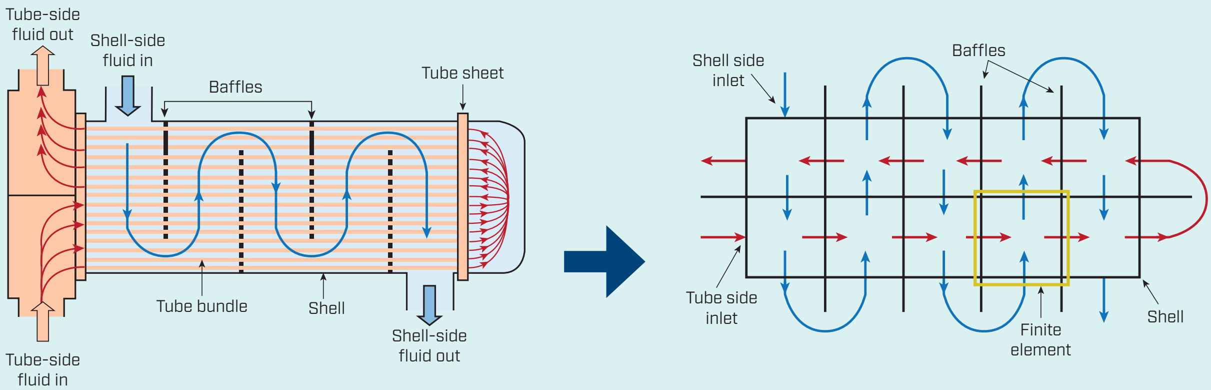


Saif Kazi, PhD, Carnegie Mellon University, USA

Mathematical Modelling & Optimisation of Heat Exchanger Design

Heat Exchangers are an important part/equipment in not only industrial processes but also in residential and commercial utility systems. Traditional methods for heat exchanger design were developed in the 1950s and 80s and are not suitable for current applications. My PhD project looked into an improved way of modelling and designing heat exchangers using advanced numerical and optimisation methods.

The strategy is to discretise the heat exchanger geometry into a discrete element structure. The idea is similar to CFD where the conservation laws are solved inside each of these elements. Our approach combined the heat transfer PDE and mass balance to the design parameters/variables of the exchanger such as number of tubes, tube length, shell diameter etc. The methodology was applied and integrated in process optimization problems such as heat exchanger network synthesis (HENS), natural gas liquefaction (NGL) process and refrigeration cycle.



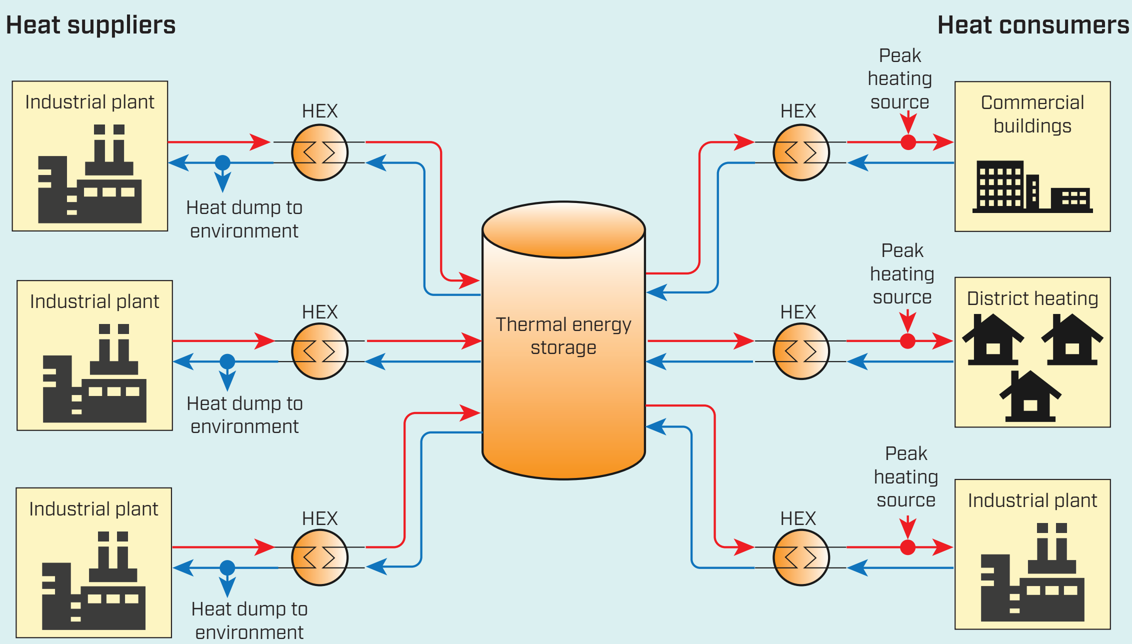
Discretization of a two-pass shell-and-tube heat exchanger

Mandar Thombre, PhD, NTNU

Robust Model Predictive Control in Energy Systems: Dealing with Uncertainty

Model predictive control (MPC) is a powerful tool that has been widely used for optimisation in the chemical process industry. A key challenge in such process optimisation is that a large majority of real-world processes lack perfect system information and must contend with significant uncertainties. An example of this is industrial waste heat recovery, where daily operation involves heat supply and demand varying significantly from their predicted profiles.

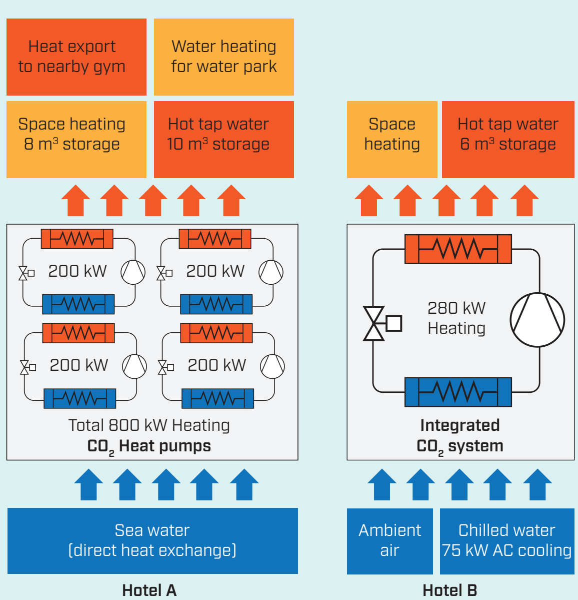
To counter this uncertainty, my PhD project investigated a framework of "robust" MPC where the uncertainty is described in form of a scenario tree, with the scenarios representing a unique combination of uncertain parameters. We proposed novel algorithms within this framework that focused on two important aspects: 1) selecting scenarios that better describe the uncertainty, and 2) improving its computational efficiency for solving large problems. The new framework was applied to benchmark problems as well as an industrial case-study focusing on thermal energy storage in district heating.



Silje Marie Smitt, PhD, NTNU (associated PhD)

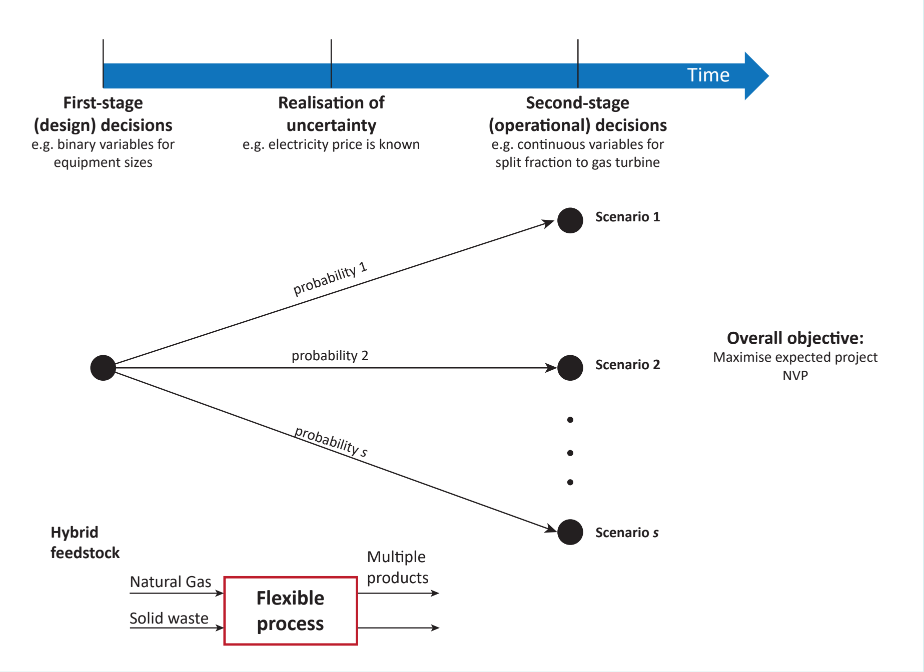
Integrated CO_2 Heat Pumping Systems for Hotels

The hotel sector features high thermal demands, often realised through processes that advance the global warming effect. Excessive energy use within the hotel sector in cold climates is primarily due to the thermal energy production of domestic hot water, space heating and cooling. Heat pump systems satisfy these criteria by reducing energy consumption and operational costs related to thermal energy production. The application of natural and environmentally friendly refrigerants, such as CO_2, has gained much attention as an approach to reduce greenhouse gas emissions from refrigeration, air-conditioning, and heat pump systems. The focus of my research has been to investigate potential, design and control strategies for "all-in-one" CO_2 heat pump and chiller units with thermal storage for the hotel sector. This research work includes a large-scale investigation of the market potential of integrated CO_2 systems within the Nordic hotel sector, an in-depth performance evaluation of an integrated CO_2 hotel unit, and, finally, numerical evaluations of designs and control strategies to enhance performance.



Avinash Subramanian, PhD, NTNU (associated PhD)
Designing Robust Energy Systems Under Uncertainty

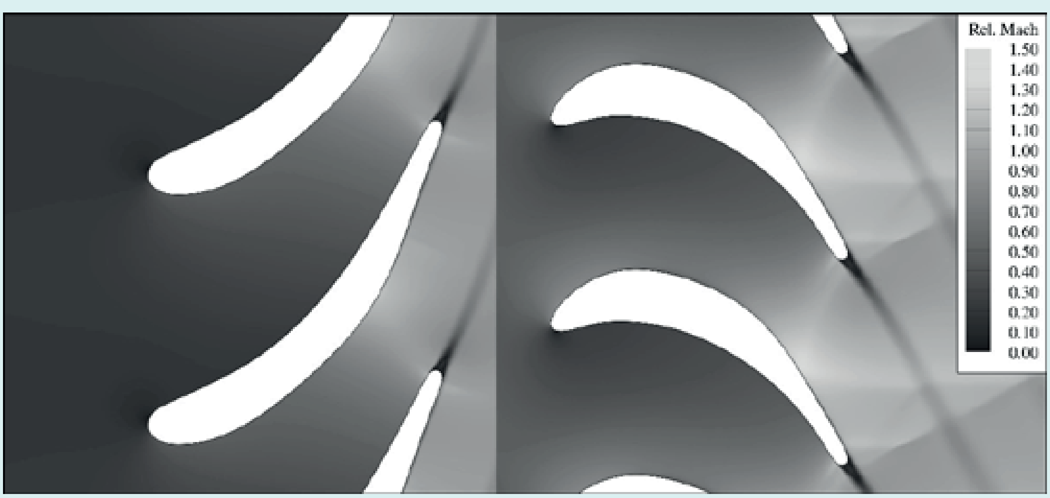
An energy system is used to denote all the process that are involved in the conversion and distribution of a primary source (such as natural gas, solar energy, uranium, wind etc.) to a final usable product such as electricity or heating. However, the economic feasibility and profitability of such an energy system remains highly dependent on external factors such as market prices, government policies and technological disruption. For this reason, it is essential to account for such uncertainties right from the early conceptual stages. My research involved the use of systematic approaches to incorporate uncertainty using methods based on mathematical programming. One key challenge is that inclusion of uncertainty implies that the size and computational requirement of the model explodes. Thus, novel decomposition algorithms and software are used in this project that allow for scalable solution of large-scale optimisation models. The PhD project illustrates the economic value of designing such a robust energy system with a case study of a process converting natural gas and solid waste tire to multiple products.



Roberto Agromayor, PhD, NTNU (associated PhD)

Automated Design of Turbomachinery Components

Automated design methods are emerging as a powerful tool for the fluid-dynamic design of turbomachinery components. Such automated methods integrate mathematical models of different level of sophistication with numerical optimisation techniques to explore large design spaces in a systematic way. This leads to higher performance gains and shortens the development time with respect to traditional design workflows based on trial-and-error. The focus of my research was to develop aerodynamic design method for turbomachinery blades operating under non-ideal thermodynamic conditions. The proposed method supports the optimisation of multiple blade rows in 2D, and it relies on a gradient-based shape optimisation framework that integrates the proposed computer-aided design (CAD) parametrisation with a computational fluid dynamics (CFD) solver. In order to demonstrate the capabilities of the method, we applied to design a new single-stage axial turbine operating with isobutane (R600a) that is going to be tested in the EXPAND facility at NTNU.



HighEFF research scientists are hard at work solving energy efficiency challenges. Shown here: Yessica Alexandra Arellano Prieto (SINTEF).

The Added Value Created by Joining FME HighEFF

Joining an FME can provide value to industrial partners on many levels.

- Top level research with significant budget and duration, directed towards industry needs
- First-rate recruitment opportunities from strong master's, PhD and post-doctoral programmes
- First access to detailed results for business development
- Improved economic and environmental sustainability through significant energy savings
- Cross-pollination effects through a varied network of engaged partners

Message from the Chair

Energy efficiency and reduction of GHG emissions have in the last couple of years become even more important than at the start of HighEFF. The topics frequently make the headlines and are the subject of much public debate. Raising awareness about energy efficiency's importance as a climate technology is a multidisciplinary challenge and the perspective for all sectors must be highlighted.

Most organisations and nations are setting tough and specific targets to protect the global environment. However, these targets are challenging to fulfill without access to relevant technologies and the expertise to implement them.

More and more companies, within retail, manufacturing, and commodities (all segments of the value chains), use sustainability as a marketing advantage and to improve business performance.

HighEFF is now in its final phase and is entering the harvest stage. Technologies for increased energy efficiency, value creation and competitiveness, while decreasing GHG emissions in a broad span of industrial processes, are developed and being made ready for implementation.

Equally important to the development of new technologies is the education of the experts that will implement these technologies. All the planned PhDs/PostDocs (25) are now well into their tasks and a several have completed their work and are ready to support industrial implementation.

Three words; communication, collaboration and implementation, are and will be at the forefront of my mind in this final phase of HighEFF.

Arne Ulrik Bindingsbø

Arne Ulrik Bindingsbø is Chairman of the HighEFF Board. His current position is Leading Researcher, Energy efficiency and CO_2 reducing technologies, Research & Technology, in Equinor. Arne Ulrik earned a PhD in Materials Science from NTH in 1992. He has more than 25 years of R&D experience from the Oil & Gas sector. His focus area is to develop and execute R&D projects within the field of Operations & Maintenance. As the field of O&M consists of many technical disciplines, Bindingsbø is very focused on collaborative innovation to obtain R&D projects that result in industrial implementation. Since 2014, he has held a position as Adjunct Professor at the Department of Marine Technology, NTNU.

Photo: SINTEF

Arne Ulrik Bindingsbø, Chair of the HighEFF Board, and Petter E. Røkke, Centre director.

Message from the Centre Director

2021 was yet another exiting and fruitful year for HighEFF. From the management side, I am particularly happy and proud of the successful outcome from the midterm evaluation of HighEFF. The evaluation panel gave HighEFF a very positive response on all aspects of the evaluation; scientific research quality, user partner involvement, academic production, collaboration, target achievement etc. An aspect for improvement is to increase the focus on innovations, which is particularly important for the remaining period of HighEFF. We are now in a phase where several students have completed their studies and results from the research are being taken further in spin-off projects and realised among industrial partners. As such, our vision "Joint effort for creating a competitive, energy efficient and environmentally friendly industry for the future" is being realised.

Several of the PhD candidates have now completed their studies and their knowledge is being taken further among industrial partners and R&D institutes. During their studies, they have published an impressive number of scientific publications (more than 150 so far!) proving that the research is in the very front internationally.

During 2021, HighEFF has become more visible in the public debate. We have published an op-ed in Dagens Næringsliv, hosted a webinar on the topic of utilising the 20 TWh of excess heat available from Norwegian industry, published input to the public hearing for a change in the Norwegian Energy Law (Energiloven), participated in the NRK P2 programme EKKO, and published several blogs for communicating our strategic messages. This has also engaged the user partners of HighEFF.

The HighEFF research centre is in itself a major effort for achieving the targets of 20-30 % reduced specific energy consumption and 10 % reduced GHG emissions in Norwegian industry, but as a research collaboration it is also a tool for joining partners to bring ideas, innovations and results further towards realisation. From the collaboration in HighEFF, more than 20 spin off projects have been established, ranging from further competence building to innovation and demonstration projects. This makes me confident that the collaborative research effort within HighEFF will have a significant impact, fulfilling the expectation to structure energy research within the topic of industrial energy efficiency.

And the basis for this is first of all from the high-quality research performed within HighEFF, by highly skilled professors, researchers, students, user partner experts and more … Industrial partners setting high expectations for us at HighEFF ensure that the research performed is not only scientifically excellent, but also relevant for future innovative implementation among industrial partners.

Petter E. Røkke

Petter E. Røkke is the Centre Director of HighEFF. His current position is Research Director for the Thermal Energy department at SINTEF Energy Research. Petter earned a PhD in Mechanical Engineering from NTNU in 2006. During his career at SINTEF, he has been active within the fields of CCS (CO_2 capture and storage), Bioenergy, and Industrial Energy Efficiency. Since 2011, he has been within the management group of SINTEF Energy Research, first as Research director for the Electric Power Technology department and since November 2012 for the Thermal energy department. He was chairman of the board for FME CenBio and is currently member of the board for FME Bio4Fuels.

Our contribution to a more sustainable world

By increasing energy efficiency, value creation and competitiveness, while decreasing greenhouse gas emissions in a broad span of industrial processes across sectors, HighEFF contributes towards all 17 UN sustainable development goals (SDGs). But we have chosen to focus on four SDGs we consider as the most relevant and where we hope to achieve significant impact through our research.

Reaching climate goals requires access to clean, affordable energy. Two of the sub-goals for SDG 7 are to increase international collaboration on research related to clean energy and to double the world's energy efficiency by 2030.

Through HighEFF being a Research Centre for Environment-Friendly Energy and having an international consortium; and by reaching the greenhouse gas emissions reduction targets and energy efficiency goals, HighEFF will have a significant impact on SDG 7.

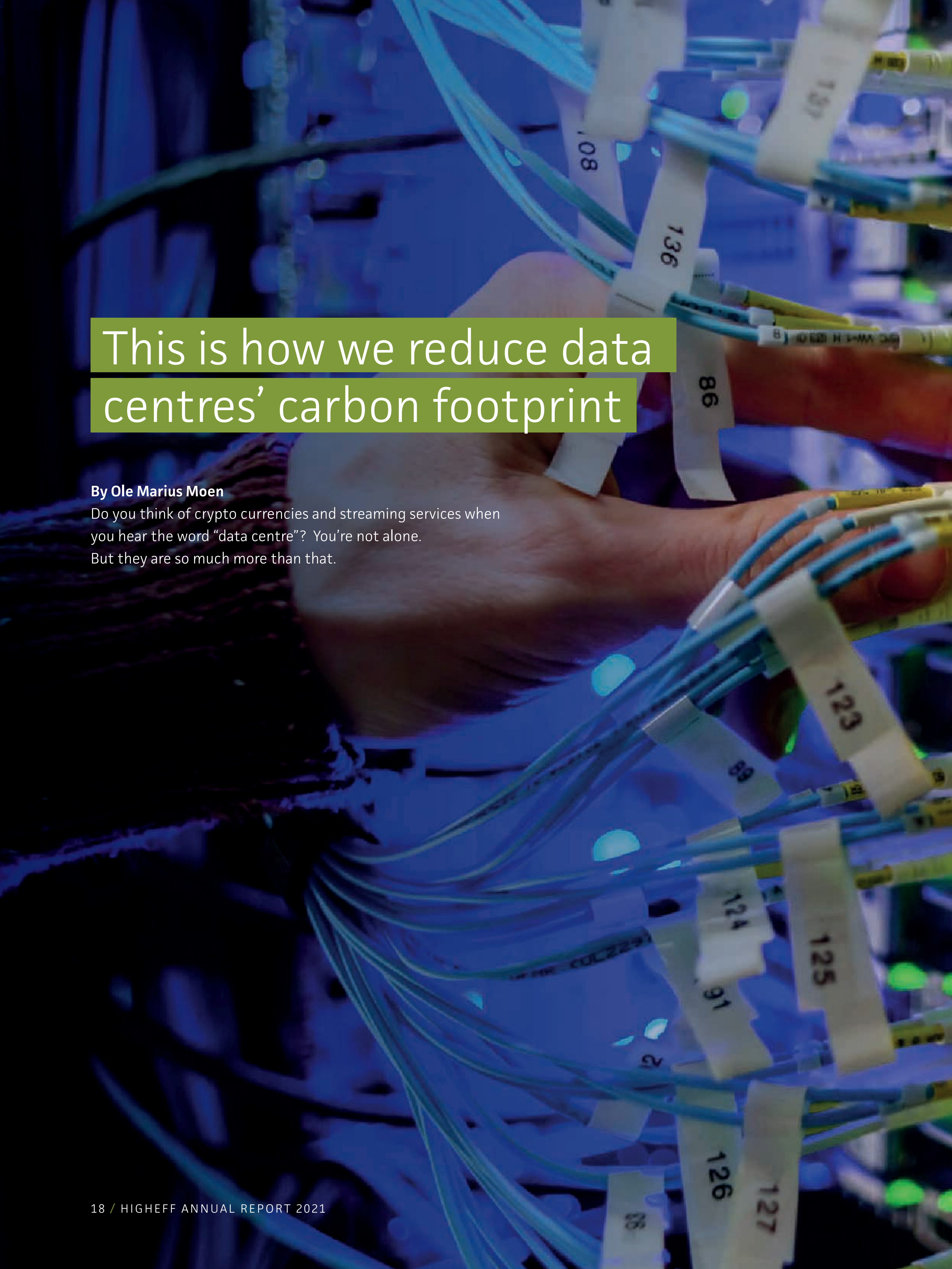
The SDGs are all dependent on cutting edge industrial innovation – one of the prime objectives of HighEFF. Together with industrial partners from a wide range of sectors, our research breeds new knowledge and innovation on components and processes to make industrial processes more energy efficient.

Not only is this important for mitigating climate change and ensure more responsible use of resources, it also brings down costs which in turn increases competitiveness. This makes it very attractive to adapt HighEFF innovations from a business standpoint as well as a sustainability standpoint.

We must use the world's limited resources more responsibly and efficiently, in terms of both production and consumption. Enabling a 20-30% reduction in specific energy use in industrial processes means industrial actors will be able to produce the same amount of goods with 20-30% less energy.

The climate is changing at dramatic speeds, and we need to mitigate and adapt quickly. As a Research Centre for Environment Friendly Energy (FME), the most important job of HighEFF's research is to contribute to reaching SDG number 13.

Many of the products and processes we as a species are most dependent on are extremely energy intensive and produce large amounts of GHG emissions. Through HighEFF research we aim to enable at least a 10% reduction in GHG emissions from industrial processes by 2024 and enable a 20-30% reduction in specific energy use. This will have a significant impact on mitigating climate change effects from industries around the world.



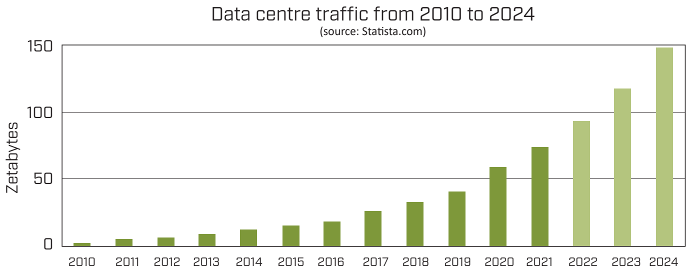
This is how we reduce data centres' carbon footprint

By Ole Marius Moen

Do you think of crypto currencies and streaming services when you hear the word "data centre"? You're not alone. But they are so much more than that.

Yes, they are the home of your favourite Netflix show. But videoconferencing, autonomous vehicles, smart cities, online banking services and health journals are just a few examples of products and services that require computational power from data centres around the world.

Over the past decade, the demand for computing power increased exponentially, making data centres a fast-growing industry. They are a huge part of what allows us to live our modern, digitised lives. And they are important enablers for more efficient services and the transition to a green economy. For instance, reducing travelling by facilitating an increased use of videoconference meetings, and enabling smart technologies that make our lives both greener and more comfortable.



But there is a flipside to the coin: data centres use immense amounts of energy.

They already use more than 2% of the world's electricity, and contribute to 2% of world's CO_2 emissions – equivalent to the world's entire airline industry. This is in great contrast to the European Green Deal's goal to make data centres climate neutral by 2030.

Data centres *must* reduce their climate footprint if we are to mitigate climate change. And many eyes look to Norway as a place that has both the infrastructure and natural resources to do that.

WHAT IS A DATA CENTRE?
A data centre is essentially a dedicated space used to house computer systems for processing, distributing, and storing data. The typical data centre consists of IT equipment like servers, networking equipment like routers and switches, and storage systems. This is typically organised in the form of severs racks, which are arranged in aisles. In addition, data centres house cooling and ventilation systems, backup power supplies, as well as security, fire protection and monitoring systems.

How can data centres become more energy efficient than they are today?

Just like the devices we use to browse the internet, data centres need electricity to work. They just need A LOT more of it. And just as your computer has a fan to prevent it from overheating, data centres need a cooling system.

From a climate footprint perspective, the need for energy and cooling are not problems in and of themselves. The problem is that most data centres' cooling systems are inefficient. They use unnecessary amounts of energy. And although the heat removed by the cooling system is a valuable resource, it is rarely used for anything.

On top of that, most data centres use non-renewable electricity sources, which means that there is a good chance your next video meeting is powered by coal, oil or gas. Even if the mobile device or computer you use to attend the meeting is powered by hydro, wind or solar energy.

But what if the video meeting was streamed from a server running on hydro or wind power, had more energy efficient cooling and utilised its excess heat? Let's take a closer look at how data centres can change from climate-foe to climate-friend, and why many think Norway might be the perfect place to build them.

Advantages and challenges of having data centres in Norway

Norway's geography and natural resources have led it to become a large producer of renewable energy. In fact, 98% of Norway's electrical production is renewable, and it has one of the lowest electricity prices in Europe. In addition, the cool climate allows for both very efficient cooling and a large potential for excess heat utilization (excess heat is also known as waste heat).

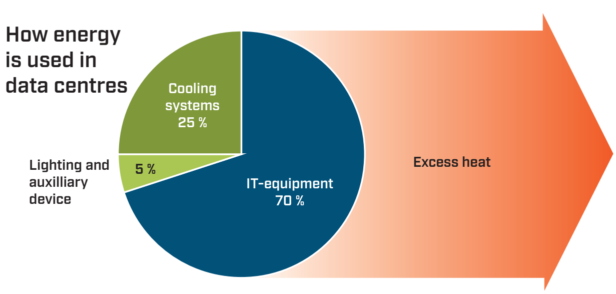
These advantages have not gone unnoticed by the industry, attracting leading data centre companies such as Microsoft and Facebook. This may facilitate the rise of a new Norwegian industry.

But a growth in the data centre industry in Norway will not come without challenges, and Norway would have to do more than just rely on its natural resources.

The need for more renewable energy production will increase: The Norwegian Water Resources and Energy Directorate estimates that the electricity consumption from data centres will grow from 0.8 TWh in 2019 to between 3 – 11 TWh in 2040. More data centres will also cause challenges to the grid in terms of its capacity. Increased demand from various consumers is already causing the need to scale-up the electrical capacity. Examples of these are new emerging land-based industries such as battery production, electrification of offshore oil and gas platforms, and increased demand from households from electric car charging. Data centres represent a large share of the increased demand: between 2018 and 2019, about 50% of new requests to connect to the electrical grid came from data centres.

So why are data centres so energy intensive?

The simple answer is computational power and cooling.



The servers require large amounts of energy for computing. This energy is dissipated as heat within a relatively small area. And because the IT equipment is sensitive to high temperatures, the heat must be continuously removed.

As illustrated in figure above, the energy requirement for cooling typically accounts for a large share of the overall energy consumption in data centres.

The energy requirement for cooling depends on several factors, for example the cooling solution and where the data centre is located. In colder climates, the energy demand from cooling will be comparatively smaller.

POWER USAGE EFFECTIVENESS (PUE)
A metric that is often used to describe the efficiency of data centres. It relates the total energy consumption of a data centre to the energy consumption of the IT equipment:

$$PUE = \frac{\text{(total data centre energy consumption)}}{\text{(energy consumption of IT equipment)}}$$

The efficiency of data centres is often described by their PUE-values. Efficient data centres can achieve PUE values below 1.2. However, it is easier to achieve low values when the ambient temperature is lower, since little or no energy needs to be spent on mechanical refrigeration systems. This means that data centres located in Nordic countries have a natural advantage.

Still, a study showed that Nordic data centres achieve on average a PUE of 1.71, which indicates that there is still significant room for improvement. This can be done by choosing more efficient cooling technologies.

How the choice of cooling technology can reduce data centres' climate footprint

Cooling technology plays an important role in the effort towards making data more energy efficient. Not only does an efficient cooling system reduce the energy consumption, but it can improve the potential for utilising the excess heat by capturing it at even higher temperatures.

The choice of cooling technology is usually driven by investment costs and the need for high heat flux from the servers.

Most data centres use conventional **air-based cooling systems**, which are simple and cheap. The downside is that they are not an efficient way of removing heat and therefore result in high energy consumption and low excess heat temperatures.

However, the market's push towards building even more computationally intensive data centres has resulted in cooling methods which can remove more heat per area.

Examples of this are **liquid-based cooling systems** which have already been commercialised, and **two-phase cooling systems** which are an emerging technology. These new cooling systems can deliver heat at 60-80°C. This is heat we can utilise directly for many purposes.

OVERVIEW OF DIFFERENT COOLING SYSTEMS FOR DATA CENTRES

Air-based cooling systems

In these systems, cool air is supplied to the server rooms. The server racks are often arranged in so called 'cold' and 'hot' aisles, to control the airflow and eliminate mixing of cold and hot air. Due to low heat capacity and heat transfer coefficient, air is not a very good medium for heat transfer, which results in high energy consumption, limitations to how close together the servers can be placed and a relatively low excess heat temperature.

Liquid-based cooling systems use a liquid such as water to dissipate heat. This can be done by circulating water in microchannels and exchanging heat in cold plate heat exchangers which are in direct contact with the server components. Water and liquids in general have significantly better heat transfer properties compared to air. Liquid-based cooling systems allow for more compact data centres, reduced energy use for cooling and higher excess heat temperatures.

Two-phase cooling is an emerging form of data centre cooling technology. Here, the liquid coolant evaporates in the cold plate heat exchanger and the dissipated energy is stored as latent heat. This allows for even greater heat fluxes and coolant return temperature, and enables an even higher computational density.

> From an overall energy efficiency perspective, the choice of cooling technology should not just be based on cost and heat dissipation rates, but also on the potential for excess heat utilisation.

Excess heat utilisation – what are the possibilities?

No matter how energy efficient a data centre is, inevitably almost all its electricity consumption turns into excess heat in the end. Today, this heat is usually not used for anything. But it can actually be a very valuable resource if it is harnessed and used properly.

The challenge is that the heat has low temperature levels, making it difficult to utilise. However, as we have seen, choosing the right cooling technology can improve the potential to make use of it.

In general, there are two ways to utilise the excess heat: Direct use, or conversion to other energy forms or temperature levels, such as:

- Increasing the temperature – for example with a heat pump
- Produce cooling – for example with sorption cooling
- Convert to electrical power – for example with an Organic Rankine cycle

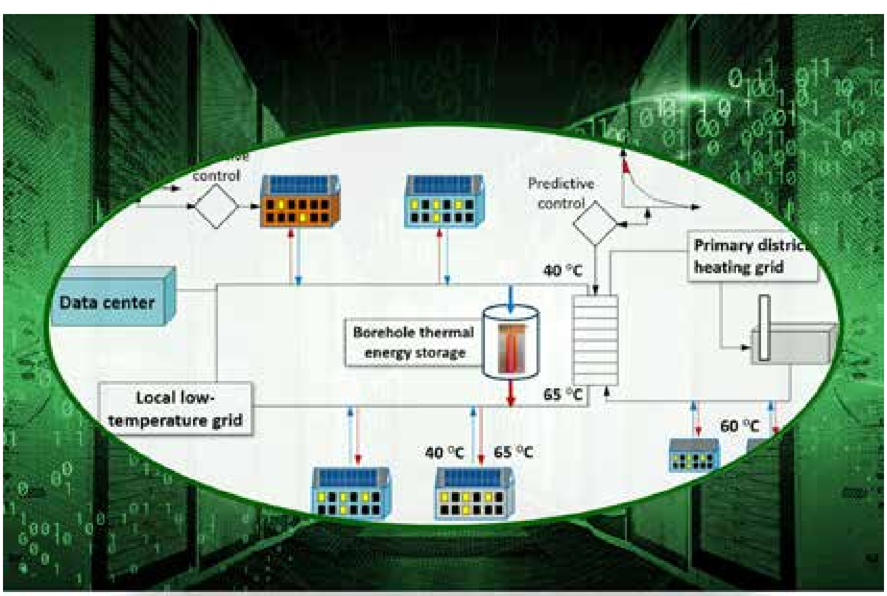
As seen in the table below, there are several potential applications that can benefit from data centre excess heat. The choice of more efficient cooling technologies opens up for even more applications.

Cooling technology and excess heat temperatures

	Air-cooled	Water-cooled	Two-phase cooled
Technology	**15-45°C**	**60°C**	**75°C**
HVAC/domestic hot water	Yes	Yes	Yes
District heating	Need heat pump	Need heat pump	Need heat pump
Boiler feedwater preheating	No	Yes	Yes
Sorption refrigeration	No	Yes	Yes
Organic Rankine Cycle	No	Yes	Yes
Desalination	No	Yes	Yes
Biomass processing	Yes	Yes	Yes
Food production	Yes	Yes	Yes

Excess heat in urban areas

In urban areas, there is a great potential to use excess heat from data centres for district heating, as heat pump technology can lift the heat to the required temperature level. This potential has gained traction in the industry and several initiatives and projects are now being realised for this purpose, such as the use of data centre waste heat for district heating in Oslo. In this context, scientists are working with how urban heat sources, such as data centres, can play the role of "urban heatplants" and provide heat to local energy grids.



Other application areas are building heating and domestic hot water heating which can be achieved without the use of heat pumps.

Rural areas

In many situations, it is advantageous for data centres to be located in rural areas due to the availability of space and electric power. Another advantage of such locations is the potential to use the local topography to achieve efficient cooling methods such as free cooling in mountains, or access to rivers or sea water. The downside of this is that the lack of potential urban heat recipients makes excess heat utilisation challenging.

Here, there is a need to raise awareness among data centre operators, the industry and local authorities about the excess heat potential of data centres. The establishment of data centres in co-location together with relevant industry that can make use of the excess heat, can lead to considerable energy and emissions savings. Examples of potential excess heat utilisation for industrial purposes include biomass processing, greenhouse food production and land-based fish farms.

The role of data centres in the future

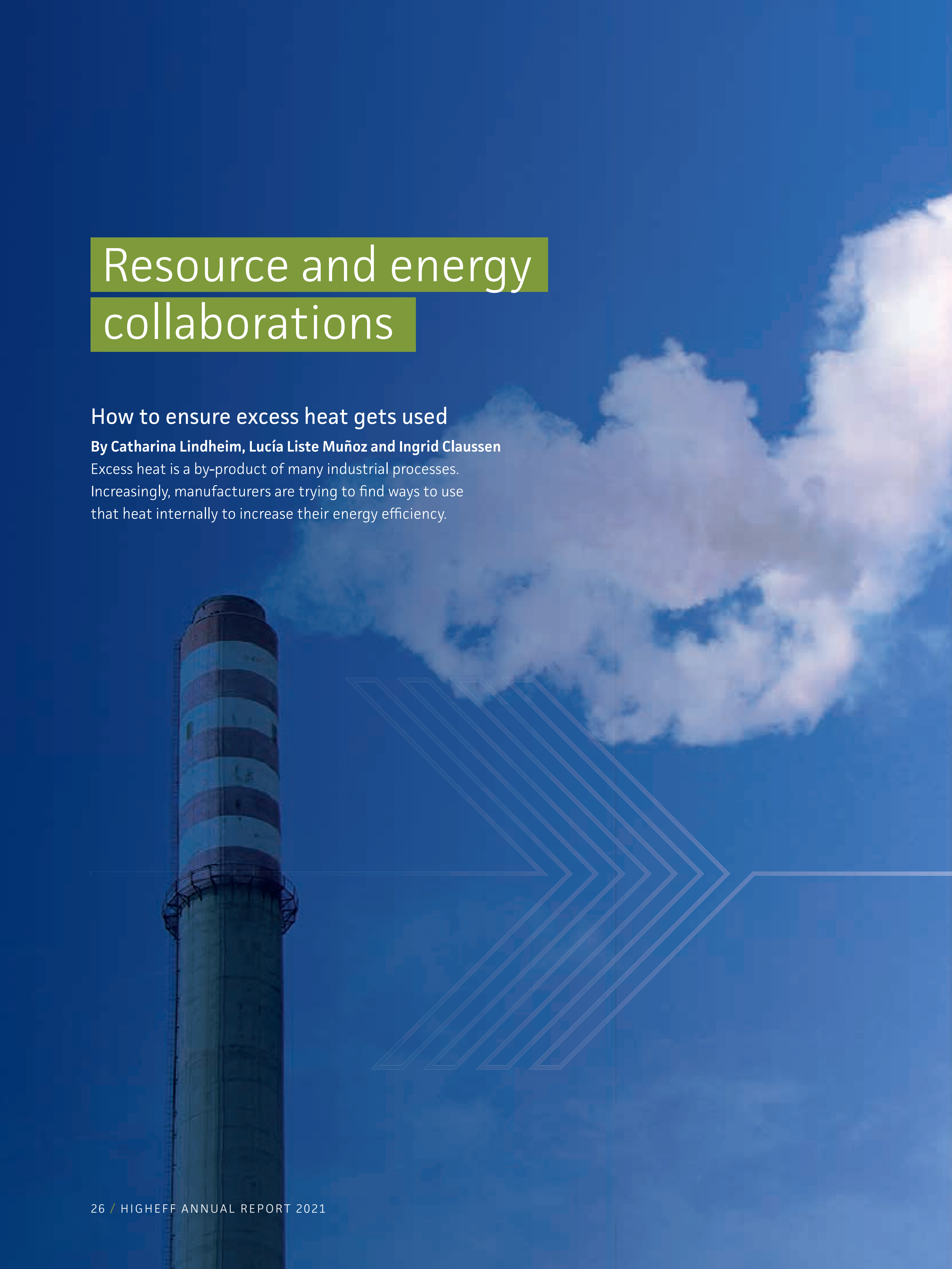
The growing data centre industry will play an ever greater part in the society in the future. And even with measures to improve their energy efficiency, it is likely that their share of the global energy consumption will grow in the years to come.

A potential key role for data centres as large energy consumers today, is to become the energy hubs of tomorrow. As energy hubs, data centres can produce, consume and store energy, and come to good use for example by load-balancing the electrical grid to cope with peak demand. They can integrate electrical and thermal energy demands, and shift between these demands depending on seasonal changes. For example, in the winter a shift to heat can be made to accommodate increased demand for district heating, while during summer a higher fraction of electricity is delivered.

HighEFF's work

HighEFF scientists are working on how to achieve optimal integration of thermal energy storage for excess heat utilisation, and industrial heat pump technology to efficiently upgrade the waste heat to higher temperatures with the smallest climate footprint possible.

Other FMEs are also doing research that is relevant to this area. FME ZEN scientists are studying the integration between electricity and district heating. FME CINELDI scientists are looking for solutions to improve the electricity grid capacity in a cost-efficient way, which will be important to get enough power to the data centres.



Resource and energy collaborations

How to ensure excess heat gets used

By Catharina Lindheim, Lucía Liste Muñoz and Ingrid Claussen

Excess heat is a by-product of many industrial processes. Increasingly, manufacturers are trying to find ways to use that heat internally to increase their energy efficiency.

F1
F2
F3

But sometimes they just don't need the extra heat. The most obvious solution – from an environmental point of view – is to try and find another business who does. But how does one establish such a collaboration? And what can help make it achievable? Research centre HighEFF wrote a handbook that helps businesses answer these and other questions.

Obstacles to excess heat use

It seems self-evident that releasing heat unused (whether into the air or a body of water) is an undesirable outcome in a context where countries have agreed to difficult climate targets that imply energy should not go to waste. But the reality is that access to cheap energy is seldom a sufficient incentive to establish an energy sharing agreement since the savings in energy costs are simply insufficient to justify the necessary investments in infrastructure.

Another obstacle is that heat does not travel very well. The factory receiving residual heat cannot be too far from the factory producing it.

Shared Resources: From obstacles to enablers

Previous projects have identified an array of barriers that restrain energy collaborations in Norwegian industry. The aim of project *Shared Resources*, however, is to shift the focus away from barriers and challenges and towards enablers.

To do so, the project maps experiences and explores new ideas for elements to be included in energy sharing arrangements – such as alternative business models, contract elements and value creating options beyond the traditional buying and selling of surplus energy. In particular, Shared Resources is concerned with the "low hanging fruits" – the cases in which collaboration is technically feasible, compatible and close to profitable.

Shared Resources is a research project aiming at exploring new possibilities and enablers for resource- and energy collaborations in Norwegian industry. It was carried out by NTNU Samfunnsforskning in collaboration with the Department of Industrial Economics and Technology Management, with funding from HighEFF.

The handbook presents its findings by means of a series of stages to be followed by the prospective parties to an energy collaboration. Each stage includes examples and guiding questions designed to make the process as simple to follow as possible.

What resources can be shared?

In addition to excess heat, businesses are encouraged to see if they can include other resources in an eventual sharing agreement – resources such as waste and by-products, services (administration, cafeteria, fire brigade, IT services), buildings (or rooms, outdoor areas, storage units, laboratories), labour (control room operators, security guards), expert knowledge, and financial resources.

In addition, the handbook reminds potential energy partners to check if they could benefit from any public incentive schemes that are in place. It also underlines the importance of taking into consideration external elements that could affect the collaboration (the authorities changing regulations or development plans, for example).

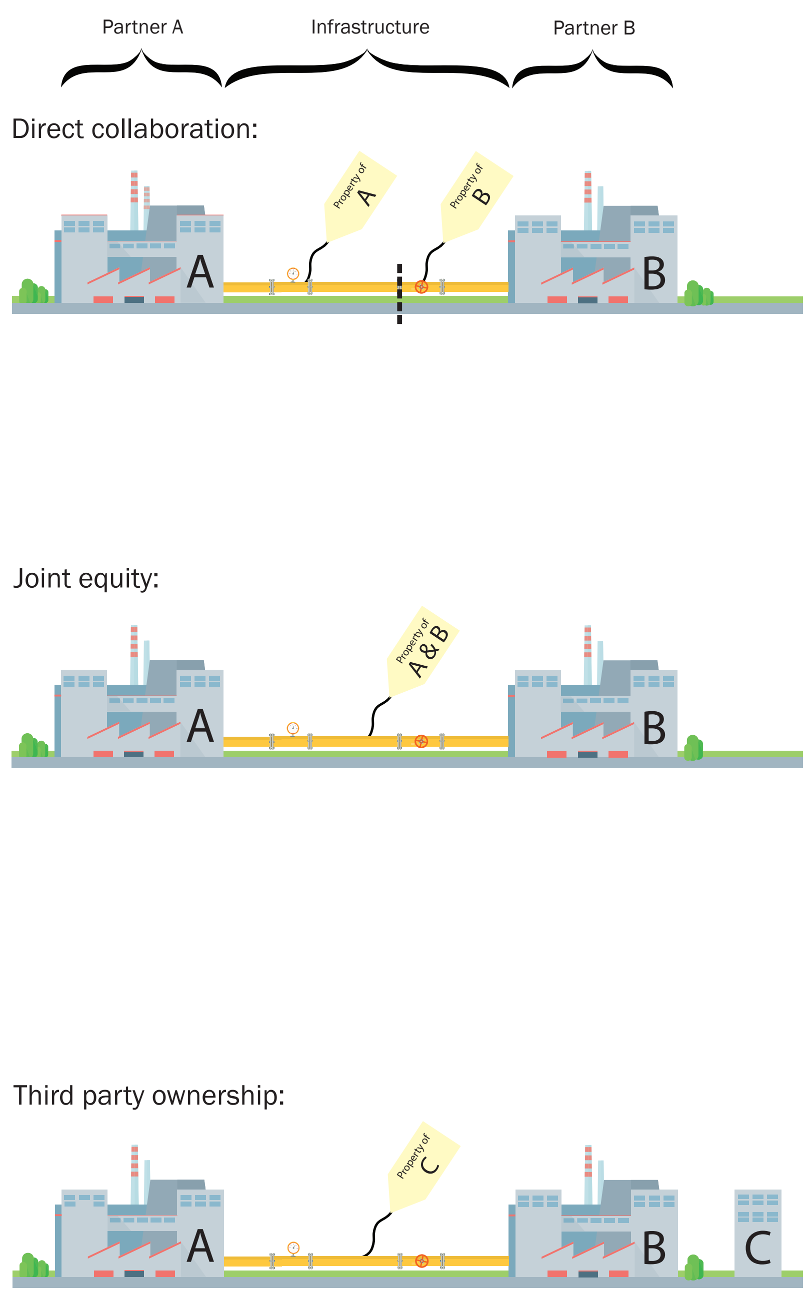
Research by SINTEF Energy concluded that the industry sectors with the highest potential for energy surplus utilisation are food, beverages and tobacco.

Who should own the infrastructure?

Energy sharing requires infrastructure. Who should own it? The handbook proposes three scenarios, as illustrated in the figure on the next page.

What should the pricing model be?

The price at which the surplus energy will be sold has to be determined by the contract between the two partners. The handbook lists several options: **Fixed energy price** (suitable when energy production and



Examples of different contract models.

Direct collaboration

Partners A and B each own part of the infrastructure, separately.

- Low start-up costs
- Lower management costs
- No sharing of equity
- Easier to terminate
- More adaptive to outside changes

Joint equity between the main partners

Partners A and B own the infrastructure together.

- Greater inter-dependency among parties
- Suitable for long-term partnerships
- Higher start-up costs
- Higher management costs
- More difficult to terminate

Third party ownership

A third party C owns and runs the infrastructure.

- Reduced risk for the main parties
- Third party takes care of the start-up costs
- Third party takes care of the management costs
- Higher energy/resource price because of the involvement of the third party
- Risk of being overcharged by a third party on which one is highly dependent

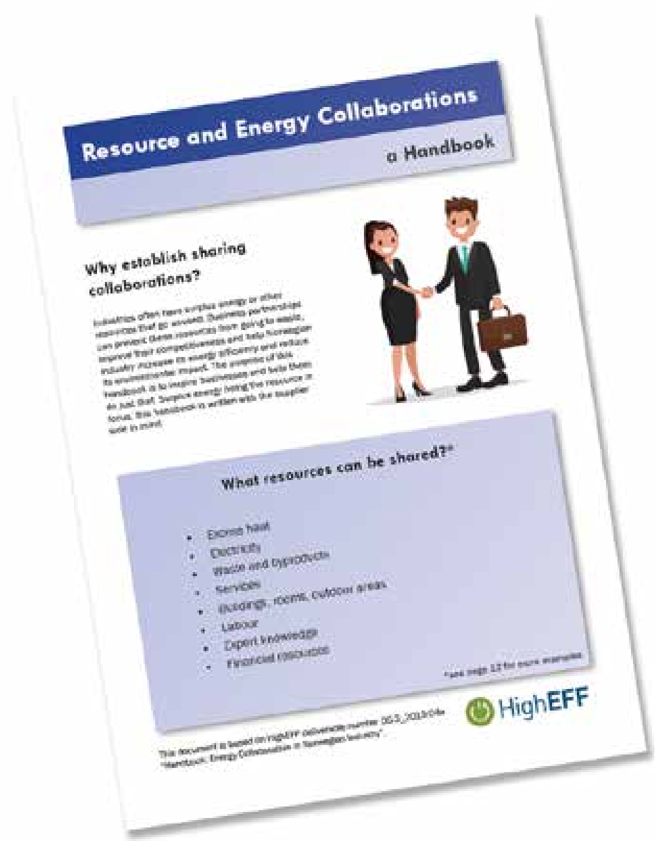
consumption are constant), **Time-varying energy price** (suitable when energy production and consumption are out of sync with each other), **Power price** (a price depending on the energy extraction rate at the time of consumption, suitable when the sharing infrastructure is over/underused at certain times), and **Volume price** (a price per cubic meter – of hot water, for example – suitable for when return temperatures are too high, meaning there is unnecessary distribution medium being used).

… and much more

The handbook examines many other aspects of energy collaborations, and provides tips to increase the likeliness that they will succeed. It has been made available online for consultation, at no cost to the businesses.

Download the handbook

The handbook titled Resource and Energy Collaborations – a handbook is now available for download free of charge. It can easily be referred to electronically, or printed onto A4 sheets and folded into a booklet. Just go to higheff.no and type the word "handbook" in the search field to get to the handbook's web page. From there you can download the PDF and view the printing instructions. You can also view the original document the handbook was based on: a more detailed report called Handbook: Energy Collaboration in Norwegian Industry.



High temperature heat pumps as a way to decarbonise Norwegian industry

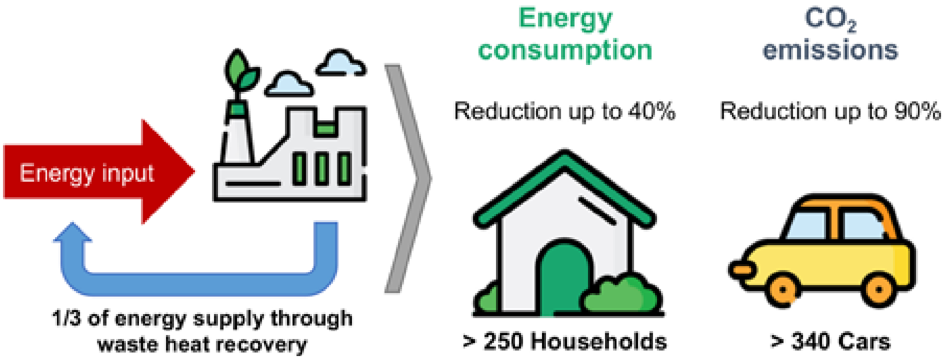
By Marcel Ulrich Ahrens and Sverre Foslie

Many industries requiring both cooling and heating currently have separate systems for the tasks. Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling allow for much better energy efficiency. This results in a corresponding reduction in energy consumption and CO_2 emissions in the industry.

Marcel Ulrich Ahren

Results of a successful integration of high temperature heat pumps

The world's first dairy with a fully integrated energy system using only natural refrigerants without additional use of fossil fuels or electric heaters was commissioned in 2018 and is located in Bergen, Norway. The integration of high temperature heat pumps and thermal storage tanks allowed for an extensive recovery and exploitation of waste heat, accounting for about 1/3 of the required energy consumption. In comparison to traditional dairy plants, the energy consumption was reduced by almost 40% or in absolute numbers by more than 5 GWh per year, corresponding to the equivalent of more than 250 Norwegian households. Thereby, for the integrated dairy, a CO_2 emission reduction of more than 90% is possible (the exact figure depends on the type of energy used – electric heater, natural gas burner or district heating). This will save the equivalent of taking more than 340 petrol cars off the street.



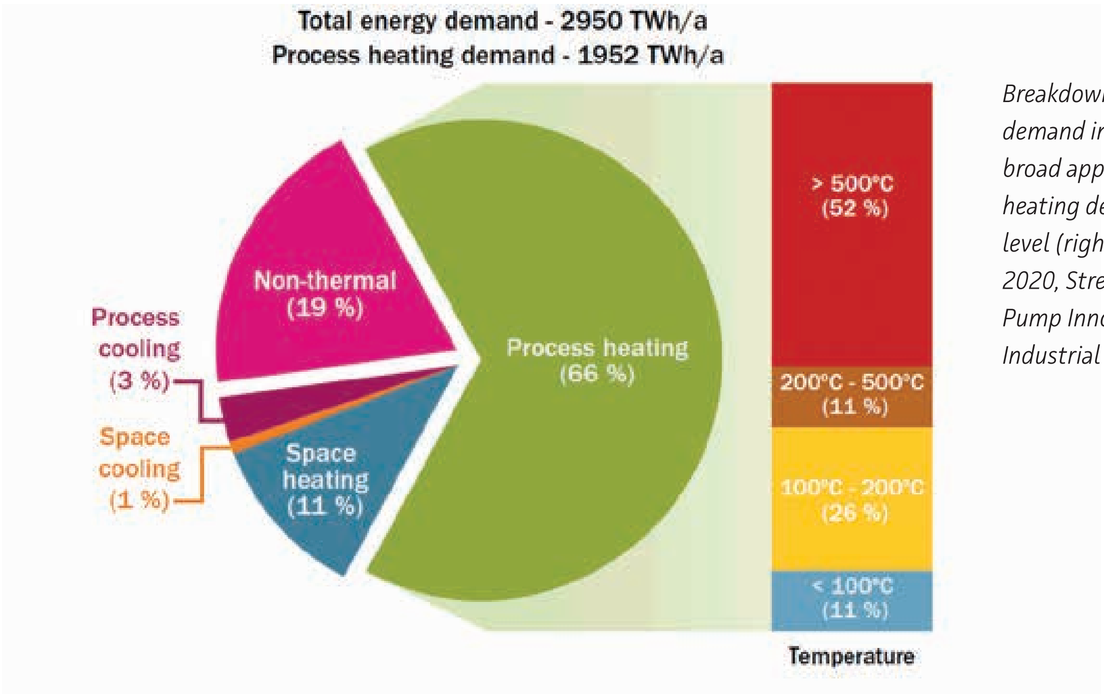
Achieved reductions in energy consumption and CO_2 emissions

Why is the decarbonisation of industrial processes important?

Decarbonisation of the industrial sector is one of the most important keys to reduce global warming. Many industries are facing increasing energy demands which result in increasing greenhouse gas emissions due to the use of fossil fuels. About 2/3 of the demand is to provide thermal energy for process heating. Additionally, several industrial processes have a thermal demand for heating and cooling at the same time. Many examples can be found in the food processing sector as well as various emerging applications with growing importance, such as the operation of data centres or the production of batteries. Here, waste heat is often available in temperature ranges that do not allow for direct use – or where the demand at the given temperature level is insufficient.

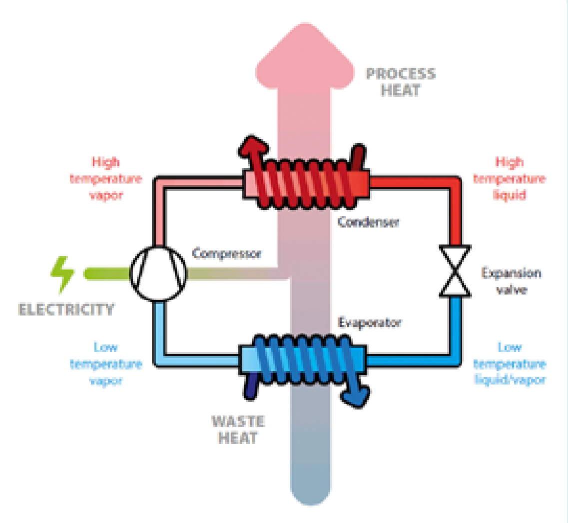
How high temperature heat pumps contribute to the decarbonisation

Heat pumps upgrade heat from a low temperature level (waste heat) to a high temperature level (process heat). This is achieved by applying additional energy, which in most cases is electricity. The usable heat output is usually greater than the electrical input by a factor of 2 to 5, which makes the implementation of heat pumps very effective for the transfer of any type and amount of heat. This ratio of heat output to electrical energy input is known as the coefficient of performance (COP) and is used to describe the efficiency of a heat pump.



Breakdown of the final energy demand in European industry by broad application (left) and process heating demand by temperature level (right). Source: de Boer et al., 2020, Strengthening Industrial Heat Pump Innovation – Decarbonizing Industrial Heat (whitepaper).

HOW DOES A HEAT PUMP WORK?
The most common system is the vapor compression cycle, where a refrigerant undergoes various changes of state in a closed circuit. Starting from the low-pressure side in the evaporator, heat is transferred from the source to the refrigerant while the liquid evaporates. Through the compressor, the vapor is then lifted to a higher pressure and temperature level. In the condenser, heat is transferred from the refrigerant to the sink while the vapor condenses back to liquid. Finally, the expansion valve expanse the liquid back to the low pressure and temperature state closing the cycle.



Simplified illustration of a vapor compression heat pump – Source: de Boer et al., 2020, Strengthening Industrial Heat Pump Innovation – Decarbonizing Industrial Heat (whitepaper).

Traditionally, heat pumps have been used almost exclusively for either cooling or heating purposes, transferring heat to or from external sources such as ambient air or groundwater. In terms of higher efficiency and due to the given requirements in many industrial processes, the best way is to use both functions of the heat pump combined. By integrating high temperature heat pumps, waste heat from cooling processes can be upgraded to valuable process heat, significantly reducing the demand for electricity or other primary fuel sources. This both increases the overall energy efficiency and reduces the dependence on external conditions compared to conventional processes against ambient temperature. Consequently, this is one of the most relevant technologies for the utilisation of waste heat, which is likely to experience a growing demand in the near future.

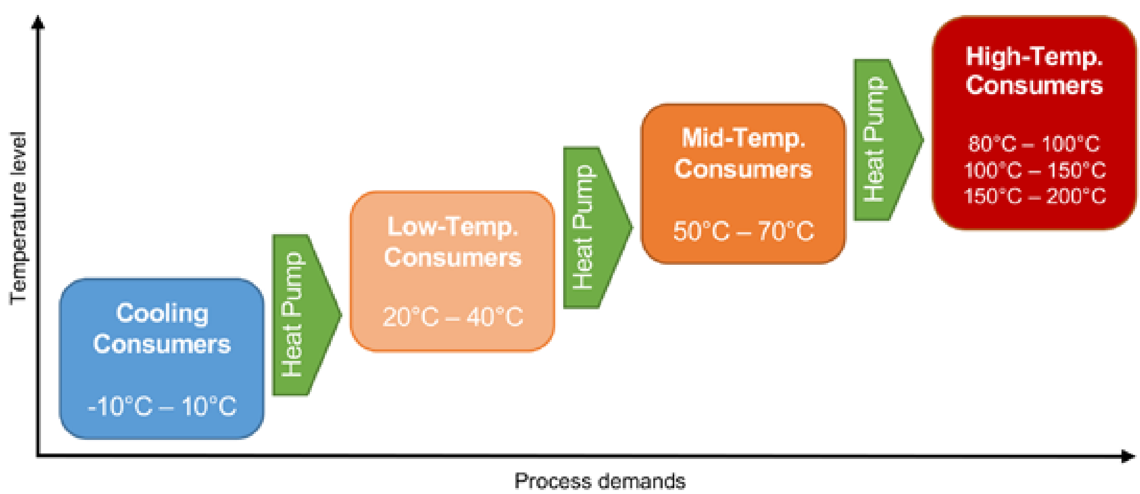
Ways to integrate high temperature heat pumps in industrial processes

The processing of dairy products requires large amounts of process cooling and heating. Traditional dairies often use stand-alone solutions to supply the various demands. Here, cooling is provided by a refrigeration system that releases surplus heat to the environment. Required process heat is provided by fossil fuel burners or electric heaters, both with efficiencies below 1 (compared to the COP of heat pumps ranging from 2 to 5). By using high temperature heat pumps to integrate the process, the waste heat from the refrigeration system can be upgraded to meet the process heat demand. An installation of several heat pump stages with heat storage tanks can further increase the efficiency in many cases. This is because processes often consist of consumers at different temperature levels and the demands can occur cyclically (in batch operation). An example of such an integrated heat pump system, where both cooling and heating demands are supplied by heat pumps at different temperature levels, can be seen in the figure.

A good integration results in extensive use of the available waste heat and thus a reduced demand for external energy inputs. During the investigation of the initially mentioned dairy, the process achieved a waste heat recovery rate of over 95% with a COP above 4 for the overall dairy plant.

What is important for the future?

With the aim of making industrial processes more efficient and decreasing greenhouse gas emissions, HighEFF – Centre for creating a competitive, energy efficient and environmentally friendly industry for the future is developing, testing and evaluating this and other solutions together with industry partners. The results of the investigated dairy have shown that the integration of high temperature heat pumps offers great potential for the decarbonisation of industry. The demonstration of possible applications and operating data of high temperature heat pumps will help to increase confidence and acceptance among potential users.



Possible process integration of heat pumps for consumer at different demand levels.

This article is based on the research paper titled "Intregrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry", which was published in the Applied Thermal Engineering Journal in 2021.

PhD work done within HighEFF

Recirculating exhaust gas in silicon production

A step towards carbon capture

By Vegar Andersen, Ragnhild Jensen and Ingeborg Solheim

Operator from Elkem Thamshavn draining liquid silicon from the furnace.


Photo: V. Andersen

Vegar Andersen

Silicon production involves releasing CO_2 in the atmosphere – about 5 tonnes of it for every tonne of silicon. CO_2 capture is a solution being explored to remove these emissions, but the CO_2 concentration in furnace exhaust gasses is often too low to make CO_2 capture possible cost-effectively. One possible solution to this problem is to increase the CO_2 concentration by recirculating the exhaust gas. Silicon manufacturer Elkem tested this in a pilot project, together with NTNU and SINTEF.

Ambitions for a carbon-neutral production

Silicon production is an important industry for Norway. Silicon is used in electronics, solar panels, silicone, and as an alloying element in casting alloys. Silicon production is done by carbothermal reduction of quartz, and results in relatively large CO_2 emissions.

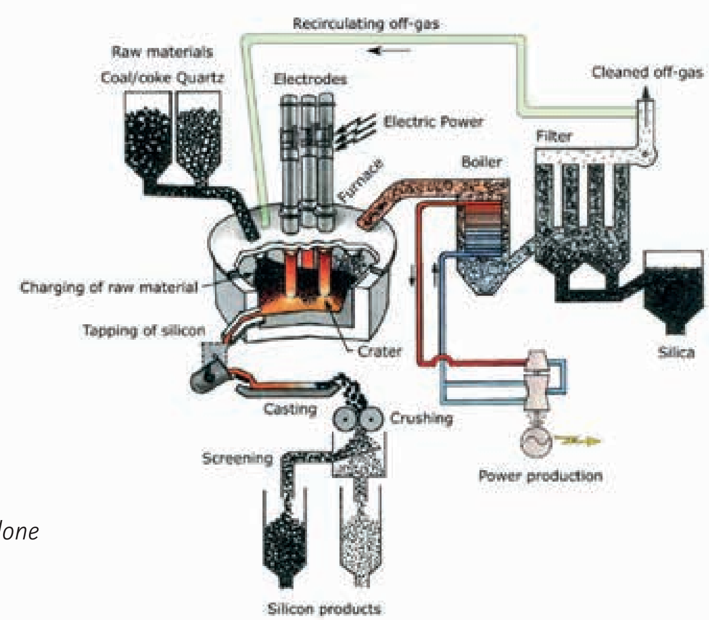


Illustration that shows how recirculating off-gas can be done in the silicon production process. Illustration modified. Illustration: Halvard Tveit, Elkem (CC BY-SA 4.0).

A look at the process of silicon production. Process gas burns over the raw materials in contact with air and recirculated exhaust gas.

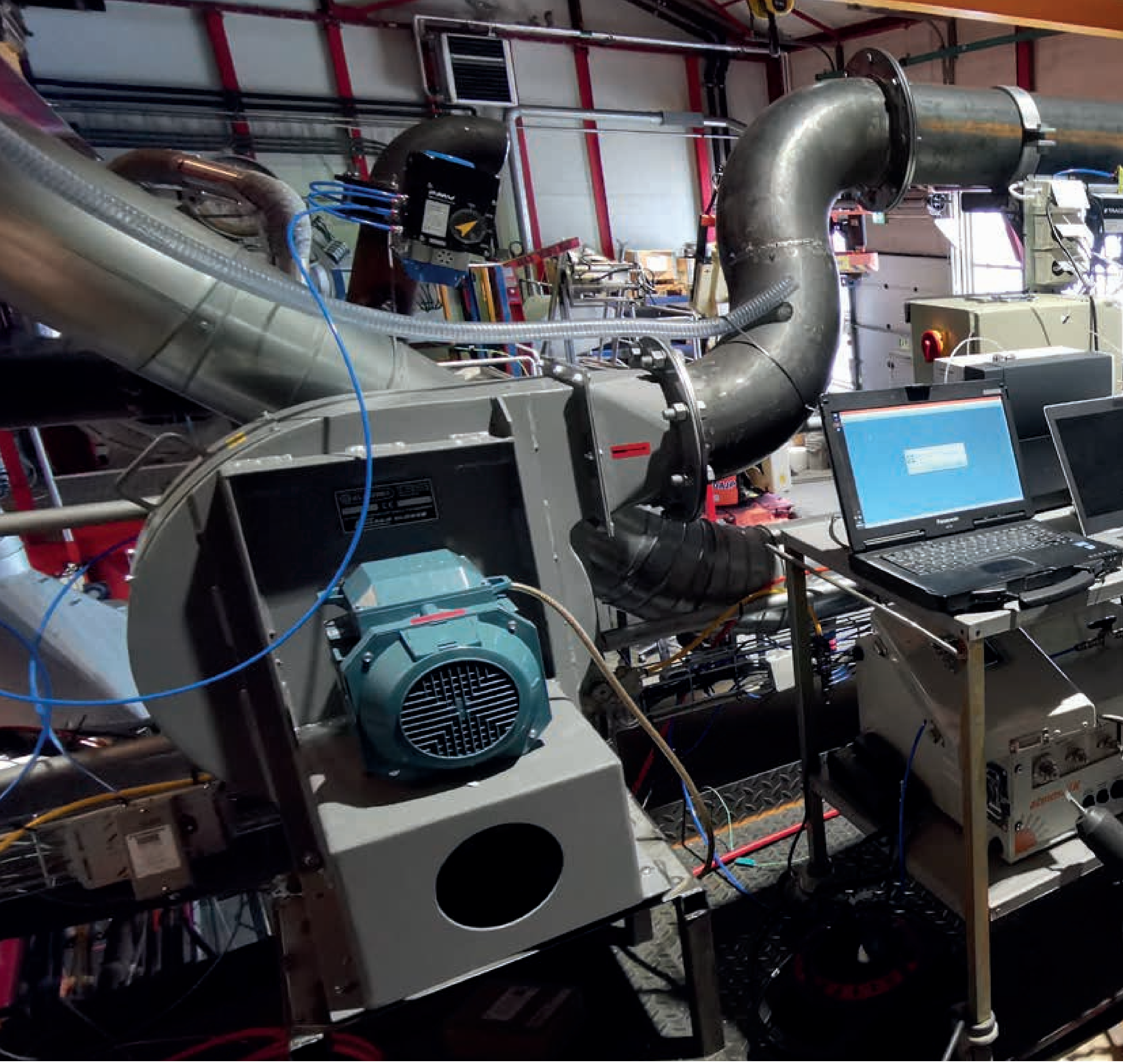
Elkem strives to achieve carbon-neutral metal production, and has launched several initiatives to reduce its climate footprint. Energy recovery, increased use of biocarbon materials and improved material yield are included in this work.

In addition to these measures, solutions must be found to enable CO_2 capture from the furnaces. Elkem conducted an initial carbon capture study, with support from the CLIMIT program. To different capture technologies were examined, in collaboration with Aker Carbon Capture and Saipem, respectively. Norsk Energi contributed to assessing optimal solutions for energy supply and recovery. One of the challenges of CO_2 capture from melting furnaces is that the CO_2 concentration in the exhaust gas is low, typically just a couple of percent. This makes setting up an integrated carbon capture plant both costly and technically challenging.

As a possible solution to increase the CO_2 concentration in the exhaust gas, Elkem – together with the research community at NTNU and SINTEF – is looking at recirculating exhaust gas. By replacing a portion of the fresh air that is normally added to the furnace with recirculated exhaust gas, cleaned of particles and cooled down, the CO_2 concentration of the exhaust gas will be increased. This is a well-known technology for NOx reduction in incinerators, but the method remains to be tested in practice for silicon melting furnaces.

The pilot project

To map the effects on the smelting process of such off-gas recirculation, a pilot scale experiment was carried out at NTNU and SINTEF's pilot laboratories at Gløshaugen, in Trondheim. There, research scientists built a unique recirculating plant around an existing 160 kW single-phase melting furnace. To obtain as much information as possible on the effects of recirculation, the furnace was equipped with instruments and analysis equipment. These would help gathering knowledge about the impact of recirculation on other products and emissions from the furnace.



The pilot project was achieved through a broad and very good collaboration between the Elkem projects Elkem CCS and Elkem Sinoco2, as well as FME HighEFF and SFI Metal Production. During an 80-hour test run, different recirculation rates were tested and mapped. Elkem provided skilled operators from Elkem Thamshavn, as well as raw materials, while SINTEF and NTNU were responsible for controlling the furnace and performing the measurements. By increasing the proportion of recirculated gas, CO_2 concentrations above 20% were achieved. A lower NOx production was also observed as the recirculation proportion increased.

A lot of data analysis remains to be done to interpret these results, but the experiment shows that recirculation has a lot of potential to reduce NOx

emissions and make CO_2 capture easier for the silicon production process. The unique infrastructure built in Trondheim will be very valuable for future experiments and projects aiming at making metal production more sustainable in Norway and around the world.

Above: Both the exhaust gas and the combustion air were analysed using two gas chromatographs, FTIR spectroscopy and LaserGas II instruments from NEO Monitors AS.

Cold thermal energy storage: boosting the efficiency of refrigeration systems

By Håkon Selvnes, Research Scientist at SINTEF Energy Research and former PhD Candidate at FME HighEFF

Large savings can be made by using refrigeration capacity during off-peak hours and "storing the cold" for when it's needed.

Photo: Allsidig Design

Håkon Selvnes

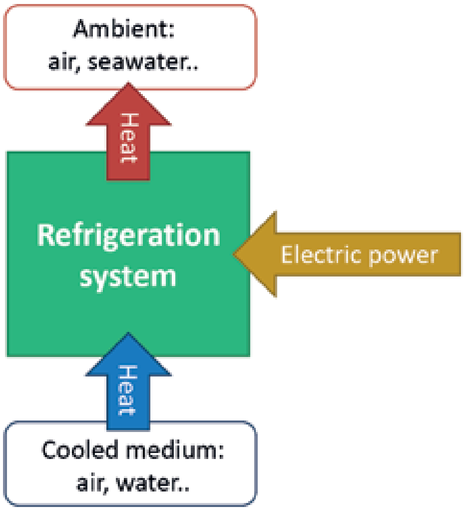


Figure 1: Principle of a refrigeration system.

About Refrigeration

Refrigeration is a key part of modern society, whether to ensure a comfortable climate in our homes and offices by air-conditioning or to keep our food cold to preserve its quality and reduce waste. The refrigeration systems we normally encounter in our daily lives, such as the domestic refrigerator and freezer, use electric power to operate. Figure 1 shows the principle of operation of a refrigeration system.

The purpose of the refrigeration system is to remove heat from a medium we want to cool and reject this heat to the ambient. Using the refrigerator at home as an example: We want to keep the air and products inside the refrigerator cold to prevent the food from going bad. The fluid (refrigerant) in the refrigeration system absorbs heat from the air inside the refrigerator and rejects the heat to the ambient air inside your kitchen. The process of transferring heat from a location of low temperature (air inside the refrigerator) to a location of high temperature (air in the kitchen) is driven by a compressor, which requires electricity.

As a general rule of thumb, the larger the difference between the low temperature and high temperature, the more electricity is required to transfer the same amount of heat. In essence, air conditioners, supermarket refrigeration systems and industrial refrigeration systems in processing plants follow this principle of operation, just with different ambient conditions and mediums to be cooled.

The electricity demand is growing worldwide due to the ongoing decarbonisation of industry and transport, as a measure to reduce emissions of greenhouse gases. Large growth in the refrigeration and air-conditioning markets, particularly in emerging economies such as India, is one of the largest drivers of the global electricity demand. The International Energy Agency predicts that air-conditioning for the residential and commercial sector is going to cause up to 40 % of the peak electric power demand in warm climates by 2050 if the current trend continues. For this reason, it is important to spread the knowledge and implementation of sustainable and clean cooling technology to emerging economies.

SINTEF participates in the project Future Refrigeration India (INDEE+), an umbrella project funded by the Norwegian Ministry of Foreign Affairs covering several dedicated projects supporting the Indian refrigeration and air conditioning sector in the transition towards more environmentally-friendly technology. Refrigeration technology is essential in the entire food cold chain from farm to fork, and is responsible for a significant share of the global greenhouse gas emissions. This is addressed in the SINTEF-coordinated EU Horizon 2020 project ENOUGH.

TES technology

To cope with the challenges of peak power consumption in refrigeration processes, technology that can provide flexibility to these systems has gained significant interest over the last decade. Cold thermal energy storage (CTES) is a technology that relies on storing thermal energy at a time of low demand for refrigeration and then using this energy at peak hours to help reduce the electricity consumption of the refrigeration system.

Figure 2 shows the principle of operation for a refrigeration system with and without thermal energy storage for a typical daily load in a processing plant. We see that without CTES the refrigeration system must provide exactly the same amount of cooling as required by the process throughout the day. This means that the maximum installed capacity of the refrigeration system has to be equal to the maximum thermal load experienced in the process. Looking at the situation when thermal energy storage is implemented gives a completely different picture: cold thermal energy can be stored by operating the refrigeration system during off-peak periods (nights, weekends). During peak hours, a part of the thermal load is covered by the storage and the rest is covered by the refrigeration system. Consequently, the refrigeration system can be dimensioned closer to the average thermal load rather than the peak thermal load. This could mean a significant reduction in investment costs for the plant owner, as well as reduced operating costs due to limiting the electricity consumption of the plant during the most expensive hours of the day.
So how can thermal energy be stored and transferred conveniently for refrigeration systems? The two key factors addressing this question are the medium in which the thermal energy is stored and how the storage is connected to the refrigeration system.

There are two methods of storing thermal energy in a material: By changing the temperature of the material (sensible CTES) or by changing the phase of the material from liquid to solid (latent CTES). Figure 3 describes the difference between these two methods. We observe that for a given temperature limit, latent CTES can store additional thermal energy compared to sensible CTES due to the change of phase occurring at a constant temperature (Figure 3 right). In most materials, including water, the amount of energy stored in the phase change from liquid to solid is

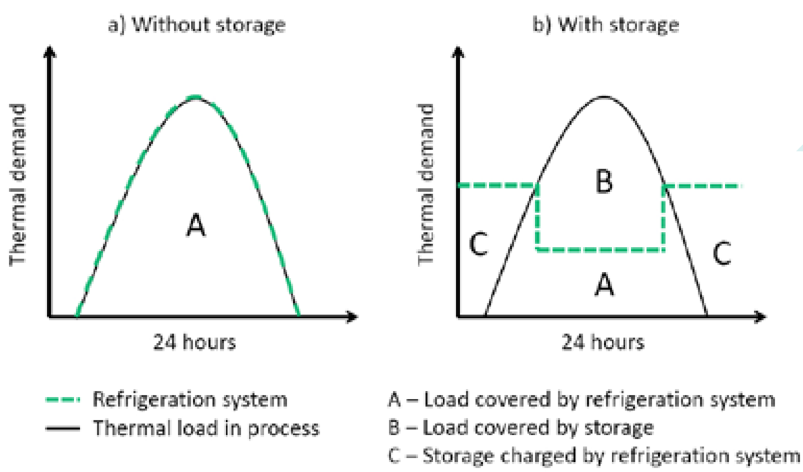


Figure 2: Operating a refrigeration system in a process a) without thermal energy storage b) with thermal energy storage.

many times larger than the energy stored by change of temperature for practical temperature ranges. A common term for materials where the latent heat capacity is used for the purpose of storing thermal energy is phase change materials (PCM). For the interested reader, the topic of PCMs was described in detail in a previous SINTEF blog post, covering the benefits and challenges of these materials.

The main benefit of PCMs related to CTES for refrigeration systems is the possibility to store and release thermal energy at a constant temperature, which matches the process in the refrigeration system very well. PCMs have become an emerging product on the market, and PCMs with a phase change temperature down to -40 °C are available.

CTES technology is not a new idea: cutting and exporting natural ice was a big business in Norway before modern refrigeration technology was invented. Fuelled by the energy crisis in the western world during the 1970s and early 1980s, there was an increased focus on energy efficiency and novel technology development in industry, government and academia. This once again sparked the interest for CTES technology among researchers and in the industry.

One of the outcomes was the completion of several demonstration projects in the US, Canada and Japan where CTES technology was implemented in large chillers for air-conditioning systems. The principle was storing cold energy in large cold-water tanks or tanks filled with ice to serve the cooling demand during peak summer periods where extra refrigeration capacity was needed, and the supply of electricity was limited and expensive. A glycol solution was circulated in tubes inside the tanks to transfer the heat to and from the storage and the refrigeration system.

This principle works well if the temperature required by the process is above the freezing point of water, such as for air-conditioning. The required temperature is significantly lower in many processes, and the

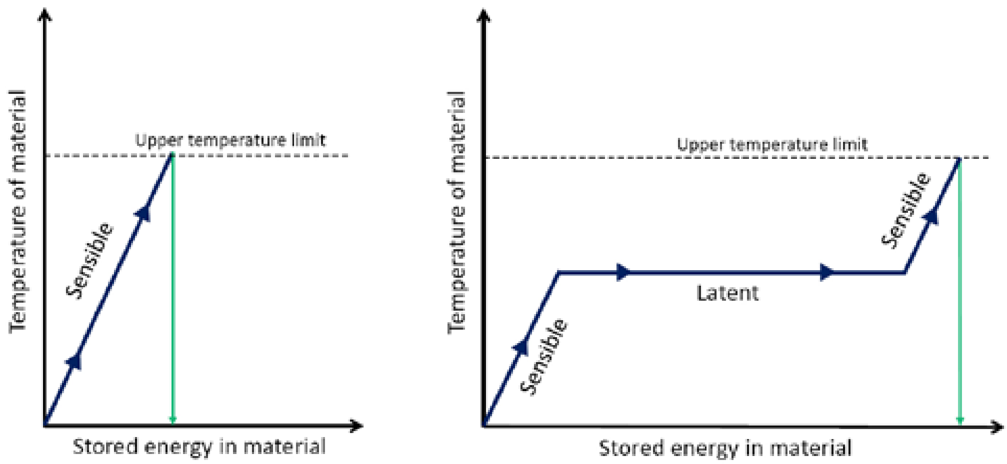


Figure 3: Comparison of storing thermal energy by latent heat and sensible heat in a material.

temperature for a CTES system must follow. The penalty in energy efficiency by using the intermediate heat transfer circuit between the refrigeration system and the storage is significant for low-temperature CTES.

The HighEFF cold thermal energy storage solution

A crucial aspect of the research covering thermal energy storage in HighEFF is developing new solutions and the hardware that allows for direct connection between the refrigeration system and the storage. For my PhD project in HighEFF, I investigated the potential for integration of CTES technology in industrial refrigeration systems. One of the motivations for doing this was the planned construction of a new poultry processing plant of Norsk Kylling in Orkanger, owned by HighEFF partner REMA 1000. Innovative energy concepts for creating a plant with a low carbon footprint were planned, where thermal energy storage technology was indicated as one important factor to reach the targets, both on the cold and hot side of the processing plant. The challenge was that a suitable technology was not yet ready for the cold side. This constituted a hurdle to fulfilling the complete energy concept of the plant.

Developing an energy efficient CTES unit suitable for industrial refrigeration became the main focus of the research, with relevance to the entire Norwegian food processing industry. A well-designed CTES unit for this application must be compact, provide efficient heat transfer to and from the storage and be suitable for upscaling to fit multiple load characteristics and storage requirements. It became clear that using PCMs was the solution to pursue, due to the large thermal energy storage capacity they provide.

To make a qualified judgement on the state-of-the-art CTES technology using PCMs for refrigeration systems, it was necessary to screen the existing literature on the topic. The previous research on low-temperature PCMs, characterisation methods and applications of CTES technology in various parts of the refrigeration sector was collected and systemised in a review paper.

Based on the findings, a prototype of a CTES unit was designed and constructed in cooperation with Skala Fabrikk in Trondheim. The unit was based on a special type of heat exchanger plate called pillow plates that were suitable for handling the pressure in CO_2 refrigeration systems used in many food-processing plants (see Figure 4a). The novelty of the new CTES unit was connecting the storage directly into the refrigeration system, avoiding any intermediate circuit of heat transfer fluid. The heat exchanger is immersed in the PCM, which solidifies during the charging process of the storage and melts during the discharging of the storage. An experimental test facility was designed and constructed at the refrigeration laboratory at NTNU Gløshaugen to map the performance of the newly developed CTES unit. Figure 4 shows the different components of the CTES unit before its installation in the laboratory's test facility.

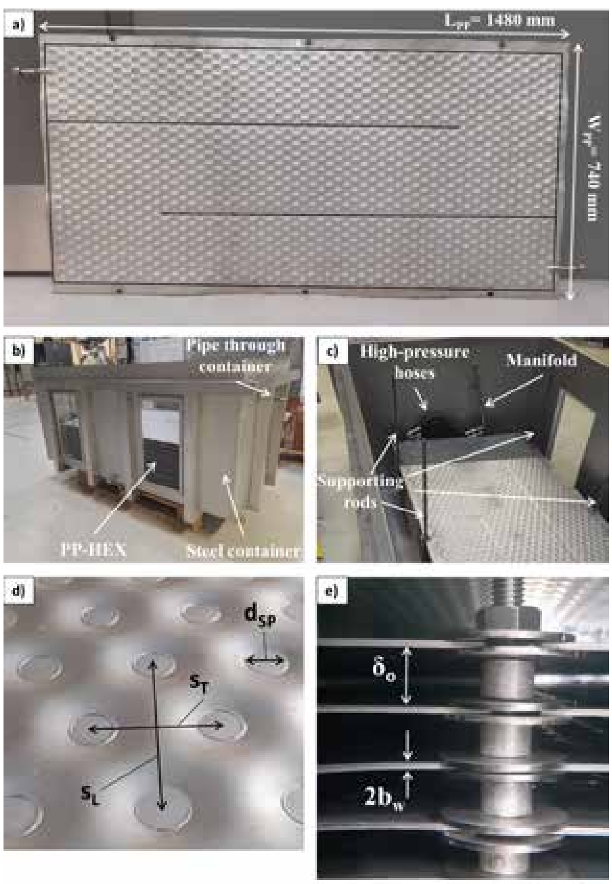


Figure 4: The developed cold thermal energy storage unit in HighEFF with pillow plate heat exchanger inside a container filled with phase change material.

Several test campaigns were carried out with different PCMs and heat exchanger configurations. The experimental test campaign showed that connecting the refrigeration system directly with the CTES unit was feasible, and successfully demonstrated the pairing of solidification/melting of the PCM with the evaporation/condensation process of the refrigeration system. It was found that the most important parameter affecting the performance of the unit was the temperature difference between the PCM and the refrigerant inside the CTES unit, both for the charging and discharging process. It was also found that the performance of the CTES unit can be manipulated by changing the distance between the pillow plates in the heat exchanger (see Figure 4e). Further development and refining of the CTES unit would be beneficial, particularly on the topic of establishing a control strategy for achieving a more constant heat transfer rate from the storage during the discharging process.

The way forward and ongoing activities

There is an increasing interest in CTES technology from both the Norwegian industry and government, as well as internationally. The research and knowledge on CTES technology generated within the PhD project at HighEFF continue to be applied within several other areas of the centre where storing thermal energy is relevant, such as in heat pump and refrigeration processes. Further development of CTES technology for refrigeration systems is the key activity in the SINTEF-project KPN PCM-STORE. The main objective is to develop the knowledge required to implement affordable and efficient low-temperature PCM-CTES units for applications in the food industry, with applications spanning the temperature range from 5°C to -50°C.

Thermal energy storage has also been identified as an important enabling technology when shifting to future low-emission propulsion systems in the maritime transport sector, such as LNG, battery-hybrid and fuel cell technology. The development of innovative and integrated cooling and heating concepts onboard modern cruise ships are investigated in the project KPN CruiZE, where storing thermal energy is central to maximise waste heat and cold utilisation. Innovative concepts and design methodologies for low-emission hotel facilities onboard passenger boats are being developed in the project IPN Lowpass, where integration of thermal energy storage technology is an important aspect.

The next step for CTES technology using PCM will be taking the results and knowledge obtained from the laboratory tests and simulation studies to design a pilot installation together with a relevant industrial partner, proving the field performance and benefits of the technology in a real process. At the processing plant of Norsk Kylling, a steam accumulator operating as a high temperature thermal energy storage has been realised with support from ENOVA. For the low temperature CTES system developed in the PhD project, the refrigeration system at Norsk Kylling is prepared for a pilot installation. Plans are to install a pilot CTES system at the plant as soon as a vendor is ready to deliver the technology. CTES pilot installation are also currently being discussed for the dairy industry and in supermarket refrigeration systems. The experience gained from field tests will be important for the stakeholders in the industry to gain confidence in CTES technology, demonstrating the potential of the technology and ensuring further implementation across multiple sectors.

Vision and goals

Vision

Joint effort for creating a competitive, energy efficient and environmentally friendly industry for the future

Energy preservation and security is a global challenge. There is a global shortage of energy supply, and the way we use and produce energy today is causing greenhouse gas emissions contributing to climate change.

Norway and the EU have ambitious targets towards energy and climate. At the same time, there will be an increased demand for energy in the years to come. There is a clear need for reduction in industrial emissions and more effective industrial energy systems. If an industrial plant becomes more energy efficient, there will be more available energy for other purposes. Norway also depends on being more energy efficient to maintain a competitive industry in the future, both nationally and internationally. As part of solving this problem, FME HighEFF was established in 2016.

Goal

HighEFF will spearhead the development and commissioning of emerging, energy efficient and cross-sectorial technologies for the industry, and:

- Enable reductions of 20-30% in specific energy use and 10% in emissions through implementation of the developed technologies and solutions for the HighEFF industry partners, thereby supporting the ambitious targets set by the EU and national authorities.
- Allow value creation for Norwegian industry by developing 15 to 20 new innovative solutions for energy and cost-efficient plants, energy recovery and use of surplus heat.
- Develop methods and tools for analysis, design and optimisation of energy efficient systems.
- Build an internationally leading Centre for strategic research within industrial energy efficiency.
- Generate 6 KPN, 8 IPN, 6 DEMOS and 4 EU spin-off projects.
- Enable competence building by educating 22 PhD/Postdoc candidates, 50 MSc candidates, and training/recruiting 30 experts in industrial energy efficiency.
- Disseminate and communicate project results; 150 journal articles and conference papers.

Gender equality

HighEFF maintains a list of people involved in centre activities. Our list for 2021 shows a total of 169 men and 71 women. For the Research and innovation partners taken together, the numbers are 70 men and 25 women. The centre's six research areas are led by 4 women and 2 men. Of the 25 recruited PhD candidates, 9 are women and 16 are men. The topic of gender equality was discussed at this year's contact meeting with the Research council, and we got several suggestions on how to improve the situation (with regards, for example, to the Board and industry representation).

How we work together

The vision of HighEFF strongly relies on creating good arenas for cooperation between industry, academia and research partners. Our vision is founded on the words of Professor Arne Bredesen, who stated that excellent research is best produced through three means: knowledge, friendship and teamwork. HighEFF will build upon and bridge these means through common goals, joint research and teamwork.

In 2021 we felt, much like in 2020, the effects of the COVID-19 pandemic. Maintaining contact with the consortium at the same level as before has proven a challenge. With partners from a wide range of business areas, it is only natural that they have felt the effects of the pandemic in different ways. Nevertheless, all partners have complied with their commitments to HighEFF.

In addition to all the meetings for specific sectors, research areas, topics, activities or tasks, 2021 saw the following larger meeting places and workshop open for all partners:

- The Annual Consortium meeting was held on 19-20 May
- The Cross-sector Workshop, highlighting communication and Centre results, and discussions about the research planned for the coming year, was held on 20-21 October
- The 2021 spring PhD seminar was held on 19 October in connection with the Cross-sector Workshop, with a large interest from both research and industry partners

To ensure that all suggestions and input to research tasks are taken into consideration, the Scientific Coordinator has the overall overview of the Centre's progress.

Cooperation with other FMEs

Energy efficiency is central to the work of many other FMEs (Centres for Environment-friendly Energy Research), and we have a close collaboration with other centres on relevant topics.

- **FME ZEN and FME CINELDI:** Joint workshop with HighEFF in February of 2021 about flexibility in energy systems. Interest was expressed on all parts for continued collaboration on the topic.
- **FME CINELDI:** Laid out plans for collaboration on the topic of the energy flexibility potential of industry clusters as a means to reduce peaks in energy demand.
- **FME NCCS:** Cooperation in the generation of spin-off projects (for example the ADVENCCS application).

Cooperation is important in order to achieve maximum impact. The different centres complement each other in many ways. In its final years, HighEFF will be cooperating with **FME NTRANS** on some policy briefs and position papers – in other words, a collaboration aiming at spreading our common message. This is in line with the guidelines laid out by the board of HighEFF.

Beyond the world of FMEs, HighEFF is also collaborating with another research centre: the petrocentre LowEmission, with a focus on reducing energy use in the oil and gas industry. We also collaborate on many levels with SFI Metal Production, regarding technologies for energy recovery in the metal industry.

WORKSHOP ON THERMAL ENERGY STORAGE FOR INDUSTRY, BUILDING AND MARINE APPLICATIONS 12. NOVEMBER 2021

A workshop on Thermal Energy Storage was arranged for the second time in November 2021, this time as a collaboration between 5 research projects: HighEFF, KSP PCM-STORE, KSP CruiZE, KPN CoolFish & FME ZEN. Applications and opportunities for different TES technologies were presented and discussed, from low to high temperatures and for applications in industry, buildings and marine sectors. The workshop gathered 24 participants physically and 69 online with Norwegian and international representatives from both industry and academia, marking the increased interest towards TES as a solution for reduced peak power demand and increased energy system flexibility in the different sectors.

International cooperation

International cooperation is emphasised in the centre activity. Among the partners in the centre, there are several international universities and research institutions. This also holds for the vendor and end-user partners, as well as many of the Norwegian companies with considerable international activities. This ensures the necessary interaction and input required to focus activities on the challenges faced by industry and the energy system in the transition to a society with considerably lower greenhouse gas emissions.

In the academic cooperation, a concept of double PhDs and MSc studies has been established, meaning that NTNU and an international university both have students within related topics in order to ensure a close exchange and development of knowledge. Furthermore, many of the students have shorter or longer research exchange periods at a partner university. The Scientific Committee monitors the academic production in order to benchmark the activity in an international perspective, as well as giving advice for further scientific focus and direction.

In addition to bilateral cooperation between academic partners, HighEFF has also implemented dedicated cooperation between academic partners and industry partners. This may for instance happen between SINTEF, NTNU, an international university and a specific industrial partner.

International projects: Horizon 2020 and Horizon Europe

HighEFF is involved in a series of international projects funded in whole or in part by the EU.

- **Waste2Products**: The goal of this project is to develop and demonstrate smarte and energy-efficient production technologies and processes for biobased materials and products.
- **GreenCarb**: This project aims to achieve energy-efficient climate control of greenhouses for increased productivity.
- **SuMaFood** (Era-Net BlueBio Cofund): Sustainable preservation of marine biomass for an improved food processing value chain. Drying technology from SINTEF's HighEFFLab will be used.
- **ReHeat**: Utilisation of excess heat from paper production, and upgrading of this heat with a Steam producing heat pump to process steam with a pressure of 5 barG. Capacity of 3-5 MW.
- **Friendship**: Integration of steam producing heat pumps to solar heat production.
- **PREMA**: Energy efficient, primary production of manganese ferroalloys through the application of novel energy systems in the drying and pre-heating of furnace feed materials.
- **TRINEFLEX**: HighEFF partner SINTEF's part of this project involves demonstrating the potential of photovoltaic thermal hybrid solar collector technology in combination with a high temperature heat pump to reduce energy consumption in post-combustion carbon capture.
- **Decagone**: Demonstrator of industrial carbon-free power generation from ORC-based waste-heat-to-energy systems

High Temperature Heat Pump Symposium 2022

29.-30. MARCH 2022

The High-Temperature Heat Pump Symposium addresses challenges linked to the use of high-temperature heat pumps in industry, and shows successful concepts and cases where the technology has been implemented.

The reduction of greenhouse gas emissions is a global challenge for today's and future generations in order to minimise the impact of global warming. In fact, the discussion is no longer if there is a global warming effect but rather *how much* global warming will occur.

The energy demand of the industry stands for around one third of the world's greenhouse gas emissions and for a successful decarbonisation of this sector, new technologies need to be phased in. Today's industry moves towards an electrified energy system based on wind, solar and other renewable sources, as well as more frequent recovery of excess industrial heat. This enables the integration of high-temperature heat pumps for process heat supply, reducing the demand for fossil fuels significantly.

Leveraging the potential of industrial heat pumps is highly attractive since it allows the industry to operate with significantly reduced emission of climate gases. However, there are challenges connected with implementing heat pump technology, especially in high-temperature applications such as industrial processes and district heating. There is a need for technical innovations to achieve lower specific investment costs and increased energy efficiency while maintaining technical feasibility and stable operation.

High-temperature heat pumps are an important research focus of HighEFF's Research Area 3.

High-Temperature
Heat Pump Symposium
Copenhagen 29.-30.3.2022

Gustav Lorentzen Conference 2022
13-15 June 2022

The biennial Gustav Lorentzen conference on natural refrigerants is back in Trondheim, the hometown of Professor Gustav Lorentzen and cradle for the revival of CO_2 as a refrigerant. Over the years, the conference has become an important meeting place for more than 350 experts from industry and research to exchange on the latest advances in the field. The conference typically has 120 presentations in plenary and parallel sessions, more than 50 posters, and world leading keynote speakers from science and government.

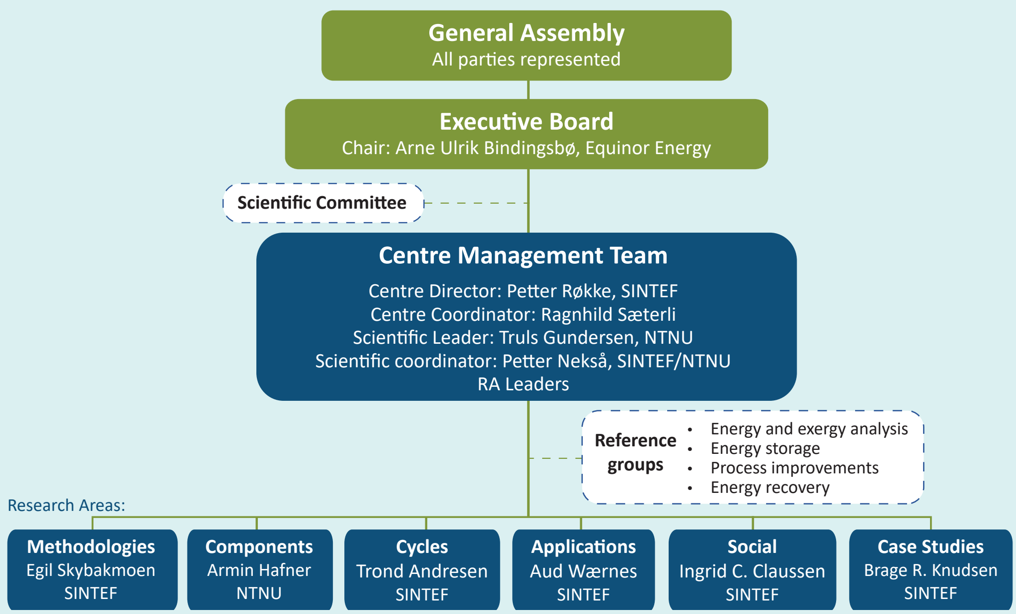
Natural refrigerants are closely examined by HighEFF research scientists, particularly in Research Area 2. The conference promises to be an important highlight of 2022 and to increase the international attention received by HighEFF.

GL2022

15th IIR-Gustav Lorentzen Conference
on Natural Refrigerants

Natural refrigerants are gasses that are already existing in the environment, and that are as such often seen as preferable to synthetic ones. Some synthetic refrigerants that were used in the past were forbidden because they destroyed the ozone layer. Others are being phased out because of their high global warming potential.

Organisation



FME HighEFF is hosted by SINTEF Energy Research. The Centre Director is Petter E. Røkke. The General Assembly (GA) where all industry partners, research partners and the Executive Board Chair are represented, makes all decisions that involve major changes to the consortium. Nancy Jorunn Holt (Hydro Aluminium) was appointed as the GA Chair at the first GA meeting in June 2017. The GA meets at least once a year.

Executive Board

Arne Ulrik Bindingsbø (Equinor Energy) was appointed Chair of the Executive Board at the first GA meeting in June 2017. In addition to Arne Ulrik Bindingsbø, current members of the EB are John Barry (Hydro Energi), Aasgeir Valderhaug (Elkem/Norwegian Ferroalloy Producers Research Association) Terje Lillebjerka (Mo Industripark), Øystein Fjørtoft (REMA 1000 Norge), Anders Sørhuus (REEL Norway), Mona Mølnvik (SINTEF Energy Research), Nina Dahl (SINTEF Industry), Terese Løvås (NTNU), and Per Morten Schiefloe (NTNU Samfunnsforskning). The EB usually holds four meetings a year.

Scientific Committee

The HighEFF Scientific Committee is comprised of three national and three international experts. The mandate of the Scientific Committee is to provide advice on the relevance and quality of the scientific activities for the Centre as a whole, as well as the individual Research Areas. In addition, they will highlight scientific trends, challenges and opportunities, and comment on how HighEFF performs relative to state-of-the-art (whether HighEFF research is world class or not). They will further provide strategic advice on scientific focus and priorities based on the performance of the various Research Areas and Work Packages. Robert C. ("Bob") Armstrong, Director at MIT Energy Initiative, volunteered to act as Chair of the Scientific Committee. The other members are Ignacio E. Grossmann (Former Director CAPD at CMU), Megan Jobson (Professor at Univ. of Manchester), Tor Grande (Vice Dean Research at NTNU), Jack A. Ødegård (Vice President Research at SINTEF Industry) and Kristin Jordal (Research Manager at SINTEF Energy Research).

Centre Management Team

The Centre Management Team (CMT) consists of the Centre Director Petter E. Røkke (SINTEF Energy Research), Centre coordinator Ragnhild Sæterli (SINTEF Energy Research), the Scientific Leader Truls Gundersen (NTNU), Scientific Coordinator Petter Nekså (SINTEF Energy Research), and the six RA leaders. The RA leaders are Egil Skybakmoen (SINTEF Industry), Armin Hafner (NTNU), Trond Andresen (SINTEF Energy Research), Aud N. Wærnes (SINTEF Industry), Ingrid Camilla Claussen (SINTEF Energy Research) and Brage R. Knutsen (SINTEF Energy Research). The CMT handles the strategic and executive centre management, including issues relating to coordination between work packages, and centre performance. CMT arrange regular meetings as needed for coordinating the activities of the Centre. The Centre management reports to EB on scientific, technical, and financial matters as well as actual progress.

Partners

Research & Education Institutes

SINTEF

Nord University

The University of Manchester

Norwegian University of Science and Technology - NTNU

KTH Royal Institute of Technologoy

AIT Austrian Institute of Technology GmbH

NTNU Samfunnsforskning AS

Carnegie Mellon University

Doshisha University

Shanghai Jiao Tong University

MIT Massachusetts Institute of Technology

User Industry

Equinor Energy

Hydro Aluminium

Rema 1000

Eramet Norway

Norsk Alcoa

Elkem

Mo Industripark AS

Gassco

Orkla

Glencore Nikkelverk ASA

TINE SA

Vedde AS,
member of TripleNine Group

Wacker Chemicals Norway AS

Finnfjord

Borregaard

Gether AS

Gether AS

Pelagia

Vendors & Technology providers

Alfa Laval Corp AB

Officine Mario Dorin

Danfoss AS

Parat Halvorsen AS

EPCON AS

MYCOM

REEL International

Hybrid Energy AS

Cadio AS

Enablers

ENOVA

Innovation Norway

HighEFF's Cross-sector Workshop, held on 20-21 October in Hell, near Trondheim, was the Centre's first large in-person event since the start of the pandemic.

Covid-19

HighEFF activities have been relatively unaffected by the pandemic. Research activity was carried out as planned, with the exception of some delays due to difficulties in getting personnel and equipment from abroad in our laboratories. Workshops were mostly held online, and PhD candidates that had planned to carry out some of their work abroad had to redefine their projects to a degree. As a result of pandemic-related delays, some of the PhD candidates obtained extensions to their project time.

Maintaining contact with consortium members at the same level as before the pandemic has been a challenge. Partners were affected by the pandemic to various degrees, which is to be expected since they come from such a broad spectrum of industries. Still, all partners have fulfilled their obligations to the centre, even though some have reported issues with keeping their in-kind contributions to pre-pandemic levels.

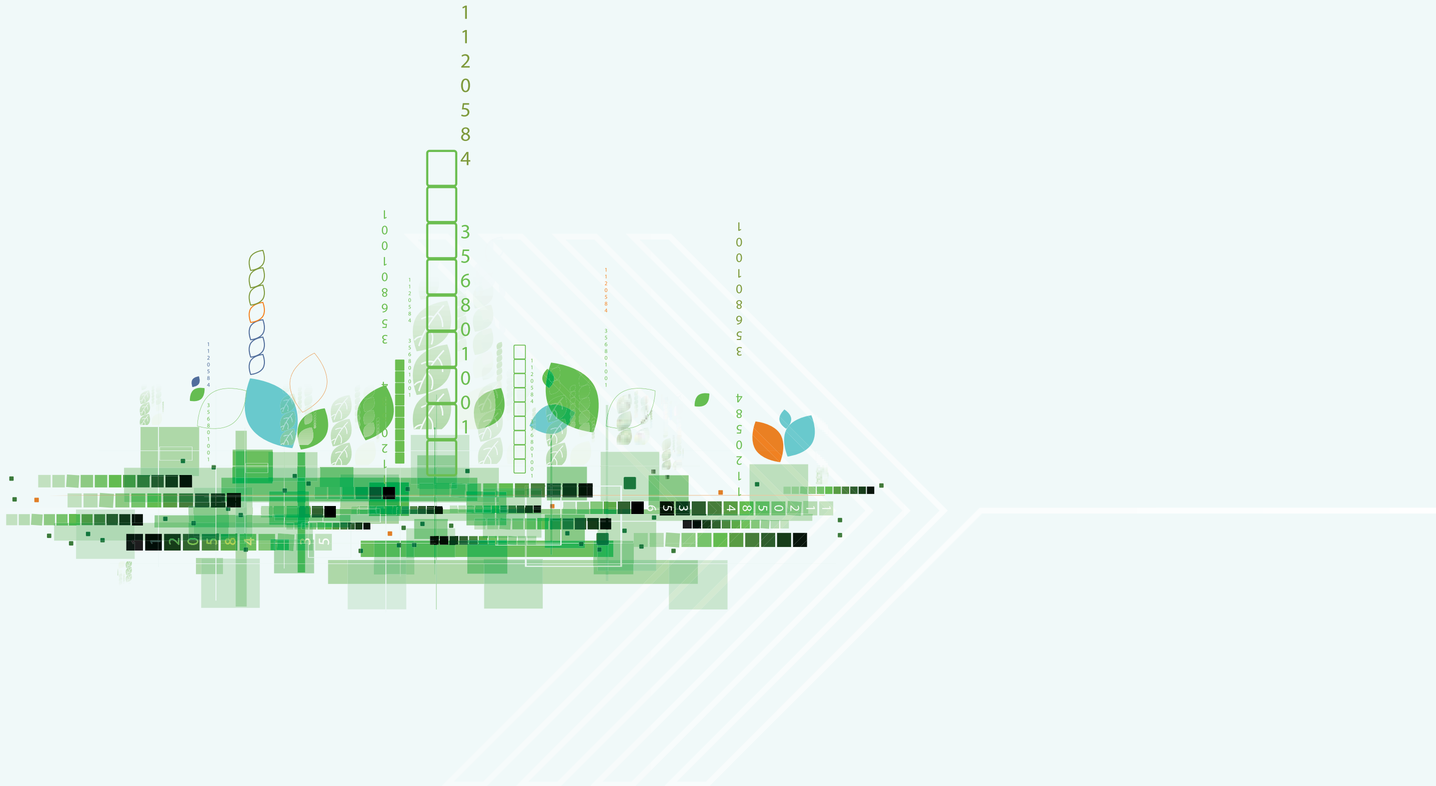
There is some uncertainty as to what impacts the rest of the pandemic will have on the centre, its partners and their economic outlook in the coming months. The centre has an ongoing dialogue with the partners about these issues, through the various research areas and work packages. Aside from the minor adjustments mentioned above, the pandemic has resulted in no significant delays or cancellations in the centre's research activities in 2021.

Innovations

HighEFF adopted the following criteria and definitions of what constitutes an innovation.

An innovation can be a product, a technology, a component, a process or a sub-process, a model or sub-model, a concept, an experimental rig or a service that is new or significantly improved with respect to properties, technical specifications or ease of use. An innovation can also be new application of existing knowledge or commercialisation of R&D results. The innovation should be adopted by somebody or be ready for utilisation provided that it is made probable that the innovation will be utilised within a limited timeframe.

When an HighEFF innovation is recorded, the probability of success and impact is evaluated simultaneously. If both criteria are high, the development of this innovation will continue with considerable effort.



Energy recovery with integrated thermal storage

The significant quantities and high temperature of the heat rejected during ferroalloy casting makes it an interesting source for energy recovery. The heat released during casting is rarely utilised today.

Innovation Type: **Concept**
Development stage: **Theoretical concept studies**
Remaining uncertainties at current stage: ***Few***

TRL: 3-4
Status: In progress, 2022
Contact: Trond Andresen (trond.andresen@sintef.no)

HighEFF Overall Goals	
Energy use & emissions	X
New solutions	X
New methods and tools	

Relevant Sectors	
Oil, Gas and Energy	**Metal and Material**
Food and Chemical	Industry Clusters

CHALLENGE

The casting processes in all Norwegian ferroalloy plants are performed batch-wise, while all common forms of heat utilisation needs a continuous supply. Furthermore, the initial temperatures of the liquid metal during casting are very high, and heat transfer will dominantly occur via radiation. A heat recovery solution will therefore somehow have to surround the metal during solidification. Combined with demand for efficient production and plant logistics, this adds significant complexity to both heat capture and practical power production.

SOLUTION

A new system concept has been proposed and is currently under evaluation and further refinement. The system utilises an actively cooled tunnel to efficiently absorb heat radiation from casting moulds, as well as thermal energy storage to buffer the intermittent heat for consistent and smooth export to heat-to-power conversion, either in a standalone system or integrated into an existing cycle.

POTENTIAL

A 2021 HighEFF case study showed *heat* recovery potential for a single plant of up to 46 GWh/y captured above ~300 °C. With identical applicability across the whole Norwegian ferroalloy sector, this would equate to over 500 GWh/y.

REFERENCE

- Andresen et al., 2020. Dynamic Analysis of Energy Recovery Utilizing Thermal Storage from Batch-wise Metal Casting. IIR Rankine Conference 2020

Coming in 2022: New case study in PhD thesis of Brede Hagen.

Cold thermal energy storage (CTES)

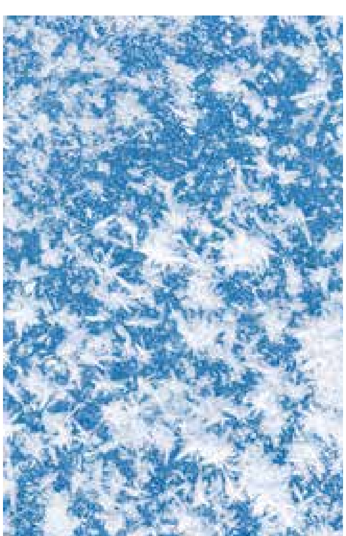
Large-scale cold TES for the food industry to balance between high cooling demand and varying availability of low-cost electricity from renewable sources.

Innovation Type: **Technology**
Development stage:
Lab scale demonstration
Remaining uncertainties at current stage: ***Few***

TRL: 4-5
Status: Finished 2021-05
Contact: Håkon Selvnes
(hakon.selvnes@sintef.no)

HighEFF Overall Goals	
Energy use & emissions	
New solutions	X
New methods and tools	

Relevant Sectors	
Oil, Gas and Energy	Metal and Material
Food and Chemical	Industry Clusters



CHALLENGE

The electricity consumption in the food processing industry is characterised by peaks and valleys due to the throughput of products in energy-intensive refrigeration processes. Refrigeration equipment must be dimensioned according to the maximum load on the warmest day. This strategy results in refrigeration systems that operate on part load for most of the hours.

SOLUTION

A novel CTES unit based on a pillow plate heat exchanger combined with latent thermal energy storage in a phase change material to achieve peak shifting of the refrigeration load. The developed CTES unit can be integrated directly into the refrigeration circuit and can handle the working pressures of CO_2 refrigeration systems (> 70 bar). The temperature which the energy is stored can be varied by changing the phase change material used in the CTES unit. The unit can operate as a thermal battery to store thermal energy at low temperatures (< 0 °C) using the excess refrigeration capacity during the night. During daytime operation, the stored cold thermal energy can be used to unload the compressors and thereby achieve peak shaving of the power consumption. When implemementing this technology the refrigeration system can be designed closer to the mean load rather than the peak load, reducing the investment costs of the plant.

POTENTIAL

The flexible design of the CTES unit enables dimensioning of the storage to a variety of load profiles in refrigeration systems, shaving peaks with a duration from less than 1 hour up to 5-6 hours. The storage capacity and discharging rate of the CTES unit can be increased by installing more units in parallel and increasing the size of the pillow plate heat exchanger.

FURTHER RELATED HIGHEFF WORK

- Demonstrating the use of the CTES unit through pilots at relevant partner industries in HighEFF and KSP PCM-Store (spin-off from HighEFF)
- Simulation studies of CTES design alternatives for commercial and industrial CO_2 refrigeration systems

REFERENCES

- Selvnes, H., Allouche, Y. and Hafner, A., 2021. Experimental characterisation of a cold thermal energy storage unit with a pillow-plate heat exchanger design. *Applied Thermal Engineering*, p.117507.
- Selvnes, H., Hafner, A. and Kauko, H., 2019. Design of a cold thermal energy storage unit for industrial applications using CO_2 as refrigerant. In *25th IIR International Congress of Refrigeration Proceedings*. IIR.

Optimal selection of thermal energy storage technology for fossil-free steam production

Methodology for identifying the most cost-efficient Thermal Energy Storage (TES) and power-to-heat (P2H) system for load shifting and exploitation of fluctuating renewable energy sources in steam production

Innovation Type:
Methodology
Development stage:
Finished
Remaining uncertainties at current stage: ***Applying the methodology to relevant cases***

TRL: 5-6
Status: Finished
Contact: Hanne Kauko (hanne.kauko@sintef.no)

HighEFF Overall Goals	
Energy use & emissions	X
New solutions	
New methods and tools	X

Relevant Sectors	
Oil, Gas and Energy	**Metal and Material**
Food and Chemical	**Industry Clusters**

CHALLENGE

Steam production is still primarily based on the use of fossil fuels, and all the major industrial energy users devote significant proportions of their fossil fuel consumption to steam production. TES combined with P2H technologies such as electric boilers or high-temperature heat pumps (HTHPs) enables the industries to decarbonize their steam production with rather small changes in the infrastructure, and at the same time shift their energy demands to periods with low electricity prices, thus allowing active participation in renewable-based electricity markets.

SOLUTION

An optimization-based method which helps to select and dimension the cost-optimal TES technology combined with P2H for a given industrial steam process has been developed. The storage technologies considered are latent heat TES, Ruths steam storage, molten salt storage and sensible concrete storage. The method is implemented in Python and uses the steam demand and electricity price profiles as an input to find an optimal TES and P2H combination for the application.

POTENTIAL

Steam generation systems were estimated to account for 9% of the global final energy consumption in 2005. Assuming that only 1% of steam demand is stored with a cycle duration of one day, roughly 70 000 steam storages of 100 m^3 are required worldwide – and much more, if a shift to renewable-based steam production is desired.

FURTHER RELATED HIGHEFF WORK

- Apply the methodology for identifying an optimal P2H-TES combination to replace fossil-based steam production at the Nidar chocolate factory in Trondheim.

REFERENCES

- Beck, A., Sevault, A., Drexler-Schmid, G., Schöny, M., & Kauko, H. (2021). Optimal Selection of Thermal Energy Storage Technology for Fossil-Free Steam Production in the Processing Industry. Applied Sciences, 11(3), 1063.

The Nidar chocolate factory in Trondheim.

Flexible offshore oil and gas platform model

Assessing different energy-efficient technologies on a variety of configuration relevant to offshore platforms requires a somewhat generic model. An entirely generic model is not practically feasible. However, a flexible and automated one would prove highly beneficial for various analyses and future use.

Innovation Type: **Model**
Development stage:
Simmulation Analysis
Remaining uncertainties at current stage: ***Few***

TRL: 3-4
Status: initial development and performance validation completed
Contact: Yessica Arellano (Yessica.arellano@sintef.no)

HighEFF Overall Goals	
Energy use & emissions	X
New solutions	X
New methods and tools	X

Relevant Sectors	
Oil, Gas and Energy	Metal and Material
Food and Chemical	Industry Clusters

CHALLENGE

Offshore oil and gas facilities are complex and often unique. Each facility is developed to the requirements of the producing field's reservoir and fluid conditions. Assessing the applicability of low-emission solutions, if no generic model is in place, requires extensive dedicated case studies. A flexible model, validated with real field data from a number of facilities, would ease evaluation and comparison of promising configuration alternatives based on key performance indicators of interest, e.g. carbon footprint, energy efficiency, costs, etc.

SOLUTION

A comprehensive and flexible oil and gas platform model to contrast energy-efficiency solutions and their relative effect in reducing emissions.

POTENTIAL

The flexible offshore platform model developed in HighEFF validated against real data for two platforms in operation. In each case, minimal deviations were illustrated. A 2021 HighEFF case study using the developed model showed that over a 30-year lifespan, a proposed configuration would reduce CO_2 emissions by 54 %. Extended applicability of the model developed for offshore platforms may facilitate important decision support for measures that can reduce the current high level of emissions in this sector.

REFERENCE

- Foulkes, J. 2021, Future Low Emission Oil and Gas Platforms. Master thesis
- Foulkes et al., 2022. Future Low Emission Oil and Gas Platforms (paper under revision)

Energy Recovery and CO_2 Capture for the Aluminium Industry

Presently, close to 40 % of the waste energy generated from aluminium production by the aluminium industry is lost in the off-gas. Also, the CO_2 concentration in the off-gas is very low, thus, making it difficult for economical carbon capture and storage (CCS) by the industry.

Innovation Type:
Process Concept
Development stage:
Theoretical Analysis
Remaining uncertainties at current stage: ***Need to be tested and developed further in pilot scale conditions***

Status: In progress, 2021-06
Contact: Samuel Senanu
(samuel.senanu@sintef.no)

HighEFF Overall Goals	
Energy use & emissions	X
New solutions	X
New methods and tools	

Relevant Sectors	
Oil, Gas and Energy	**Metal and Material**
Food and Chemical	Industry Clusters

CHALLENGE

50 % of the ca. 13.4 MWh required to produce a tonne of aluminium is lost as waste heat during production. Close to 40 % of this waste heat ends up in the off-gases leaving the electrolysis cell. Additionally, the CO_2 concentration in the off-gas is very low for economical carbon capture and storage (CCS).

SOLUTION

A concept involving recycling of the off-gases to increase the CO_2 concentration and recover the waste energy by using a heat exchanger (HEX) provides a possible solution.

POTENTIAL

2 TWh annual energy savings for the Norwegian Aluminium industry
Increased CO_2 concentration in the off-gas to ca. 3-4 vol%
A CO_2 -free aluminium production by 2030 using a suitable CCS technology.

HIGHEFF ACTIVITIES

- WP1.3 and WP4.2 2022: Design a PGR system fitted with a CO to CO_2 catalyser, and HEX unit that fits into the PIA system by REEL Norway.
- WP1.3: Run tests with the installed PGR system to investigate the potential for increased CO_2 and energy recovery.

REFERENCE

- [1] Solheim A, Senanu S (2020): Recycling of the Flue Gas from Aluminium Electrolysis Cells Light Metals 2020, 803-810.
- [2] Senanu S, Solheim S (2021): Gas Recycling and Energy Recovery. Future Handling of Flue Gas from Aluminium Electrolysis Cells Light Metals 2022.

Heat Exchanger test rig

To enable testing of novel heat exchanger prototypes, working fluid mixtures, heat transfer coefficients and pressure drops, a new heat exchanger test rig is constructed in SINTEF and NTNUs thermal laboratories in Trondheim. The rig is designed with a main focus on hydrocarbon working fluids. Heating, cooling, evaporation and condensation experiments can be performed at temperatures from 0 – 150 °C and pressures up to 70 bar(g), for heat exchangers with thermal capacities up to 20 - 30 kW.

Innovation Type:
Experimental rig
Development stage:
Operational rig

TRL: 4, rig for laboratory verification
Status: Operational rig
Contact: Stian Trædal (Stian.Tradal@sintef.no)

HighEFF Overall Goals	
Energy use & emissions	X
New solutions	
New methods and tools	

Relevant Sectors	
Oil, Gas and Energy	**Metal and Material**
Food and Chemical	Industry Clusters

CHALLENGE

New heat exchanger concepts and working fluid mixtures are usually developed using computer modelling and simulations. Promising concepts that emerge needs to be experimentally validated. There are however few existing test rigs to test heat exchangers using hydrocarbon working fluids.

SOLUTION

A new heat exchanger test rig has been built in the HighEFFLab project and was finalised in 2021. The rig design and engineering was supported by simulations and input from RA2.

POTENTIAL

The test rig is operational and can be used to test prototypes and working fluids.

FURTHER RELATED HIGHEFF WORK

Heat exchanger tests are planned within HighEFF

REFERENCE

- https://www.sintef.no/projectweb/highefflab/

Improving prereduction behaviour to decrease energy and carbon consumption

The ore-gas reactions occur in today's process at a temperature range favoring the occurrence of the Boudouard reaction causing increased energy and carbon consumption. It further leads to a high-energy off-gas rich in CO(g).

Innovation Type: **Process**
Development stage: **Theoretical analysis supported by lab scale experiments**
Remaining uncertainties at current stage: ***Some***

TRL: 2-3
Status: On progress
Contact: Trine Asklund Larssen (Trine.A.Larssen@sintef.no)

HighEFF Overall Goals	
Energy use & emissions	X
New solutions	
New methods and tools	

Relevant Sectors	
Oil, Gas and Energy	**Metal and Material**
Food and Chemical	Industry Clusters

CHALLENGE

The ore-gas prereduction reactions in ferromanganese production are well-known to be governed by kinetics and dependent on the characteristics of the manganese ores. Due to complex and multistep reaction schemes, in addition to a high number of commercial manganese ores, the behaviour of the ores in the furnace is not well understood. Promoting optimal reduction while still maintaining operational requirements (e.g. ore size due to decrepitation and fines generation during heating) is thus a complex affair.

SOLUTION

Tailoring the sizing and feed location of the ores:
Size requirements for the ores may be specific for the given ore. Ores are less/more sensitive towards decrepitation, and the reaction rate is more/less promoted by the ores' particle size, so an optimum size range exist for each ore.

Introduction of pretreatment unit:
Utilization of the high-energy off-gas may be utilized through a pretreatment unit. This may also decrease the occurrence of the Boudouard reaction, as well as giving increased stability of the furnace, both resulting in lowered energy and carbon consumption. This is now currently being investigated in the EU HORIZON 2020 PREMA project, where data obtained in HighEFF is used to determine optimum conditions of such a unit.

POTENTIAL

Mass and energy balances show that the Boudouard reaction may typically consume 15-25% of the total energy consumption in production of HC FeMn alloys.

FURTHER RELATED HIGHEFF WORK

- Larssen, T. A., & Tangstad, M. (2021). Off-Gas Characteristics for Varying Conditions in the Prereduction Zone of a Ferromanganese Furnace–A Basis for Energy Recovery. Available at SSRN 3926228.
- Larssen, T. A., Senk, D., & Tangstad, M. (2021). Reaction Rate Analysis of Manganese Ore Prereduction in CO-CO_2 Atmosphere. Metallurgical and Materials Transactions B, 52(4), 2087-2100.

REFERENCE

- Larssen, T. A. (2020). Prereduction of Comilog-and Nchwaning ore. Dr. Ing thesis, NTNU.

RESEARCH AND RESULTS

Methodologies - RA1

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The main objective of Methodologies is to improve existing – and develop new – methodologies for improved energy efficiency in industrial plants. We believe that technological enhancements and diverse innovations are better than cost reductions. For that reason, solutions that are thermodynamically more efficient will serve as our main driver. Also, changes in the framework conditions related to energy, environment, new technologies and markets are closely considered in our work.

A summary of our work in 2021

The activities in RA1 are of fundamental character with a total of 5 PhD students (1 PhD defended in 2020). Due to some delays, we did not have defences in 2021 but we assume there will be 3 defences in 2022. The PhD activities include a close cooperation between MIT and NTNU with one PhD student working on the same topic. There is also an international cooperation between UoM and NTNU with 2 PhD students. Professor Robin Smith from UoM actively co-supervises the PhD at NTNU. Here, the topic is to explore energy storage technologies for the shift from fossil to renewable energy sources for future distributed energy hubs.

Another task in RA1 is to discuss the taxonomy of KPIs within the scope of HighEFF and suggest a basis for common assumptions that can be used for assessing the goals of the HighEFF program.

The evaluation of case studies has been discussed in a delivered report, and the importance of establishing the basis for the comparison is emphasised. A section is also devoted to the Best Available Techniques Reference Documents (BREF) available from the European IPCC Bureau. To enable a consistent evaluation of HighEFF results, it is important to establish a common ground for comparisons. The use of a taxonomy for key performance indicators enables a clearer and unambiguous communication of what the indicator represents. Being clear about the scope and boundaries of the analysis also aids comparisons both against multiple base case references and across case studies. Additionally, it is important to establish common ground by using the same reference parameters and conversion factors, or as a minimum clearly state the basis used. Having a well-defined basis makes sure that the results can be re-assessed if required when the energy market and production technology change. HighEFF has an emphasis on Norwegian industries. With the proximity and close integration with the EU it is a natural choice to adopt the methodology described in the Best available techniques Reference documents (BREF) from The European IPCC Bureau. In some sectors such as the ferro-alloy industries, Norway is a leading country and reference for the BREF. Making systematic use of the available BREFs when establishing reference cases and assessing the innovations is therefore highly recommended.

Also, this year, we have – together with the Aluminium industry: Hydro, Alcoa and REEL Norway – evaluated some ideas concerning the flue gas from aluminium electrolysis plants, focusing on the possibilities for increased heat recovery and increased concentration of carbon dioxide. The emission of CO_2 from the aluminium industry in Norway is at around 2 Mton/year. However, the concentration of CO_2 is only 1 vol % and too low for economic future CO_2 capture technology. Furthermore, close to 41 % of the waste heat corresponding to ca. 3 MWh/ton Al is lost via the flue gas.

Flue gas recycling and energy recovery provide an excellent opportunity for the aluminium industry to reduce the total energy consumption and to prepare for a possible future carbon capture and storage or utilisation technology. Gas recycling enables increased CO_2 concentration and more efficient recovery of energy from the flue gas. The work performed in 2021 presented some of the challenges with this technology, including increased concentrations of other pot gases such as CO, SO_2 and HF and possible increased fugitive emissions due to reduced suction. Increased concentration of CO is particularly unwanted, since it is a lethal compound. Thus, catalytic conversion of CO to CO_2 is crucial for HES (Health, Environment and Safety) reasons, and it also increases the amount of collectible heat. However, high concentration of SO_2 can pose problems to equipment, including the heat exchanger units, due to the formation of sulfuric acid when the acid dew point is reached. Two papers with this topic will be presented at the TMS 2022 conference and a Teams WS with around 30 participants was arranged in December.

The potential for increased heat recovery is huge in the aluminium industry (up to 1.8 TWh estimated in RA1 and RA6), and if part of this energy could be used in the CCS process, it would enhance future developments for CCS from Al electrolysis process in the future. But several technological issues need to be solved before implementation. We will address those topics in more detail in 2022 together with our industrial partners.

Senanu, Solheim and Skybakmoen also published a popular science article in Gemini and TU "Sju veier til grønnere aluminium" in July 2021, with many comments as well.

Components – RA2

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Our main objectives are to develop components required for cost-effective implementation of efficient systems for heat pumping and conversion. The focus is on heat exchangers, compressors and work recovery.

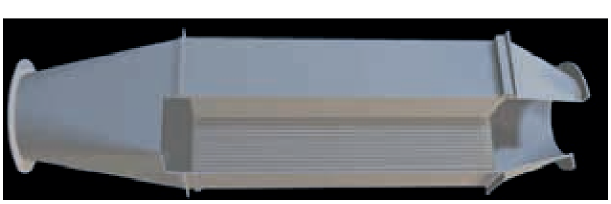
To achieve these goals, we develop methods and tools required for designing components. Focus is given to cycles with natural working fluid mixtures, thermodynamic properties, system optimisation, and experimental development. The research area also performs design, support integration and maintains flexible component test facilities for the HighEFFLab infrastructure.

A SUMMARY OF OUR WORK IN 2021

Heat Exchangers

VARGEO

In order to realise useful heat recovery from off-gas cooling, it is important to get the size of the large heat recovery heat exchanger (HRHE) to an acceptable level. Another issue is that the off-gas contains particles. The target is to design a heat exchanger that will have low velocities at the inlet, to avoid particles entering further into the heat exchanger – but for good heat transfer properties, the gas should accelerate once inside.



In 2020, we studied such a HRHE by extending the general heat exchanger modelling framework to create a simulation model that allows the geometry to be adapted to the changes in the off-gas conditions. In 2021 the variable geometry model was extended to have a continuous change of flow area on the hot and cold side represented by a smooth curve. In addition, the shape of the curve was added into an optimisation framework so that such a heat exchanger could be designed for minimum weight given an allowable off-gas pressure loss and required duty.

CFD MODEL

Much of the work in WP2.1 is to develop models and methodology to study the simultaneous effects of process and heat exchanger geometry optimisation. The methodology depends on the underlying physical descriptions being valid over the operating range and on the models including the effects of all the geometry parameters subjected to optimisation. The underlying models are developed by laboratory measurements, but to be able to "measure" over a wider range of geometries these can be supplemented with Computational Fluid Dynamics (CFD). In 2020, we have established a link between the optimisation models and a CFD model, so that we can numerically verify the result. This led to a paper where we compared CFD results with literature data from experiments, and with results from the developed heat exchanger optimisation model using a traditional tube-in-fin heat exchanger as case. This work continued in 2021 in combination with a NTNU master's student's work.

Work Recovery & Compressors

The R&D focus is tuned towards compressors and technologies for expansion work recovery. The application of environmentally friendly and future proof natural refrigerants is a novelty of the research conducted by FME HighEFF. While the experimental investigation on the compressors was delayed due to Covid-19, the modelling achieved a major step.

COMPRESSORS

New compressors are under development that have an extended operation envelope e.g.: towards higher temperatures. These compressors are paving the way for compact and reliable industrial high-temperature heat pumps (HTHP) as applied in WP 3.2 (HTHP, Cooling and Drying). HTHP's delivering process heat up to 200°C will work with renewable energy and may cover up to 37% of all industrial process heat.

A 3-dimensional dynamic ring plate valve model for reciprocating compressors, as applied in refrigeration, heat pump and HTHP applications, was developed. The model investigates the three-dimensional dynamics of the ring plate discharge valve, using loosely coupled computational fluid dynamics (CFD) and finite element method (FEM). The model was further compared to measurement results giving an insight into key elements of the compressor valve dynamics. The dynamic motion of the valve ring is controlled by the combined actions of forces resulting from applied pressure, spring reaction, impact with the valve's plate and cage, and damping effects. Examining these phenomena in greater depth will allow to understand the wearing of the valve and enable the compressor manufacturers to build more efficient and reliable compressors.

EXPANSION WORK RECOVERY

The implementation of ejectors for expansion work recovery enables increased efficiency and makes environmentally friendly refrigeration systems more competitive. Investigations of the real system performance of an ejector-supported supermarket refrigeration system have been performed. 3 months of various system operation modes were analysed, concluding with an energy saving potential of about 10% when using the ejector technology in a real supermarket. Further improvements were identified, which have to do with heat recovery of the CO_2-based refrigeration system. The largest benefits of the investigated systems are seen in warmer climates, such as southern Europe or India.

Natural Working Fluids

Ehsan Allymehr finished his PhD work performed at NTNU with HighEFF funding (see page 7).

The HighEFFLab Heat Exchanger test rig was installed and connected to local infrastructure in NTNU and SINTEFs thermal laboratories at Gløshaugen during the spring of 2021. Shake-down testing was performed and by the end of the year the rig was tested with both propane and a propane/ethane mixture. The rig is now operational and the first heat exchanger test campaign has started. The rig can be used to test novel heat exchangers and hydrocarbon working fluids. Both heating, evaporation, cooling and condensing of hydrocarbons against water or water/glycol can be performed. Plans have been made to use the rig in 2022 to investigate a cascade heat exchanger used in high temperature heat pumps. For these tests, propane (R290) will be condensed on one side while butane (R600) is evaporated on the other side in the heat exchanger. The results will be used to develop and validate a detailed model of such cascade heat exchangers to be used as a design and optimisation tool.

Cycles - RA3

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The overall goals are to develop improved cycles and concepts for converting and upgrading energy sources, including surplus-heat-to-power conversion, energy storage systems, and heat upgrade using heat pumps. Technologies and applications where HighEFF research has a large impact potential are emphasised.

Research in RA3 targets novel developments and improvements for important production processes across different industry sectors. A few example activities and results from 2021 are:

Advanced energy recovery systems for ferroalloy industry

The significant amount of thermal energy contained in liquid metal makes the casting process at metal producing plants an interesting option for energy recovery. However, practical exploitation using current technology is complicated due to high temperatures, a highly dynamic process and strict product quality requirements. Previous HighEFF research proposed a system concept for capturing the heat released during casting. In 2021, practical approaches for utilising this heat through integration with a pre-existing steam cycle for off-gas energy recovery has been studied. A detailed, dynamic model of the Elkem Thamshavn energy recovery system has been used for this purpose, with results indicating an 11 % increase in electrical power production to be feasible with the additional recovered heat. The model was expanded with a thermal energy storage (TES) component to account for the batch-wise heat availability, which also benefitted the performance of the already dynamic conditions of the off-gas energy recovery system. Results will be published at the Gustav Lorentzen 2022 Conference.

High Temperature Heat Pumps for the industry

When it comes to reaching the targets of the Paris agreement and decarbonising industry, high temperature heat pumps (HTHP) are considered the "hidden champions". Utilising the potential of industrial heat pumps is highly attractive since it allows the industry to operate with significantly reduced emission of climate gases as well as energy costs reductions.

Steam producing heat pumps are of particular interest for the industry since they can substitute existing fossil (steam) boilers. Conventional supply systems are based on 8-15 barG process steam. The steam supply pressure from HTHP will for practical reasons be lower and is currently limited to around 5 barG, also due to efficiency reasons.

HTHP for the process industry will in most cases utilise industrial excess heat as heat source, however concepts based on ambient air and renewable energy sources are also being evaluated. Several case studies were focusing on how to match specific on-site requirement to a technically and economically feasible HTHP solution.

The following lab-based investigations were performed during 2021:

1. Ammonia-Water Hybrid heat pumps: a lab installation is currently under construction in which heat sink temperatures of up to 140°C will be investigated. Start-Up is scheduled for early 2023 and a PhD student will work with this system.
2. Hydrocarbon cascade heat pump: the concept allows to supply process heat of up to 115°C and process cooling as low as 0°C from one HP system. The HighEFFLab test facility was upgraded during 2022 in order to reach more stable process conditions. Durability tests are scheduled for 2023.
3. Steam producing heat pumps: an improved turbo-compressor design was designed in 2022 and is under construction. Durability tests are planned for 2023.

SINTEF also organized the 3rd High Temperature Heat Pump Symposium: https://hthp-symposium.org/ Different Spin-Off activities for HTHP were initiated and are presented to the HighEff consortium.

Fossil-free steam production for Nidar Orkla

Orkla's confectionary factory in Trondheim needs large amounts of steam for various cooking processes. The factory currently has a propane-based steam production system, responsible for 30-40 % of the factory's annual CO_2 emissions. In order to reduce the emissions, Orkla is interested in applying and electric boiler instead; however, this is currently not possible due to limited grid capacity in the area. To address this issue, the CETES-methodology developed previously in HighEFF was applied to see if introducing a thermal energy storage unit could allow satisfying the steam demand at a lower power demand. The study showed that by combining an electric boiler with a steam accumulator, the steam demand could be covered with a boiler capacity up to 41 % lower than the capacity of the current gas boiler. A steam accumulator would additionally allow shifting the steam production to periods with low demand in the power grid, thus reducing the pressure for grid capacity expansion. Depending on the electricity prices and emission taxes, as well as the allowed boiler capacity limit, the estimated payback period for the implementation was between 3 and 6 years.

Applications - RA4

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The overall goals are to:

- Integrate the components, cycles and concepts developed in other RAs into specific industry settings to generate more energy-efficient processes and improved heat capture and utilisation concepts.
- Recovery of surplus heat with a focus on high utilisation of significant industrial sources
- Develop further the potential of green industry clusters and local thermal grids

Recycling off-gas from silicon furnaces

An important activity has been the recycling of off-gas from silicon/ferrosilicon-furnaces, to increase the CO_2 content of the off-gas and make CO_2 capture easier. A highlight of this activity in 2021 has been the PhD work of Vegar Andersen and the 80-hour long pilot experiment he organised and ran in a collaboration between HighEFF and several other projects at NTNU/SINTEF/Elkem (see page 38).

Off-gas recycling also influences the gas-phase chemistry in other ways such as PAH emission. Controlling PAH-emissions is important for the industry, so it is necessary to establish how any new process or process modification influences PAH formation and oxidation. SINTEF Industry developed kinetic methods for PAH-formation and PAH-oxidation based on a chemical reactor network (CRN) approach to be used in post-processing of CFD-models to model the formation, oxidation and distribution of PAH during gas recycling.

Gas-recycling may also indirectly influence the conditions below the charge surface of the furnace. Changes in SiO-gas condensation will mean a change in how much SiO-gas leaves the charge surface (influencing Si-yield), and the concentration of SiO-gas that enters the combustion zone (influencing amount and possibly also quality of micro silica produced). SINTEF Industry are looking at how this influences the conditions for SiO-gas condensation, by modelling the kinetics of relevant reactions.

An important motivation for the recycling of off-gas is the potential to capture and store/utilise the CO_2. As part of the HighEFF New Emerging Concepts (NEC) project INTERCUR, "A mixed integer linear model for optimising material and energy flows in industrial clusters" was developed. The INTERCUR-model represents a general framework for decision support in the design of industrial clusters, but also presents some potential for application to a single plant. The possibility of using the INTERCUR-model to optimise energy use in a ferroalloys plant incorporating CCS has been briefly outlined in WP4.1.

Ferromanganese: status update

Variations in energy efficiency in Mn-furnaces occur due to variations in the prereduction zone. Ferromanganese prereduction mechanisms have been studied previously in HighEFF by PhD-candidate Trine Larssen. Large amounts of experimental data have been produced over the years, as well as several models. This data and models are being evaluated for consistency and general applicability of results. Gaps are being identified that need to be filled with further models or experimental data. It is expected that experimental work will start within this task in 2022.

Recovering excess heat from aluminium production

The Norwegian industry produces approximately 20 TWh of excess heat every year, where the aluminium industry is the largest producer of low temperature excess heat (below 250°C). The off-gas from aluminium electrolysis is a significant source of surplus heat that is currently unused. In order to possible utilise this surplus heat, the industry requires cost- and space-efficient heat exchangers that can withstand the challenging conditions in the off-gas channels. In HighEFF, we have explored a modified plate-type heat exchanger concept without fins on the gas-side for this purpose. New developments in the in-house heat exchanger modelling software at SINTEF Energy Research have made it possible to study any type of heat exchanger geometry. This improved model was used in 2021 to design a prototype for a heat exchanger to be tested for aluminium electrolysis off-gas. This was based on the plate-no-fin concept developed at HighEFF, and the goal is to eventually validate its proposed resistance to scale formation. The proposed test site and the accompanying constraints were taken into consideration in the development of the design of the prototype.

Model predictive control

High-EFF PhD student Mandar Thombre defended his PhD in 2021. His PhD work was titled "Novel Approaches in Robust Multistage Nonlinear Model Predictive Control". The work focuses on developing data-based methods for scenario selection, and on sensitivity-based methods for faster solution of large-scale optimisation problems that arise in model predictive control. Industrial data from our HighEFF partner Mo industry park was used to develop a realistic case study on energy storage.

Society - RA5

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The overall aims are to manage the innovation activities and handle dissemination, communication and the general flow of information in the Centre. Additionally, the goals are to form the innovation strategies and technological roadmaps for the industry sectors and share them among partners to enhance cooperation and synergies.

Innovation management includes research on internal and external interaction, as well as on the barriers and enablers for innovation and realisation of HighEFF technologies and concepts.

Innovation, barriers and enablers

Through a close collaboration with NTNU Social Research and Nord University, we studied how researchers and companies collaborate in HighEFF to develop and implement radical energy efficiency innovations. We discovered that the interplay between collaboration dynamics in the research centre and organisational factors can help explain why such innovations are (or are not) implemented, which led to a paper published in the Journal of Cleaner Production.

We provided research-based knowledge on how industry and research partners manage to collaborate for the enhancement of knowledge and innovation. More precisely, we examined how the activities of firm representatives and centre managers (boundary spanners) might enable knowledge integration between firms and research partners. We also examined the role of proximity between companies and university partners in establishing successful collaboration in a research centre and looked into additional effects from participating in university-industry collaboration that might be enhanced by companies over time. Moreover, we contributed with a edited Handbook on Innovation for a Circular Economy, providing knowledge on how companies can manage the circular economy transition. The handbook also includes a chapter on how surplus heat is valuated in local contexts based on the research in HighEFF.

To summarise, our research provides important insight to companies and research partners, about how to participate in research centres, and how to manage their outcomes; and to policymakers, about how such engagement should be funded and structured to reach the goals of generating new knowledge and industrial innovations. Furthermore, our research provides insights into political, organisational, and collaborative challenges for energy efficiency innovations and surplus heat exchanges.

HighEFF student Irina Isaeva defended her Thesis "Managing multiple goals in university-industry collaboration" in December where the purpose has been to survey the university-industry collaboration to achieve the common goals within an FME Centre.

Novel Emerging and Innovative Concepts (NEIC)

Our internal funding scheme allows us to invest in ideas that are not covered by ongoing or enabled activities within HighEFF. The scope of the former Novel Emerging Concepts calls was further developed and extended during the autumn of 2021 to also include the innovation aspect. The new call is now Novel Emerging and Innovative Concepts (NEIC) and is built upon the idea that new ideas and innovations are created through collaboration and research in HighEFF. The evaluation criteria and the HighEFF NEIC evaluation committee was set in 2021. The project proposals will be evaluated by an internal group, in addition to two external evaluators from the industry.

Throughout 2021, the novel emerging concept (NEC) call was still valid, and we had one internal call. The result from this call was two applications. *Biochar from Seaweed for Metal Production* received funding, focussing on the utilisation potential of sustainably farmed seaweed from the Norwegian coastline to produce biochar for metal production, and the possibility to use surplus heat from the industry in the processing of seaweed to applicable carbon products. The project is a cooperation between three SINTEF institutions: Industry, Ocean and Energy.

Dissemination and Communication

Our communication goals for 2021 have been to increase knowledge and awareness about energy efficiency in industry, through presenting its impact on sustainability and value creation, with increased use of the Centre's social media channels and newsletter.

Focus on visibility of the overall project results and the work performed in HighEFF have been followed up in HighEFF's communication strategy for 2021. Our strategy ensures widest possible outreach, involvement and cross-sectorial interaction with relevant industry and academia. The dissemination strategy is built up to maximise the use of existing physical meeting points (seminars, centre workshops and RA meetings) and existing communication platforms and media channels, such as project partners' existing communication channels.

For more details, see the Communications chapter on page 95.

Case Studies - RA6

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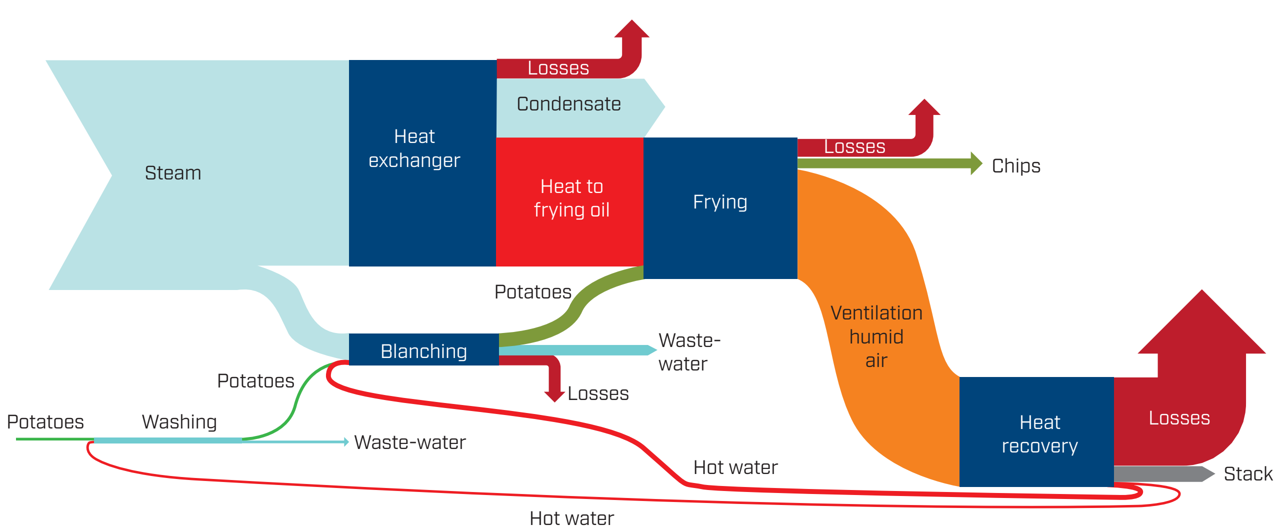
Case Studies are performed to promote HighEFF innovations and obtain measurable results from the implementation of HighEFF technologies in the different industrial sectors. The overall goals for the case studies are to develop technology concepts that can lead to a 20-30% reduction in specific energy use and/or a 10 % reduction in CO_2 emissions through implementing technologies and solutions.

Heat integration on offshore platforms

A comprehensive and generic oil and gas platform model was developed to contrast energy-efficiency measures, focusing on recovery and utilisation of surplus energy. Upon validation against real data for two platforms, various scenarios where compared based on carbon footprint, energy efficiency, and operational costs (CO_2 tax and fuel cost). The use of steam bottoming cycles, H_2 blending, and wind energy were found to be the most effective configurations. Based on the most promising technologies, a low-emission scenario was developed with the use of a smaller, more efficient gas turbine with a steam bottoming cycle and wind energy during the first 15 years of operation. Subsequently, it was proposed to gradually introduce H_2 fuel, starting with 50 molar % blend up to 90 molar %. Over a 30-year lifespan, the proposed low-emission scenario would reduce CO_2 emissions by up to 2.7 Mtonnes.

Energy efficiency in food processing

A case study at the Orkla's production site at Skreia identified a large energy saving potential in the potato



chip production line. Preliminary results indicate that the use of high-temperature heat pumps could reduce energy consumption by up to 60% and reduce CO_2 emissions by up to 93%. This investigation represents a first phase in the study, and it is based on preliminary data received from Orkla. The considered processed data should be verified before investment costs are further evaluated.

Joint mapping of metallurgical surplus heat and potential seaweed growing

The cultivation and farming of seaweed on the Norwegian Continental Shelf is a growing industry with large potential for sustainable production of biomass. As the water content of the products is very high, preservation by drying is needed. The drying processes used today are very energy-intensive but done at relatively low temperatures. As such, this industry represents a potential use case for low-grade surplus heat. In 2021, the potential and implications of recovering this heat from the metallurgical industry has been studied, hoping to benefit from plants being situated along the coast, close to potential farming areas. Ongoing efforts at HighEFF to map available surplus heat from metal producers in Norway have been combined with maps of offshore seaweed cultivation conditions to provide an overview of the potential. Based on these mapping efforts, a case study considering heat from Hydro Karmøy was performed. It was found that in a 2-month long harvesting season, 66 GWh of heat could potentially be used to dry 63 Mt of raw seaweed, corresponding to a CO_2 uptake from the atmosphere of around 5750 tons. Compared with the use of an electric boiler for seaweed drying, the use of surplus heat provides an additional CO_2 avoidance of roughly 1000 tonnes.

Jacob Stang, Research scientist (SINTEF) conducting an experiment at the Heat Exchanger Laboratory.

Photo: SINTEF

Research Infrastructure

Industry seldom implements new technology without a thorough testing period, to ensure efficiency and reliability. Such testing requires pre-industrial lab installations for performance analyses, component validations and prototyping to enable successful implementation in the industry. These needs are covered to some extent by HighEFFLab installations. We see that the infrastructure will make emerging, sustainable solutions feasible to the industry, closing the gap between TRL1-4 and TRL7-9.

HighEFFLab is a joint national laboratory between various departments at SINTEF and NTNU. The facilities are mainly located at the NTNU Gløshaugen campus in Trondheim except for one installation situated at SINTEF Energy Lab at Blaklia. HighEFFLab is a national research infrastructure and aims to be the leading platform for experimental research within industrial energy efficiency through the operation of unique and excellent laboratory facilities. The research infrastructure is accessible for all industry, research and academia interested in experimental testing of components, processes or products related to our areas of research.

HighEFFLab consists of six laboratories, with a total of 12 experimental rigs and 8 analysis instruments. In addition, tools for calibration and field measurements, and computers and software for designing, modelling and simulations, are also part of this infrastructure. The HighEFFLab laboratories are:

1. The Heat Exchanger Laboratory
2. The Expander Tests Laboratory
3. The Natural Refrigerants Laboratory
4. The Dewatering Laboratory
5. The Gas and Material Characterization Laboratory

The laboratories include novel components and process equipment that can be found in different industrial processes:

Heating, cooling and drying technologies for food preservation in a more energy and environmentally friendly way using natural refrigerants.

High-temperature heat pumps making it possible to cover a larger part of industrial heat demands utilising low-quality excess heat sources.

Heat-to-power conversion, utilising excess heat at high temperatures and in high quantities from, for example, the metal industry.

Gas and material characterisation instruments to reduce the environmental impact from (for example) off-gas and to improve the processes in the metal industry.

2021 was also marked by the Covid-19 pandemic. On many occasions, this has meant that the delivery of components has been postponed due to shortages, and further delays in the building and assembling of the last remaining HighEFFLab riggs has been unavoidable. The expander test rig will be up and running during the first quarter of 2022, and the hybrid ammonia-water heat pump system will be available for industry and students by the end of 2022.

A description of the specific instruments and test facilities is available on the HighEFFLab website: www.sintef.no/highefflab

Spin-off projects

HighEFF contributed to the lauch of several spin-off projects, solving specific challenges for the industry. The following were awarded funding in 2021.

Collaborative and Knowledge-building Project (KSP)

Financed by the research programme ENERGIX.

LEAn – Low energy anodes for sustainable electrowinning
Metal electrowinning means extracting a metal from its ore by electrochemical processes. The energy consumption associated with the process is substantial. The LEAn project aims at designing alternative, energy efficient anodes that are more durable than current models and avoid the use of costly and scarce elements. The project involves the following partners: NTNU, SINTEF Industry, Glencore Nikkelverk, Boliden Odda and Permascand AB.

Green platform

Financed through funds managed by the Research Council of Norway, Innovation Norway and Siva.

AlgScaleUp – Scaleup of the production of microalgae as a sustainable salmon feed raw material for the salmon industry
AlgScaleUp aims to secure the technological foundation needed for scaling up the production of microalgae at the Finnfjord AS ferrosilicon plant. The concept utilises emission gasses and heat surplus in a circular loop through a photobioreactor, to sustainably produce microalgae as a raw material for salmon feed. The project involves the following partners: SINTEF Ocean, Industry and Energy, Finnfjord AS, Cargill Norway AS, UiT (Arctic University of Norway).

EU Horizon Europe

Financed by the European Union, with a supplementary contribution from the Research Council of Norway for the Norwegian portion of the research.

TRINEFLEX – Transformation of energy-intensive process industries through integration of energy, process, and feedstock flexibility
TRINEFLEX is a large EU project aiming at helping energy-intensive industries meet their climate targets through the adoption of digital technologies such as digital twins, big data infrastructures and AI. HighEFF partner SINTEF's part of the project involves demonstrating the potential of photovoltaic thermal hybrid solar collector technology in combination with a high temperature heat pump to reduce energy consumption in post-combustion carbon capture.

Decagone – Demonstrator of industrial carbon-free power generation from orc-based waste-heat-to-energy systems
Decagone aims at improving systems based on Organic Rankine Cycle (ORC) to achieve scalability to higher power levels, higher cost effectiveness, wider input temperature ranges, and significantly reduced system size, allowing wider take up of heat recovery and its conversion to power from more industrial processes.

ERA-NET project

Financed in part by the Research Council of Norway and EU Horizon 2020, through the BlueBio cofund.

SuMaFood – Sustainable preservation of marine biomasses for an enhances food value chain
SuMaFood intends to reduce food waste and increase the productive use of marine biomass by devising

innovative methods of processing and preservation, and developing ingredients that will serve as the basis for new food products. The project involves the following partners: Ekonek, Praxi, Nuas Technology, SINTEF, NTNU, Transilvania University of Brașov, and National Technical University of Athens.

Helen Langeng (SINTEF) is Laboratory Manager at the Thermal engineering laboratories in Trondheim.

Education, researcher training and recruitment

Developing knowledge and expertise at various levels is a main objective and major task at HighEFF. The focus is on energy efficiency in industrial processes, and the main sub-activities are (i) methodologies for analysis, design and optimisation, (ii) improved equipment and cycles, and (iii) systems integration including industrial parks (clusters). The education activity takes place at different levels: Master students having theses related to HighEFF; PhDs and Postdocs with research and publications related to energy efficiency in industry; and employees from user partners taking tailormade intensive courses to become energy efficiency experts in their companies.

Photo: Inge Knoff

By the end of 2021, HighEFF had recruited all their 25 candidates (20 PhDs, four Postdocs and one researcher). Considerable contributions (research and publications) have also been made by our so-called Associated PhDs (working on HighEFF related topics); a total of 9 since we started HighEFF. Four PhDs, one Postdoc and three Associated PhDs finished in 2021.

Our education program also spans across countries and continents. HighEFF academic partners currently include two from Norway (NTNU and Nord University), two more from Europe (KTH in Sweden and University of Manchester in the UK), three in the US (MIT, CMU and University of Illinois) and two in Asia (Shanghai Jiao Tong University in China and Doshisha University in Japan) – a total of nine universities.

The considerable number of recruited candidates resulted in a large number of publications and conference presentations. HighEFF had 40 journal publications and 8 conference presentations in 2021 (the 1st is close to "all time high", the 2nd was affected by Covid-19) with at least one of the recruited candidates as author/co-author.

PHDs, Postdocs and Master Students

With an early recruitment start in HighEFF, the PhDs and Postdocs have already spent around 91% of the time and funding available for their research. A large number of candidates (around 9) are expected to finish in 2022, with more following in 2023. Master's students are also contributing to the research at HighEFF, and 12 Master's theses were submitted in 2021 – the highest number so far since the Centre started its activities.

Communications

HighEFF innovations and researchers enjoyed significant, relevant media coverage in 2021, a result of a sustained effort with media relations by the communications team.

During the first years of the research centre, much effort went into establishing a brand and a communications platform, in our case the HighEFF website and newsletter. Now the centre is moving into its final years, the emphasis switches into making the most of the excellent innovations and stories within the centre. Media relations therefore became a much more important task in 2021, and will continue to do so in the years to come.

Against the continued backdrop of the pandemic, digital communication continued to play a vital role for HighEFF in 2021. While this was once again effective, we were delighted to also support the cross-sector workshop, the first in-person HighEFF event since the pandemic began.

Why communications matters for HighEFF

Reaching HighEFF's vision of making Norwegian industry the world's cleanest requires sharing new knowledge and information to industry. It also requires industrial and political willingness as well as public acceptance. Communication is therefore a core strategic activity of HighEFF.

Communication activities extend beyond the HighEFF consortium and scientific community to provide facts about energy efficiency and promote innovations to industry.

Strategic communication efforts

The communications team supported HighEFF management in its response to the government consultation on the amendment to the Energy Act's requirement for utilisation of waste heat. A summary of the science-based response was repurposed as a blog post.

In the media

"Norway will take better care of the heat we use, the Ministry of Petroleum and Energy has decided. What can the excess heat be used for?" That was the question posed by NRK when Peter Røkke joined the NRK radio show 'Ekko' in April. It was a similar story when Petter Røkke and Petter Nekså joined the Teknisk Ukeblad podcast 'Teknisk Sett', to discuss the enormous potential in excess industrial heat.

An opinion piece by Petter Røkke, Petter Nekså and Brage Rugstad Knudsen was placed in the leading Norwegian business newspaper Dagens Næringsliv. The story, describing how waste heat could be used to support avocado farming in Norway, received great media attention and successfully communicated the potential for reusing excess industrial heat in Norway. TV2 and Teknisk Ukeblad were among the media outlets that ran stories based on the original opinion piece.

HighEFF events

We supported an 'innovation breakfast' meeting about data centres, an important topic that was widely discussed in the media during 2021 due to the popularity of videoconferencing platforms, streaming services, and cryptocurrency. SINTEF researcher Hanne

Kauko joined representatives from the business community and the Ministry of Petroleum and Energy on how data centres can reduce their carbon footprint. A follow-up blog post was produced for the SINTEF Blog based on the webinar.

The communications team supported October's cross-sector Workshop held in Trondheim, which was the first large in-person event for project partners since the beginning of the pandemic. Among other tasks, professional photographs were taken of presenters and participants, which will prove valuable for future communications work and media coverage.

The communications team has also supported preparation for the 15th IIR-Gustav Lorentzen Conference on Working Fluids, to be held in June 2022.

Industry handbook

The communications team supported the production of the handbook 'Resource and Energy ' during 2021. This included the production of the handbook itself and the promotion of it, including a blog post by Catharina Lindheim, Lucia Liste Muñoz and Ingrid Claussen. The launch of the handbook was covered by Teknisk Ukeblad.

Website, blogs & newsletters

The website www.higheff.no is the communications hub for the research centre, and is the first port-of-call for those interested in finding out more. It was updated throughout the year with the latest news from the project.

HighEFF participants are encouraged to create blog posts about their tasks throughout the year. Many blog posts summarise project results or scientific publications, but targeted at different groups such as private industry or decision-makers in governments. Other blogs are aimed at fellow researchers working in energy-efficiency and related fields.

During 2021, eight blogs were published across a variety of HighEFF topics, three in English and five in Norwegian. Eight newsletters were sent to the HighEFF newsletter list.

Social media

Following the success of LinkedIn for other major scientific research centres, the communications team established a HighEFF page on the platform during 2021. The page has 67 relevant followers and is expected to grow during 2022..

The HighEFF communications team also maintains a Twitter account (@HighEFF_FME). At the end of 2021 it had 124 followers.

Images and short videos were custom made for social media channels, to spread our message about the importance of using excess heat.

Appendix

Statement of accounts

Costs (1000 NOK)	Amount
Host institution (SINTEF Energi)	22 448
Research partners	23 081
User partners	4 816
Equipment	365
Total	**50 710**

Funding (1000 NOK)	Amount
Research Council of Norway	23 648
Host institution (SINTEF Energi)	7 500
Research partners	6 477
User partners	13 085
Total	**50 710**

Personnel

Key researchers

Name	Institution	Main research area
Adriana R Lua	SINTEF Energi	Industry clusters
Afaf Saai	SINTEF Industri	FEM modelling, WP2.2
Alexis Sevault	SINTEF Energi	High-temperature TES for industrial processes
Ángel Pardiñas	SINTEF Energi	Expander test laboratory
Anton Beck	Austrian Institute of Technology	Steam thermal storage
Armin Hafner	NTNU	RA2 leader. High temperature heat pumps, cold thermal storage
Arne Petter Ratvik	SINTEF Industri	Novel emerging concepts
Asbjørn Solheim	SINTEF Industri	Chloride Al processes, inert anode, HH improvement, Case study Al
Asle Gauteplass	NTNU Social Research	Society - NEC shared resources and alternative business models
Aud N Wærnes	SINTEF Industri	RA4 leader. Process improvements
August Brækken	SINTEF Energi	Case Study HighTemperature Heat Pump
Avinash Subramanian	NTNU	Polygeneration systems for chemical and energies
Balram Panjwani	SINTEF Industri	Process improvements
Bin Hu	Shanghai Jiao Tong University	Steam high temperature heat pump
Brage Knudsen	SINTEF Energi	RA6 leader. Thermal energy storage potential for the industry, modelling and optimziation of energy exchange in clusters. Industrial cluster case studies and measurement of HighEFF overall goals.
Brede Hagen	NTNU	Surplus heat-to-power conversion
Catharina Lindheim	NTNU Social Research	Society - NEC shared resources and alternative business models
Cecilia Gabrielii	SINTEF Energi	Low temperature cooling, steam production aluminium industry
Christian Schlemminger	SINTEF Energi	High temperature heat pumps and thermal energy storage for industrial processes
Cristina Zotica	NTNU	Optimal Operation and Control of flexible Heat-to-Power Cycles

Name	Institution	Main research area
David Perez Pineiro	NTNU	Optimal operation and control of energy storage systems
Egil Skybakmoen	SINTEF Industri	RA1 Methodoogies leader. HH improvements, Case study Al, Surplus Heat recovery Al
Ehsan Allymehr	NTNU	Heat transfer and pressure drop in small diameter pipes for natural working fluids and mixtures
Einar Jordanger	SINTEF Energi	Management
Einar Rasmussen	Nord Universitet	Supervisor Irina Isaeva
Elisa Magnanelli	SINTEF Energi	WP4.2-leader, Surplus heat recovery
Gabriella Tranell	NTNU	Recycling of furnace gas, supervisor for Vegar Andersen
Geir Skaugen	SINTEF Energi	Heat exchangers
Gerwin Drexler-Schmid	Austrian Institute of Technology	High-temperature thermal energy storage, High Temperature heat pumps
Goran Durakovic	SINTEF Energi	Surplus heat-to-power conversion, RA6 case studies; industry clusters
Gudveig Gjøsund	NTNU Social Research	Organizational analysis
Halvor Dalaker	SINTEF Industri	Process improvements
Han Deng	SINTEF Energi	Heat exchangers, natural working fluids
Hanne Kauko	SINTEF Energi	Thermal energy storage (TES) potential in industry clusters, High-temperature TES for industrial processes, Industrial Clusters
Haoshui Yu	NTNU	Work and Heat Integration, ORCs
Heiko Gaertner	SINTEF Industri	Process improvements
Helle Børset Eidissen	SINTEF Energi	Heat exchangers
Hiroshi Yamaguchi	Doshisha University	Refrigeration technology
Håkon Selvnes	NTNU	Cold thermal storage for industrial applications
Ida Teresia Kero	SINTEF Industri	Metallurgy, materials science, process improvements
Ingrid Camilla Claussen	SINTEF Energi	RA5 leader. Dissemination, society
Irina N. Isaeva	Nord Universitet	Industry/University collaboration for environmental innovations
Ivar S. Ertesvåg	NTNU	Exergy Analysis of Offshore Oil & Gas Processing Systems
Jason Foulkes	NTNU	Master student oil and gas case studies
Jens Olgard Dalseth Røyrvik	NTNU Social Research	Societal, social and organizational conditions for energy efficiency
Jens Petter Johansen	NTNU Social Research	Barriers and enablers for energy- efficiency and exchange
Jingwei Zhu	University of Illinois	Vortex Control for Two-phase Ejectors and other Expansion Devices
Johannes Jäschke	NTNU	Optimization of Energy Efficiency in large-scale Industrial Systems under Uncertainty

Name	Institution	Main research area
Juejing Sheng	NTNU	Exergy Analysis of Offshore Oil & Gas Processing Systems
Julia Jimenez Romero	The University of Manchester	Reduction of Industrial Energy Demand through Sustainable Integration of distributed Energy Hubs
Julian Straus	SINTEF Energi	RA6 case studies; industry clusters
Karl Erik A Lindqvist	SINTEF Energi	Heat exchangers
Khalid Hamid	NTNU	Compression-Absorption High Temperature Heat Pump
Knut Emil Ringstad	NTNU	CFD for improving components of R744 vapor compression units
Kristian Leonard Aas	SINTEF Industri	Thermo electric generation, Surplus energy utilisation
Kristina Norne Widell	SINTEF Ocean	HTHP, Cooling and Drying and Case studies food
Lars O. Nord	NTNU	Supervisor
Leif Andersson	SINTEF Energi	Dynamic modeling of steam storage applications
Lorenz T. Biegler	Carnegie Mellon University	Supervisor Siaf Kazi
Lucia Liste	NTNU Social Research	Society - NEC shared resources and alternative business models
Magnus K. Windfeldt	SINTEF Energi	Heat-to-power conversion
Mandar Thombre	NTNU	Optimization of Energy Efficiency in large-scale Industrial Systems under Uncertainty
Marcel Ahrens	NTNU	High temperature Hybrid heat pump
Marcin Pilarczyk	NTNU	Compact bottoming cycles for offshore power production
Marianne T Steinmo	Nord Universitet	Industry/research collaboration in FME centres
Matias Vikse	SINTEF Energi/Industri	Development of Optimization Models for Work and Heat Exchange Networks, NEC INTERCUR
Merete Tangstad	NTNU	Energy Distribution in Mn-alloy Furnaces
Michael Bantle	SINTEF Energi	High temperature heat pump (HTHP), low temp cooling next gen drying systems, food and chemical case studies
Michael Jokiel	SINTEF Energi	Seasonal thermal energy storage
Michael Lauermann	Austrian Institute of Technology	High Temperature Heat Pump
Michael Schöny	Austrian Institute of Technology	NEC CETES
Mina Shahrooz	Kungliga Tekniska Högskolan	Low temperature waste-heat-to-power conversion
Morten Dahle Selfors	Nord Universitet	Society
Olaf Trygve Berglihn	SINTEF Industri	KPIs, energy & exergy analyses, process improvements
Ole H Meyer	SINTEF Energi	RA2 Components
Ole Marius Moen	SINTEF Energi	High temperature heat pump
Paul I Barton	Massachusets Institute of Technology	Supervisor Suzane Cavalcanti
Per Lundqvist	Kungliga Tekniska Högskolan	Supervisor Mina Shahrooz

Name	Institution	Main research area
Per M. Schiefloe	NTNU Social Research	Innovation
Petter Nekså	SINTEF Energi/NTNU	Energy efficiency in industry
Petter Røkke	SINTEF Energi	Centre Management
Ragnhild Sæterli	SINTEF Energi	Centre Management
Rahul Anantharaman	SINTEF Energi	Oil and gas case studies
Roberto Agromayor	NTNU	Turbomachinery for waste heat recovery applications
Robin Smith	The University of Manchester	Reduction of Industrial Energy Demand through Sustainable Integration of distributed Energy Hubs
Saif Rahaman Kazi	Carnegie Mellon University	Optimization of Multi-Stream Heat Exchangers with Phase Change
Samuel Senanu	SINTEF Industri	HH improvement, Gas recycling Al cells.
Sander Holum	NTNU	Summer researcher oil and gas case studies
Signe Kjelstrup	NTNU	Establish KPIs with Focus on Energy Efficiency in HighEFF
Sigurd Skogestad	NTNU	Process systems engineering
Silje Marie Smitt	NTNU	HVAC systems in high performance buildings
Stefan Andersson	SINTEF Industri	Process improvements
Stefan Elbel	University of Illinois	Supervisor Jingwei Zhu
Stefanie Blust	NTNU	Detector cooling with R744 refrigeration technology
Stian Trædal	SINTEF Energi	Heat exchanger laboratory HighEFFlab
Suzane Cavalcanti	Massachusets Institute of Technology	Nonsmooth Approaches for Process Flowsheet Simulation and Optimization
Sverre Foslie	SINTEF Energi	High temperature heat pumps and thermal energy storage for industrial processes
Tom S. Nordtvedt	SINTEF Ocean	HTHP, Cooling and Drying and Case studies food
Trine A Larssen	SINTEF Industri	Process improvement Mn
Trond Andresen	SINTEF Energi	RA3 leader, Surplus heat-to-power conversion
Truls Flatberg	SINTEF Industri	NEC INTERCUR
Truls Gundersen	NTNU	Pinch and Exergy analyses, low temperature processes
Trygve Eikevik	NTNU	Natural refrigerants
Tuva Grytli	SINTEF Industri	NEC INTERCUR
Vegar Andersen	NTNU	Recycling of furnace gas
Yessica Arellano	SINTEF Energi	Heat integration - oil and gas applications
Zawadi Mdoe	NTNU	Optimal control for industrial processes under uncertainty
Zhongxuan Liu	NTNU	Modeling and Optimization for the Design and Operation of a Network of Distributed Energy Hubs
Åsmund Ervik	SINTEF Energi	RA2 components, work recovery and compression

Postdoctoral researchers with financial support from the Centre budget

Name	Nationality	Period	Sex	Topic
Elisa Magnanelli	Italy	04 2017 - 04 2019	F	Establish KPIs with Focus on Energy Efficiency in HighEFF
Haoshui Yu	China	03 2017 - 06 2019	M	Thermodynamic Approach to Work and Heat Exchange Networks
Håkon Fyhn*	Norway	11 2017 - 10 2021	M	Future success factors of industrial clusters (PD/Researcher)
Àngel Àlvarez Pardinas	Spain	05 2018 - 05 2020	M	Expander Test Laboratory
Marcin Pilarczyk	Poland	07 2018 - 07 2022	M	Compact and efficient bottoming Cycles for offshore Power Production

*Technically *research scientist* position

Postdoctoral researchers working on projects in the centre with financial support from other sources:

None

PhD students with financial support from the Centre budget

Name	Nationality	Period	Sex	Topic	Completed?
Brede A. L. Hagen	Norway	08 2018 - 01 2022	M	Power production from medium temperature heat sources	No
Cristina Zotica	Romania	08 2017 - 06 2021	F	Optimal Operation and Control of flexible Heat-to-Power Cycles	No
David Pérez Piñeiro	Spain	08 -2019 – 08 2022	F	Optimal operation and control of energy storage systems	No
Ehsan Allymehr	Iran	07 2018 - 12 2021	M	Heat transfer and pressure drop in small diameter pipes for natural working fluids and mixtures - Measurement and modelling	No
Håkon Selvnes	Norway	08 2017 - 06 2021	M	Cold Thermal Energy Storage for Industrial Applications	No
Irina Nikolayevna Isaeva	Norway	01 2018 - 12 2021	F	Industry/University collaboration for environmental innovations	No
Jens Petter Johansen	Norway	09 2017 - 06 2021	M	Barriers and enablers for energy-efficiency and exchange	No
Juan Cristancho	Colombia	06 2017 - 02 2018	M	Compact and efficient bottoming Cycles for offshore Power Production	Terminated
Juejing Sheng	China	09 2017 - 02 2022	F	Exergy Analysis of Offshore Oil & Gas Processing Systems	No

Name	Nationality	Period	Sex	Topic	Completed?
Julia Jimenez Romero	Ecuador	10 2017 - 03 2021	F	Reduction of Industrial Energy Demand through Sustainable Integration of distributed Energy Hubs	No
Khalid Hamil	Pakistan	08 2021 - 08 2024	M	Experimental Investigation of Absorption-Compression with Liquid-injected twin screw compressors for high temperature heat pump applications	No
Knut Emil Ringstad	Norway	08 2018 - 10 2021	M	CFD based calculation tools for improving components of R744 vapor compression units	No
Mandar Thombre	India	08 2017 - 12 2020	M	Optimization of Energy Efficiency in large-scale Industrial Systems under Uncertainty	Yes
Matias Vikse	Norway	09 2016 - 12 2019	M	Development of Optimization Models for Work and Heat Exchange Networks	Yes
Mina Shahrooz	Iran	05 2017 - 04 2020	F	Low Temperature Power Cycles for Waste Heat utilization with Mixtures of natural Fluids	No
Saif Rahaman Kazi	India	01 2017 - 12 2020	M	Optimization of Multi-Stream Heat Exchangers with Phase Change	Yes
Suzane Cavalcanti	Brazil	06 2017 - 05 2021	F	Nonsmooth Approaches for Process Flowsheet Simulation andf Optimization	No
Trine Asklund Larssen	Norway	08 2017 - 07 2020	F	Energy Distribution in Mn-alloy Furnaces	Yes
Vegar Andersen	Norway	01 2020 – 12 2022	M	Recirculating of furnace offgas	No
Zhongxuan Liu	China	09 2018 - 10 2022	F	Modelling and Optimization for Design and Operation of a Network of Distributed Energy Hubs	No

PhD students working on projects in the centre with financial support from other sources (associated PhDs)

Name	Funding	Nationality	Period	Sex	Topic	Completed
Adriana Reyes Lúa	NTNU	Mexico	09 2016 - 08 2019	F	Optimal Operation and Control of Vapor Compression Cycles	Yes
Julian Straus	Yara/NTNU 50/50	Germany	09 2016 - 03 2018	M	Minimizing Energy Consumption in an Ammonia Plant by Optimal Operation	Yes
Avinash Subramanian	NTNU	India	09 2017 - 08 2021	M	Optimal Design and Operation of Polygeneration Production Chains	Yes
Daniel Rohde	KPN INTERACT	Germany	09 2016 - 12 2018	M	Dynamic Simulation of Future Integrated Energy Systems	Yes
Roberto Agromayor	KPN COPRO	Spain	01 2017 - 07 2020	M	Turbomachinery for Waste Heat Recovery Applications	Yes
Silje Marie Smitt	NTNU	Norway	08 2017 - 08 2021	F	Design and Control of Energy Efficient, Integrated Vapor Compression Units for HVAC and Sanitary Hot Water Systems in high performance Building	PhD defense 9 December
Marcel Ulrich Ahrens	NTNU Energy / xx	Germany	10 2018 – 09 2022	M	Development of a combined absorption compression heat pump test facility at high temp operation	No
Stefanie Blust	NTNU	Germany	02 2019 – 01 2023	F	Large Hadron Collider (LHC) detector cooling with R744 refrigeration technology	No
Zawadi Mdoe	NTNU	Tanzania	09 2019 – 08 2023	M	Optimal Control of Energy Efficient Industrial Processes under Uncertainty	No

Master degrees (total over Centre period)

Name	Sex	Period	Topic (title)
Avinash Subramanian	M	2017	Reducing Energy Consumption in the production of Hydrogen from Natural Gas
Roxane Giametta	F	2017	Integration of LNG Regasification and Air Separation Units
Morten Dahle Selfors	M	2017	HighEFF partners' expectations for innovation
Jakub Bodys	M	2017	Design and simulations of Refrigerated Sea Water Chillers with CO_2 ejector pumps for marine applications in hot climates
Kun Wan	M		Surrogate model development for an Ammonia synthesis process
Monika Nikolaisen	F		Evaluation of Rankine cycles with mixed component working fluids
Alessandro Francesco Castelli	M		Optimization of ORCs for low grade heat recovery: working fluid selection, methodology and applications
Mathias Grønberg Gustum	M	2018	Modelling of gas-solid reactions: Usage of industrial off-gas for pre-reduction of manganese ores
Goran Durakovic	M	2018	Effect of design specifications for off-design operation of low temperature Rankine cycles using zeotropic mixtures and pure working fluids
Inés Encabo Cáceres	F	2018	Techno-economic and thermodynamic optimization of Rankine cycles
Jacopo Degl'Innocenti	M	2018	Compressed air energy storage for clean offshore energy supply
Marius Reed	M	2018	Nonsmooth modelling of multiphase multicomponent heat exchangers with phase changes
Oliver Sale Haugberg	M	2018	Model predictive control of an LNG liquefaction process using Jmodelica.org
Francisco Javier T Garzón	M	2018	Improvement of energy efficiency in a brewery
Espen Halvorsen Verpe	M	2018	Low temperature plate freezing of fish on boats using R744 as refrigerant and cold thermal energy storage
Simon Birger B Solberg	M	2019	Energy-Efficient Designs of Systems – From Nature to Chemical Engineering
Håkon Helland	M	2019	Modeling and Optimization of an Organic Rankine Cycle
Eskild Aas	M	2019	Optimization of Heat Exchanger Networks using Aspen Energy Analyser and SeqHENS
Martin Grimstad	M	2019	Using surplus heat to pre-heat carbon anodes for aluminium electrolysis
Simon Lingaas	M	2019	Energy recovery from batchwise metal casting
Ida Andersskog	F	2019	Plantwide control of thermal power plants
Zawadi Mdoe	M	2019	Optimal control of thermal energy storage under supply and demand uncertainty
Eirik Starheim Svendsen	M	2019	Energy flow analysis of a poultry process plant
Hamza Bajja	M	2019	
Hendrik Poetting	M	2020	Optimization of Energy Systems for Polygeneration Plants
Changhun Jeong	M	2020	Dynamic use of Energy Storage
Andreas S Bunæs	M	2020	Synthesis of Heat Exchanger Networks using SeqHENS

Name	Sex	Period	Topic (title)
Sandeep Prakash	M	2020	Optimal operation of Thermal Energy Storage
Johannes Doll	M	2020	Evaluation of Ejector supported Supermarket Refrigeration Systems
Patrick Koschel	M	2020	Experimental Investigation of "Waterloop" Refrigeration Systems for Supermarkets
Marie Roux	F	2020	Experimental Study of evaporating Hydrocarbon Flow Characteristics in different small sized Test Tubes
Luca Contiero	M	2020	Experimental Analysis of advanced R744 Refrigeration System
Merethe Selnes	F	2020	Experimental Analysis of an advanced R744 Multi-Ejector
Hesam Pourfallah	M	2020	Dynamic models for combined mass- and energy exchange
Kjetil-Andre Sponland	M	2020	Heat balances and -usage in anode baking furnaces
Jason Foulkes	M	2021	Future Low Emission Oil and Gas Platforms
Agnes Camilla Tysland	F	2021	Optimal Operation and Design of a Thermal Energy Storage Tank

Publications 2021

PEER REVIEWED JOURNAL PUBLICATIONS

Search criteria: *From:* 2021 *To:* 2021 *sub-category:* Academic article *sub-category:* Academic literature review *sub-category:* Short communication *All publishing channels*

1. **Ahrens, Marcel Ulrich; Foslie, Sverre Stefanussen; Moen, Ole Marius; Bantle, Michael; Eikevik, Trygve Magne.** Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry. *Applied Thermal Engineering* 2021 ;Volume 189. p. 1-10. ENERGISINT NTNU
2. **Ahrens, Marcel Ulrich; Loth, Maximilian; Tolstorebrov, Ignat; Hafner, Armin; Kabelac, Stephan; Wang, Ruzhu; Eikevik, Trygve Magne.** Identification of Existing Challenges and Future Trends for the Utilization of Ammonia-Water Absorption–Compression Heat Pumps at High Temperature Operation. *Applied Sciences* 2021 ;Volume 11.(10) p. - NTNU
3. **Allymehr, Ehsan; Pardiñas, Ángel Á.; Eikevik, Trygve Magne; Hafner, Armin.** Comparative analysis of evaporation of isobutane (R600a) and propylene (R1270) in compact smooth and microfinned tubes. *Applied Thermal Engineering* 2021 ;Volume 188. ENERGISINT NTNU
4. **Allymehr, Ehsan; Pardiñas, Ángel Á.; Eikevik, Trygve Magne; Hafner, Armin.** Condensation of hydrocarbons in compact smooth and microfinned tubes. *Energies* 2021 ;Volume 14.(9) p. 1-20. NTNU ENERGISINT
5. **Allymehr, Ehsan; Skaugen, Geir; Will, Torsten; Pardiñas, Ángel Á.; Eikevik, Trygve Magne; Hafner, Armin; Schnabel, Lena.** Numerical Study of Hydrocarbon Charge Reduction Methods in HVAC Heat Exchangers. *Energies* 2021 ;Volume 14.(15). NTNU ENERGISINT
6. **Beck, Anton; Sevault, Alexis; Drexler-Schmid, Gerwin; Schöny, Michael; Kauko, Hanne.** Optimal Selection of Thermal Energy Storage Technology for Fossil-Free Steam Production in the Processing Industry. *Applied Sciences* 2021 ;Volume 11.(3). ENERGISINT
7. **Hagen, Brede; Agromayor, Roberto; Nekså, Petter.** Equation-oriented methods for design optimization and performance analysis of radial inflow turbines. *Energy* 2021 ;Volume 237. NTNU ENERGISINT
8. **Isaeva, Irina Nikolayevna; Steinmo, Marianne Terese; Rasmussen, Einar.** How firms use coordination activities in university–industry collaboration: adjusting to or steering a research center?. *Journal of Technology Transfer* 2021 p. - NORD
9. **Johansen, Jens Petter; Almklov, Petter Grytten; Skjølsvold, Tomas Moe.** From practice to policy — exploring the travel and transformation of energy savings calculations and its implications for future energy transitions. *Energy Efficiency* 2021 ;Volume 14.(6) p. 1-20. NTNU SAMFORSK
10. **Johansen, Jens Petter Kirkhus; Isaeva, Irina Nikolayevna.** Developing and (not) implementing radical energy efficiency innovations: A case study of R&D projects in the Norwegian manufacturing industry. *Journal of Cleaner Production* 2021 ;Volume 322. p. - NTNU SAMFORSK NORD
11. **Kazi, Saif R.** A Trust Region for Heat Exchanger Network Synthesis with detailed individual Heat Exchanger Designs. *Computers and Chemical Engineering* 2021
12. **Kazi, Saif R.** Synthesis of Combined Heat and Mass Exchange Networks via a Trust Region Filter Optimization Algorithm including Detailed Unit Designs. *Computer-aided chemical engineering* 2021
13. **Knudsen, Brage Rugstad; Rohde, Daniel; Kauko, Hanne.** Thermal energy storage sizing for industrial waste-heat utilization in district heating: A model predictive control approach. *Energy* 2021 ;Volume 234. ENERGISINT
14. **Larssen, Trine Asklund; Senk, Dieter Georg; Tangstad, Merete.** Reaction Rate Analysis of Manganese Ore Prereduction in CO-CO_2 Atmosphere. *Metallurgical and Materials Transactions B* 2021 ;Volume 52B. p. 2087-2100. NTNU SINTEF
15. **Larssen, Trine Asklund; Tangstad, Merete.** Off-gas characteristics for varying conditions in the prereduction zone of a ferromanganese furnace – a basis for energy recovery. *Social Science Research Network (SSRN)* 2021. SINTEF NTNU
16. **Lindheim, Catharina; Liste Munoz, Lucia; Albert, Daniel.** Resource and Energy Collaborations – a Handbook. *NTNU Samfunnsforskning (rapport)* 2021. SAMFORSK ENERGISINT
17. **Lindheim, Catharina; Liste Munoz, Lucia; Claussen, Ingrid Camilla.** Resource and energy collaborations. How to ensure waste heat gets used. *#SINTEFblog* 2021. SAMFORSK ENERGISINT

18. **Lindheim, Catharina; Liste Munoz, Lucia; Gauteplass, Asle; Gjøsund, Gudveig; Backe, Stian; Qiu, Xinlu; Stokke, Raymond Andreas.**
Deliverable <D5.3_2019.04a> Handbook: Energy Collaboration in Norwegian Industry. *SINTEF Energi. Rapport* 2021. NTNU SAMFORSK
19. **Lindqvist, Karl; Skaugen, Geir; Meyer, Ole.**
Plate fin-and-tube heat exchanger computational fluid dynamics model. *Applied Thermal Engineering* 2021 ;Volume 189. ENERGISINT
20. **Liu, Zhongxuan; Kim, Donghoi; Gundersen, Truls.**
Optimal recovery of thermal energy in liquid air energy storage. *Energy* 2021. NTNU ENERGISINT
21. **Mazzetti, Marit Jagtoyen; Hagen, Brede; Skaugen, Geir; Lindqvist, Karl Erik Artur; Lundberg, Steinar Henning; Kristensen, Oddrun Anglevik.**
Achieving 50% weight reduction of offshore steam bottoming cycles. *Energy* 2021 ;Volume 230. ENERGISINT
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2. **Ahrens, Marcel Ulrich.** Hybrid Absorption-Compression Heat Pumps using Ammonia and Water – State of the Art and ongoing Development. HighEFF PhD/Post.doc seminar; 2021-10-19 - 2021-10-19. NTNU
3. **Ahrens, Marcel Ulrich.** System perspective of HTHP and TES in electrified industrial processes compared to Hydrogen. HighEFF annual consortium meeting 2021; 2021-05-19 - 2021-05-20. NTNU
4. **Ahrens, Marcel Ulrich; Schlemminger, Christian; Bantle, Michael.** System perspective of HTHP and TES in electrified industrial processes compared to Hydrogen. HighEFF Annual Consortium Meeting 2021; 2021-05-19 - 2021-05-20. ENERGISINT NTNU
5. **Allymehr, Ehsan.** Refrigerant Charge Requirements in an optimized Fin and Tube Evaporator. HighEFF PhD/Post.doc seminar; 2021-10-19 - 2021-10-19. NTNU
6. **Álvarez Pardiñas, Ángel; Selvnes, HÃ¥kon; Vingelsgård, Erling.** Opportunities for compact TES on board fishing vessels and cruiseships. SINTEF Workshop on Thermal Energy Storage for industry, buildings and maritime applications; 2021-11-12 - 2021-11-12. OCEAN ENERGISINT
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13. **Andresen, Trond.** Heat recovery considerations in aluminium electrolysis off gas recirculation. Recycling of Pot Gas from Aluminium Electrolysis Cells II; 2021-12-14. ENERGISINT
14. **Andresen, Trond.** NECcast Energy recovery system analysis. NECcast - Industrimøte; 2021-05-04. ENERGISINT
15. **Andresen, Trond.** RA3 Introduction and overview. HighEFF Cross-sector Workshop 20 - 21 October 2021; 2021-10-20 - 2021-10-21. ENERGISINT
16. **Andresen, Trond; Windfeldt, Magnus Kyrre.** Improving behaviour of industrial energy recovery steam cycle using dynamic models. HighEFF Heat and Power Integration - case studies and technologies; 2021-12-17. ENERGISINT
17. **Bantle, Michael.** High temperature heat pumps – technology and cases in HighEFF. HighEFF Heat and Power Integration - case studies and technologies; 2021-12-17. ENERGISINT
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25. **Evenmo, Kjetil.**
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30. **Fyhn, Håkon; Johansen, Jens Petter Kirkhus.**
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33. **Gundersen, Truls.**
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35. **Hagen, Brede.**
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67. **Schlemminger, Christian.**
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68. **Schlemminger, Christian.**
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69. **Schlemminger, Christian.**
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76. **Sevault, Alexis; Widell, Kristina Norne; Gabrielii, Cecilia H; Kauko, Hanne.**
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77. **Shahrooz, Mina.**
Performance of Binary Zeotropic Mixtures. HighEFF PhD/Post.doc seminar; 2021-10-19 - 2021-10-19
78. **Skaugen, Geir; Allymehr, Ehsan.**
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81. **Trædal, Stian.**
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83. **Valderhaug, Aasgeir.**
Elkems new climate strategy. HighEFF Cross-sector Workshop 20 - 21 October 2021; 2021-10-20 - 2021-10-21
84. **Wang, Ruzhu.**
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85. **Widell, Kristina Norne.**
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86. **Windfeldt, Magnus Kyrre.**
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87. **Windfeldt, Magnus Kyrre.**
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88. **Wærnes, Aud Nina.**
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PART OF A BOOK/REPORT

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1. **Ahrens, Marcel Ulrich; Selvnes, Håkon; Henke, Leon Hendrik; Bantle, Michael; Hafner, Armin.**
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2. **Ahrens, Marcel Ulrich; Tønsberg, Even Kristian; Tolstorebrov, Ignat; Hafner, Armin; Eikevik, Trygve Magne.**
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1. **Kauko, Hanne.**
Datasenter bruker mye strøm og produserer mye varme. FME HighEFF 2021 . ENERGISINT
2. **Røkke, Nils Anders.**
Utvikler verdens hittil heteste varmepumpe. FME HighEFF 2021 ENERGISINT
3. **Røkke, Petter Egil.**
Miljøvennlige datasenter i Norge. SINTEF Energ 2021. ENERGISINT
4. **Røkke, Petter Egil.**
Slik kan datasentre bli mer miljøvennlige. SINTEF Energ 2021 ENERGISINT
5. **Røkke, Petter Egil.**
Spillvarme er en ressurs vi ikke kan la gå til spille. SINTEF Energ 2021. ENERGISINT
6. **Røkke, Petter Egil.**
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1. **Ahrens, Marcel Ulrich.**
   High Temperature Heat Pumps as a Way to Decarbonise Norwegian Industry. NTNU
2. **Ahrens, Marcel Ulrich.**
   Høytemperatur varmepumper – et bidrag til dekarbonisering av norsk industrisektor. NTNU
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4. **Andersen, Vegard; Solheim, Ingeborg.**
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5. **Foslie, Sverre Stefanussen.**
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6. **Lindheim, Catharina.**
   Resource and energy collaborations How to ensure waste heat gets used. SAMFORSK
7. **Moen, Ole Marius.**
   Slik gjør vi datasentre mer miljøvennlige. ENERGISINT
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   Slik gjør vi datasentre mer miljøvennlige. ENERGISINT NTNU
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MEDIA CONTRIBUTIONS

Search criteria:
From: 2021 *To:* 2021 *Main category:* Media contribution *sub-category:* Popular scientific article *sub-category:* Interview Journal *sub-category:* Article in business/trade/industry journal *sub-category:* Sound material *All publishing channels*

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