ANNUAL REPORT 2019

Centre for an Energy Efficient and Competitive Industry for the Future

HighEFF

Selected highlights from 2016–2019

–10 %
Greenhouse gas emissions

–30 %
Specific energy consumption

Increased value creation

2016

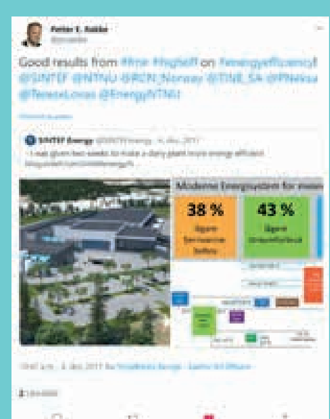
November

September

2017

October

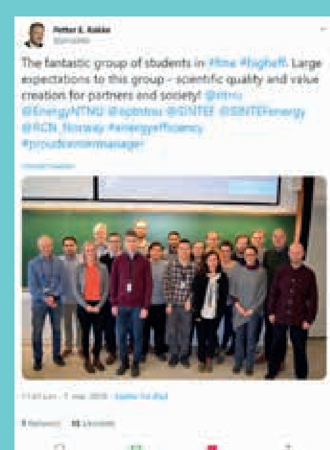
December



2018

January

March

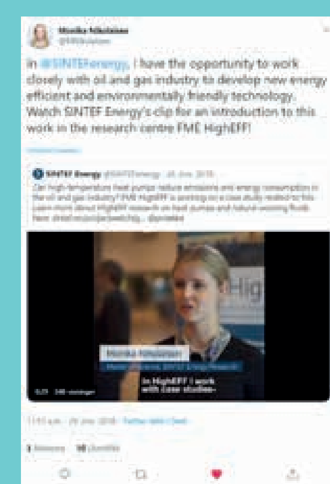


April

June

October

November



2019

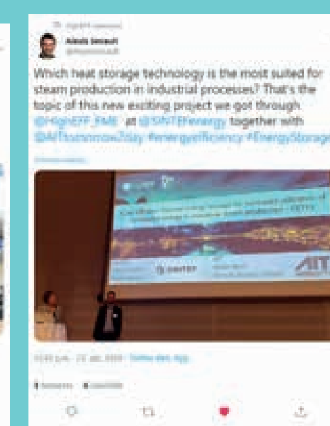
May

June

August

October

October



Selected highlights – find more videos and stories on www.higheff.no -> Annual report

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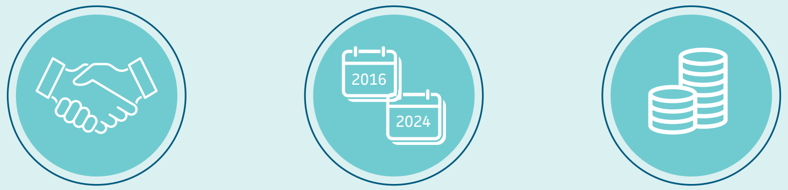
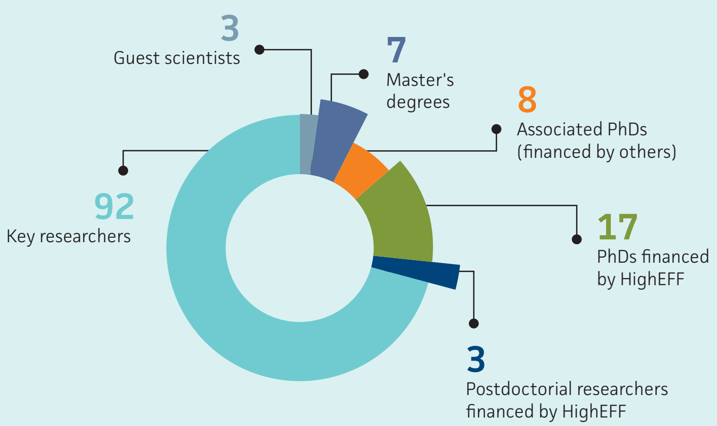
2019 by numbers



43 PARTNERS **8** YEARS **400** MNOK

People



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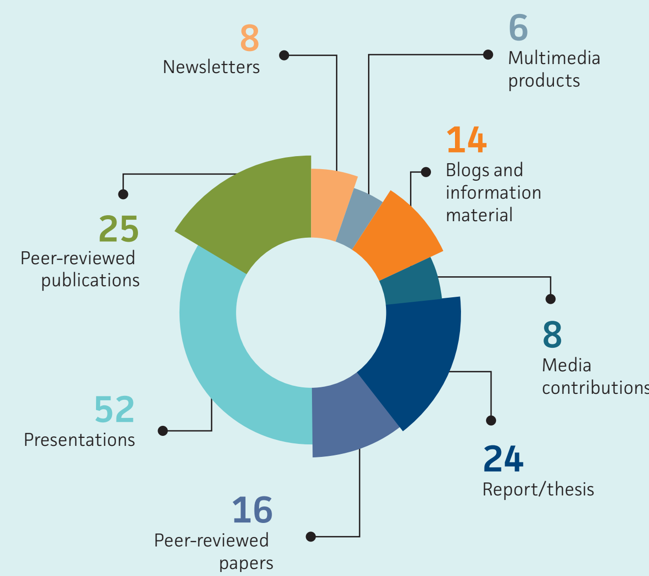
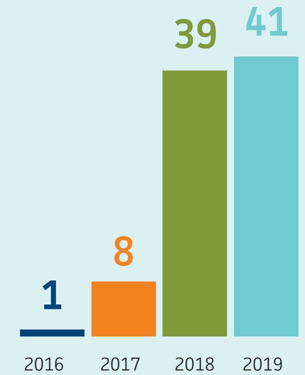
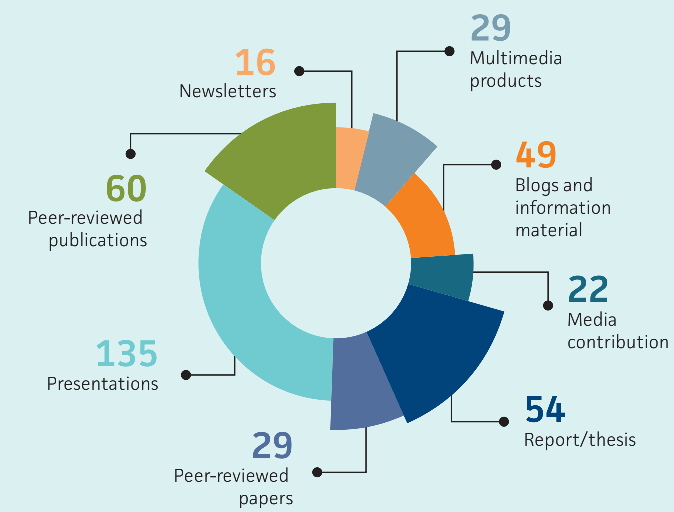
Communication and dissemination 2019



Peer-reviewed publications and peer-reviewed papers



Communication and dissemination 2016–2019



There might be some discrepancies between the numbers in figure and numbers registered in Cristin, mainly due to FME partners that do not have a university or research institute affiliation or because the FME project code has not yet been registered in the post.

Hanne Kauko, Research Scientist, SINTEF Energy Research

Industrial energy consumption is massive, but thermal storage can boost energy efficiency

Thermal storage research is being carried out at both high and low temperature levels at the FME HighEFF centre. In the field of Cold Thermal Energy Storage (CTES), a new technology based on the use of Phase Change Materials (PCMs) is being developed by Ph.D. student Håkon Selvnes, in collaboration with a local supplier Skala Fabrikk. CTES technology is ideal for application in the food industry, which has large and fluctuating cooling needs, and which wants to use renewable energy when prices are low.

Find out more on:
www.higheff.no – Annual report 2019

Online monitoring of perfluorcarbon (PFC) emissions from aluminium industry

Perfluorocarbon (PFC) gases are extremely potent greenhouse gases (GHGs) and industrial emissions contribute to global warming. The atmospheric lifetimes of the gaseous PFCs are very high. For tetrafluoromethane, CF4, it is in the range of 50,000 years. Over a 100-year perspective, the global warming potential (GWP) for CF4 and C2F6 are 6,630 times and 11,110 times that of CO_2! Through the HighEFFLab infrastructure grant, SINTEF has acquired a LaserGas Q CF4 from NEO. SINTEF has tested the instrument calibration in the laboratory. Since the instrument uses a single frequency to quantify CF4, it was important to investigate the impact of relevant impurities like water and methane.

Find out more on:
www.higheff.no – Annual report 2019

Thor Aarhaug,Senior Research Scientist, SINTEF Industry

Trond Andresen, Senior Research Scientist, SINTEF Energy Research

Additive manufacturing of heat exchangers

Today, heat exchanger design and possibilities are limited by current production processes. But what new potential could be realised if heat exchanger design and manufacturing were made free from current production methods and constraints? Additive manufacturing of heat exchangers might provide this freedom. In the HighEFF spin-out project HighEx, researchers team up to solve two specific technical problems connected to additive manufacturing of novel heat exchanger concepts: Thermal stresses and deformations and (uncontrolled) surface roughness.

Find out more on:
www.higheff.no – Annual report 2019

The story of CO_2 as a refrigerant

Carbon Dioxide is so often cast as the villain in climate change debates. Yet that very same substance along with other natural working fluids has the potential to cut more emissions than any other climate change mitigation technology. Now HighEFF is poised to build on years of Norwegian research and push the technology through to commercialisation in new areas.

For thousands of years, we have worked to first understand, then manage our relationship with temperature. When it is too hot, we need to keep food and ourselves cool. When it is too cold, we need to heat our homes. Closed-circuit circulation technologies like refrigeration, air conditioning systems and heat pumps solved that problem, but they require working fluids to extract heat from one source and transfer it to another.

The CFC and HFC problem

A group of odourless manufactured chemicals, chlorofluorocarbons (CFCs) were widely used in aerosols, refrigerators, air conditioners and more until they were banned by the Montreal Protocol – which entered into force in January 1989 – because of their impact on the ozone layer. Their replacement – hydrofluorocarbons (HFCs) – have no ozone depletion potential, but it has since been discovered that they are very potent greenhouse gases.

In January 2019, the Kigali Amendment to the Montreal Protocol entered into force, which will phase down the use of HFCs. A switch to ozone- and climate-friendly alternatives will avoid an increase of more than half-a-degree in global temperature by the end of the century. What are those alternatives? Step forward Norwegian research.

Researching an old solution to a new problem

The discovery of the harmful nature of CFCs triggered a period of significant work at NTNU and SINTEF on natural working fluids (NWF) as an alternative. While HFCs became a commercial success in many applications, the research into NWFs as a climate-friendly solution continued. Retired NTH Professor Emeritus Gustav Lorentzen was the figurehead behind the research, first proposing CO_2 as a refrigerant in 1987. Through his leadership, Norwegian research began to collaborate closely with Norsk Hydro who had a strong interest in alternative refrigeration systems for their aluminium products, such as heat exchangers and lines. That collaboration led to the formation of shecco, a group that spearheaded the drive for CO_2-based solutions for many years.

The first refrigeration system using CO_2 actually dates back to 1879. The system was popular in military and shipping due to its non-toxicity and inflammable properties. But technical issues and heavy promotion of CFCs by the chemical industry saw CO_2 disappear from the market by the 1940s.

> Everyone agrees that the greenest energy is the one that is never used.

NTNU Professor Armin Hafner was first drawn to Trondheim in 1995 by the early advances being made in CO_2 research and has since worked for both NTNU and SINTEF. He leads the HighEFF Research Area on components, including natural working fluids. "The research was desperately needed to further improve the energy efficiency of CO_2 systems. We had good infrastructure here in Trondheim, but the involvement from industry, notably Hydro and the creation of shecco, were important drivers too. We have come a long way to this point, where we now currently have the world's most energy efficient large capacity CO_2 compressor here at SINTEF & NTNU," says Armin.

New applications for climate-friendly working fluids

Much of the early research done at SINTEF is related to mobile air conditioning, heat pumps and commercial refrigeration. Three-quarters of Norwegian supermarkets now use a CO_2-based refrigeration system, contributing to the more than 18,000 supermarkets across Europe using the solutions. Now, building on decades of research, HighEFF researchers are looking at applying CO_2 and other natural working fluids in new industrial applications.

"We have cooperated with Rema 1000 on refrigeration plants in their supermarkets but recently that cooperation has branched out to other industrial applications in their supply chain," says Petter Nekså, HighEFF Scientific Coordinator.

> Investment in energy efficiency measures can be profitable for industry.

He also explains the diversity of applications under investigation in HighEFF. "NTNU funds a HighEFF associate PhD student who has worked closely with a Norwegian hotel on a new

Petter Nekså, Chief Scientist, SINTEF Energy Research (Right) and Michael Bantle, Senior Research Scientist (Left).

CO_2-based air conditioning and heat pump system. She has obtained very promising results from the follow-up energy benchmarking. We are also actively investigating other applications with a wide range of industrial partners, including Orkla and TINE."

CO_2 is ideal for heat pump systems, commercial refrigeration and automotive air conditioning, but isn't suitable for every industrial application. However, in many cases there is an opportunity for an efficient NWF-based solution. For example, TINE recently chose an ammonia- and water-based heat pump over a CO_2-based solution for their new dairy.

The roadblocks to widespread adoption

If NWFs offer a climate-friendly alternative to CFCs and HFCs that could take such a major bite out of the climate targets, then what's stopping a widespread commercialisation?

To understand the problem, we must look back at what happened once CFCs were banned. NWF's could have been developed then, but the money and influence of the chemical industry saw HFCs quickly adopted. The same thing could happen now, explains Petter: "CFCs and HFCs were in use for many decades before their problems were discovered. There may be no issues with new chemical solutions, but we don't know what we don't know. We need proven climate-friendly solutions now in order to meet climate targets, and only NWFs can meet that need."

From Norway to the world

Beyond HighEFF and Norwegian industry, there is huge potential for NWF technologies worldwide. Much of this potential lies in developing countries, which can leapfrog from HFCs still in use straight to long-term sustainable solutions.

Armin says a highlight for him was the installation of a CO_2-based refrigeration system in Jordan, supported by the United Nations Industrial Development Organization (UNIDO). A UNIDO representative called the technology "truly state-of-the-art."

Following this success, a HighEFF spin-off project aims to perform technology transfer to India, a rapidly industrialising country home to approximately 17% of the world's population. A key factor in the successful application will be to further development the ejector technology to allow a CO_2-based refrigeration system to be energy efficient in warmer climates.

Armin Hafner, Professor, NTNU.

Teaching industry an integrating approach to energy efficiency

If HighEFF is to succeed with its ambition to transform Norwegian industry over the long-term, then finding ways to effectively transfer knowledge from research into practical industrial use is essential. To kick-start that important goal of HighEFF, Scientific Leader Truls Gundersen has put together an energy efficiency course that he will deliver to a diverse cross-section of Norwegian industry during 2020.

While partly based on knowledge first gained during the 1980s such as the Pinch Concept, the course is geared towards the specific needs of Norwegian industry by including new applications for that previous knowledge and recent developments at NTNU and within HighEFF that consider a more integrated approach to energy efficiency. "We look not only at heat, but how heat and power interact," explains Truls.

That will be achieved through a series of four lectures. Heat integration will be covered through the analysis and targeting of industrial heat recovery systems, the design of heat recovery systems with focus on heat exchanger networks and integration of heat pumps, heat engines and distillation columns, and the retrofit of existing heat recovery systems. Finally, heat and work integration will come under the spotlight with a brief introduction to exergy, a method for assessing energy quality in order to make better comparisons within a system.

Much of what is taught will challenge common practice in industrial plants such as the operational conditions of compressors and expanders. Truls expects some of the participants to be surprised about the alternative approach: "When you consider the overall heating and cooling requirements of the plant as one integrated system, the picture is completely different. We suggest it's more energy efficient from an overall system perspective to run compressors at a high temperature. Not the highest possible temperature, but in such a way that compression heat can be given away above the pinch point. This is based on many examples, both theoretical and industry-like case studies that show the benefits."

Although there can be a reluctance to change in traditional industries, the potential financial benefits resulting from an integrated approach to energy efficiency can provide the necessary incentives. Not only is it good for the environment, it's good for the bottom line too. "Everyone agrees that the greenest energy is the one that is never used, so we need to find methods to make that happen, and then communicate them," says Truls.

However, simply approaching the problem by seeking out quick wins is not necessarily the best for long-term results. Truls promotes an integrated systems approach that can sometimes be at odds with an "energy hunter" approach that focuses on end-of-pipe solutions. "The kind of methodology we are teaching goes deep into the process to uncover potentially significant savings. HighEFF shows that investment in energy efficiency measures can be profitable for industry," says Truls.

HighEFF Chairman of the Board Arne Ulrik Bindingsbø has encouraged his colleagues in Equinor to attend, even though he says that Norwegian land-based industry and offshore oil & gas production are already among the world leaders in energy efficiency compared to similar industries in other countries: "Nevertheless, the greenhouse gas emissions from these operations account for a large part of Norway's total emissions. There is a need for technology development and subsequent implementation to further increase the energy efficiency and reduce the greenhouse gas emissions."

He adds that another important reason for professionals to attend is that the topics of energy efficiency and CO_2 emissions are complex and multidiscipline: "People working within the area have a wide range of backgrounds and there is a clear need to increase the basic competence for several of us, on both the basic theory and its applications."

Thermodynamic principles

Many thermodynamic concepts are used within engineering analyses of industrial processes ranging from individual plants to total sites. The course will introduce some of them in the context of integrated energy systems.

The Pinch Concept: A process engineering methodology that can help find energy-saving opportunities in industrial contexts. The Pinch temperature is a function of process stream data and a specified minimum temperature difference in heat exchangers, and it decomposes the process into a heat deficit and a heat surplus region. This fundamental decomposition guides the design of all heat recovery systems.

Exergy: A measure of energy quality, or the capacity of energy to produce work. The technical definition is the maximum useful work which can be extracted from a system as it reversibly comes into equilibrium with its environment.

That basic competence includes existing theory such as Pinch Analysis, a thermodynamics fundamental that isn't always used in the analysis and design of heat recovery systems where it can often provide hidden insights. Other teaching will be based in part on recent findings from NTNU and the FME HighEFF.

"I expect another big takeaway from the course to be the insights we provide in dealing with the simultaneous integration of heat pumps, distillation columns and so on. There has been a lot of HighEFF-funded PhD work at NTNU on these topics," says Truls.

Course participants will learn a methodology that the hydrocarbon industry has used to make substantial savings over the years. But it applies just as much to smaller factories such as pulp and paper or dairies. Because the methods are systematic, they can be applied to almost all energy-intensive operations, irrespective of industrial sector.

Should the course be received well, there are plans for further courses throughout the life of FME HighEFF. "At the very beginning of HighEFF our industrial partners suggested that short courses were desirable. The need to improve energy efficiency is urgent, so while education through Master and PhD programmes remains important, giving Norwegian industry the tools they need to make a difference today is equally important. That's how HighEFF can make an immediate impact and leave a lasting legacy."

Making Norwegian industry the world's greenest - HighEFF's Past, Present and Future

HighEFF is a long-term Research Centre focused on reducing energy consumption in industrial processes. Industry and academia work together in the Centre, ensuring innovations contribute to reducing emissions from industry, while also making industry more energy efficient.

"Energy efficiency is the one action that contributes to all 17 United Nations Sustainable Development Goals. It reduces emissions, increases efficiency and provides surplus energy for other uses. The product that comes out of the processes will be produced for less input. So, more value for less input", says Petter Røkke, HighEFF Centre Director.

"The collaborative efforts are what I see as one of the main goals", says Arne Ulrik Bindingsbø, Chairman of the HighEFF Executive Board. The Centre collaborates with many partners, such as academia, research institutions and partners from a range of industries including the food processing industry, metals and gas, and minerals. "All these together help us to reach our goals", he adds.

Energy efficiency is the one action that contributes to all 17 United Nations Sustainable Development Goals.

In today's globalized world the pressure of sustainability has a serious impact on society and industry. An important aspect of HighEFFs objective is to increase energy efficiency and reduce greenhouse gas emissions, which again is key for industry in both Norway and abroad.

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 Bindingsbø 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, Department of Marine Technology, NTNU.

Petter E. Røkke

Petter E. Røkke is the Centre Director of HighEFF. His current position is Research Director for the Thermal Energy department in SINTEF Energy Research. Petter earned a PhD in Mechanical Engineering from NTNU in 2006. During his career in 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, is currently member of the board for FME Bio4Fuels. Internationally, he is coordinator of the Joint Programme «Energy Efficiency in Industrial Processes» within the European Energy Research Alliance.

Results from the first four years of HighEFF

During the first four years, the Centre has developed numerous technical solutions and concepts that can be realized in society, but also revealed other issues critical for the implementation of such solutions, such as contractual issues, legal issues and societal acceptance.

"From a technical perspective, HighEFF has worked on several specific projects. One of them is the production processes for heat exchangers, using for instance 3D-printing as a method. Another project focused on industrial heat pumps and how they can produce heat in a more efficient way. Implementation of high temperature heat pumps (HTHP) can potentially reduce emissions and heat demand in industrial processes. As a result of the research and development together with FME HighEFF, TINE has achieved a reduction of 40 percent in the new dairy established outside of Bergen in 2019" says Røkke.

"We have also done a mapping of ideas that we see as potential innovations. A further follow-up on these ideas is highly interesting in terms of detecting real innovations that can have a positive impact on the industry. The Centre works with this both on the fundamental side, towards real applications (e.g. piloting) and through a specific work package called Novel Emerging Concepts", Røkke continues.

Bindingsbø adds that HighEFF's focus on innovation is already giving great results. Since start-up, 15-20 R&D spin-off projects have evolved out of HighEFF, which directly impacts the industry in terms of value creation. Another contribution has been the initiation of meeting arenas and cross-sector workshops: "This is an eye-opener for us because we can see that one industry using one technology has an effect on other industries as well. This makes the implementation phase between industries more efficient", says Bindingsbø.

Specific results from 2019

When asked about 2019's most important highlights, Røkke is quick to mention that they have developed a new method to measure achievements. Fulfilling industry expectations of up to 30 percent reduction in specific energy use requires a methodological approach to our reporting. Comparing data between industries can be challenging, and this approach makes it more manageable.

"Another highlight of 2019 is our approach to innovations in the Centre: *The Novel Emerging Concept package*" Røkke adds. "We have initiated yearly calls for ideas and "out of the box" thinking that is not strictly specified in any work plan or description. This creates a low threshold for suggestions and creative thinking, which can benefit all parties involved".

In 2019, the first of the 17 HighEFF PhD candidates has finished his studies. "One of our most important missions is to educate professional PhD candidates that can contribute to research and industry in the future. This is one of our proudest achievements of the year. I would also like to add that we have reached a good balance of nationalities and gender, which is very important to us. Involving international students brings lots of knowledge and competence across borders, which benefits Norway and the candidates' respective home countries", says the Chairman.

Bindingsbø and Røkke also highlight the recent cross-sector workshops as proud achievements, in addition to praising enabling partners like Enova and Innovation Norway as observers in the Centre.

Positioning Norway as the leading lighthouse on energy efficiency

It is no secret that the need for good collaborations in the Centre is crucial to achieve such results. In terms of innovation, placing researchers together with industry serves as a good arena for creating value. However, "although much of the responsibility in reducing CO_2-emissions and increased energy efficiency lies on industry, building knowledge and awareness to the general public so that individuals can improve in their daily lives is just as important for us to reach our goal", says Bindingsbø.

"Communicating what HighEFF achieves, the way we work and how we should work together with industry

is highly valuable in order to reduce greenhouse gas emissions and increase energy efficient technologies. It is especially important to position Norway as a leading lighthouse in the field", he adds.

By becoming a front runner in the field of energy efficiency, Norway seizes the opportunity given by the high international focus on sustainability and greenhouse gas emissons. The Centre is considered an important contributor to this notion. "By giving us license to operate and continuing our mission, there is an enormous opportunity to establish best practice in Norway for energy efficient processes and technological solutions", says Røkke.

Our expectations for the Centre and further research

"Obviously, the Centre itself has high expectations from the government and funding instruments. On the other hand, our industry partners also have high expectations to us, and we appreciate that. I like having high expectations", Røkke points out.

To further emphasize that notion, the interaction and involvement between industry and academia is the one asset that makes HighEFF unique. "This asset is crucial for bringing knowledge to the field, which brings up the next level of technological solutions, and helps us reaching our goals. Based on the four last years of research, I think that an even closer interaction together with industry is crucial for realizing ideas and concepts being developed in the Centre. This also includes expectations from us on the educational side, as PhD-candidates are encouraged to use their knowledge to improve society," he adds.

The management team and the Centre as a whole is continuously being challenged by the board. "Targets are easy to establish. However, it is more challenging to reach them. When the HighEFF project started, the board set some tough targets. This makes it important for us to continuously measure how far we have come, and how far we have left ", says the Chairman.

Future research – making use of the full value chain

"With four years left of the Centre's life span, we are now aiming to implement technology out in industry. We need to show the results of HighEFF's solutions and further our international collaborations, "says Bindingsbø.

In order to do this, HighEFF must collaborate and exchange knowledge with vendors operating in international markets, so they can transform their technological products and make them more efficient and sustainable. Today, the Centre collaborates with international vendors such as GE, Danfoss and others.

When taking the full value chain into consideration, from resource to product, the implementation of technological solutions in Norway also has an impact on technological products developed abroad. This indicates that technology being developed in (or as a result of) HighEFF can have a positive ripple-effect in other industries and nations to increase industry efficiency and reduce operational emissions. "Furthermore, this confirms that research has an enormous impact and contributes to a more sustainable society", Røkke concludes.

Vision

Joint effort for creating a competitive, energy efficient and environmental 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 changes.

The EU has energy and climate targets of 40 % reduction in greenhouse gas emissions and 27 % increase in energy efficiency by 2030. 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. For instance, if one industrial plant can be more energy efficient, there will be more available energy for other purposes. Also, Norway 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, hence support the EU target of 40% reduction in greenhouse gas emissions and 27 % increase in energy efficiency by 2030.
- Allow value creation for the Norwegian industry by developing 15-20 new innovative solutions for energy and cost-efficient plants, energy recovery and utilization of surplus heat.
- Develop methods and tools for analysis, design and optimization 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/recruitment of 30 experts in industrial energy efficiency.
- Disseminate and communicate project results; 150 journal articles and conference papers.

Enable reductions of 20-30% in specific energy use and 10% in emissions through implementation of the developed technologies and solutions, hence support the EU target of 40 % reduction in greenhouse gas emissions and 27 % increase in energy efficiency by 2030.

Allow value creation for Norwegian industry by developing 15-20 new innovative solutions for energy and cost-efficient plants, energy recovery and utilization of surplus heat.

Develop methods and tools for analysis, design and optimization of energy efficient systems.

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 has an impact on all 17 UN sustainable development goals (SDGs). Still, no one organisation, research centre or person can hope to significantly impact everything. We have chosen to focus on four SDGs where we hope to achieve significant impact through our research.

Affordable and Clean Energy

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

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

Industry, Innovation and Infrastructure

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 more responsible use of resources. It also brings down costs which in turn increases competitiveness, making it very attractive to adapt HighEFF innovations from a business standpoint as well as sustainability standpoint.

Responsible Consumption and Production

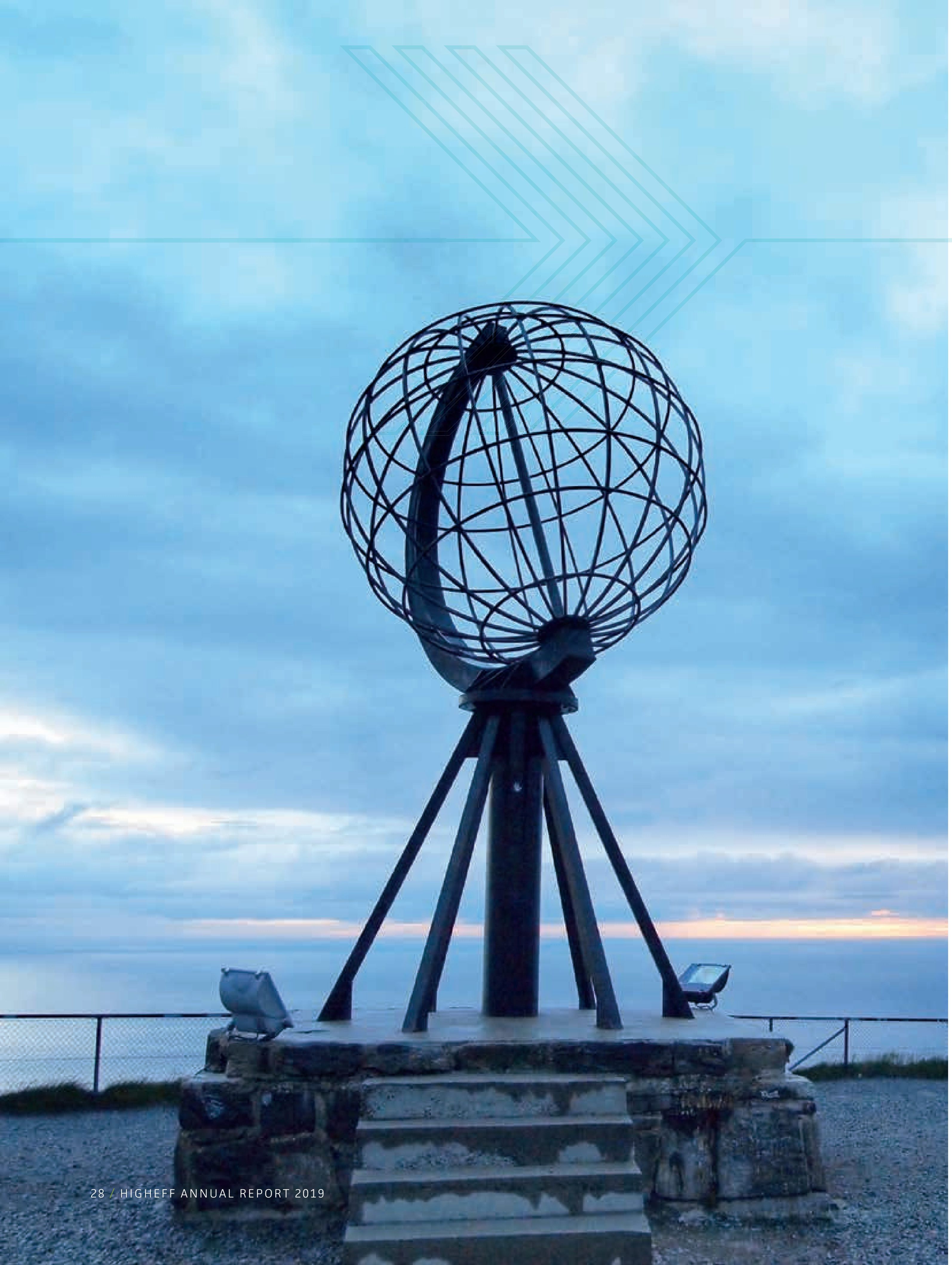
We must use the worlds limited resources more responsibly and efficiently, this in regards to both production and consumption. Enabling 20-30% reduction in specific energy use in industrial processes means industrial actors will be able to produce the same amount with 20-30% less energy.

In a world where poverty is declining, and consumption levels are rising, energy- and resource-efficient production will be key.

Climate Action

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 consuming and/or 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 across the world.



Research plan

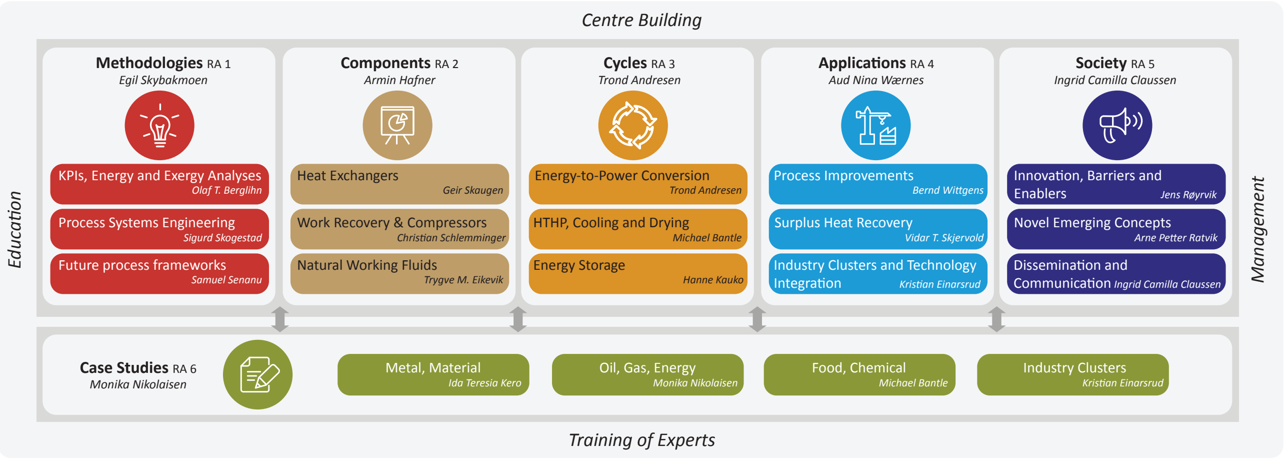
The research topics covered by HighEFF require in-depth studies of fundamental aspects related to research on thermodynamic systems and operation, heat and mass transfer processes and fluid dynamics, in addition to social science. The fundamental knowledge is implemented in development of components, cycles and applications.

HighEFF addresses the research and development areas in 6 Research Areas (RA), with a special focus on industry related case studies in RA6 where measurable results from the implementation of HighEFF technologies in the different industry sectors are obtained.

Sector-based workshops identify the path for concept development and the key areas where undertaking energy efficiency measures is likely to give the most significant impact. The KPIs and energy and exergy analyses from RA1 (Methodologies) will be utilized in making these decisions. The case studies give input to the innovation strategies and roadmaps in RA5 (Society) as well as to the concepts studied in RA2 (components), RA3 (Cycles) and RA4 (Applications).

To ensure collaboration and exchange of results across the RAs and WPs, researchers from academia and research institutes are working closely with industrial experts. The research methods include lab experiments, industrial measurements and pilot plants, as well as modelling efforts at different levels for simulation and optimization. Fundamental technological R&D involving thermodynamics, kinetics and transport phenomena are conducted for increased insight and competence building that could act as a catalyst to innovation. The international partners participate in research and education activities.

Education at PhD and Postdoc level, as well as at a Master level, is an important part of the centre activity.



Innovation strategy

Innovation targets

The HighEFF ambition is to be a platform for innovation for energy efficiency in the industry. Our main targets are to implement new and novel technology and knowledge in addition to value creation for the Norwegian industry through 15-20 new novel emerging concepts for energy and cost-efficient industry plants, heat recovery and utilization of surplus heat.

In addition, the ambitions will:

- Shape the innovation strategies and technology roadmaps for the industry to ensure a consistent direction towards national and international energy- and emission targets
- Communicate centre activities and results internally, to stakeholders, legislator and to the public.
- Enhance the knowledge on barriers and enablers for collective innovation processes.
- Allocate funding for at least one *Novel Emerging Concept* every year.

How do we work with innovations in HighEFF?

The recommendations pointed out by the expert group "FME Innovation Task Force" in 2018 are followed up by the HighEFF team during 2019. Special attention has been given to systematisation and registration of innovations as well as visibility of innovations internally and externally.

In order to meet the goals, set up by HighEFF, we have worked to facilitate for innovations through the following:

1. Defining criteria for what an innovation is
2. Dedicating an internal workshop to the topic *innovation* and presenting the actual innovations in HighEFF so far
3. Systematic reporting of innovations through Annual Work Plans (AWP), status reporting and communication internally and externally
4. Centre calls for Novel Emerging Concepts (NECs)
5. As part of one dedicated research area in HighEFF, RA5 Society, covering innovation strategies and enablers and barriers for innovation in FME Centres and in the point of intersection between research/ academia and industry.

In HighEFF the following criteria and definitions of innovation is agreed on: *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. Innovation can also be new application of existing knowledge or commercialization of R&D results. The innovation should be adopted by somebody or be ready for utilization provided that it is made probable that the innovation will be utilized within a limited timeframe.*

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

Possible new ideas for innovations are examined by the management team yearly and updated status of already registered innovations and those under development are updated. At this point of date 36 innovations are registered in HighEFF. Specific innovations covering reduced emission and energy consumption in industry processes are summed up in "one-pagers". Illustrative presentations are easy to communicate and have a broad impact.

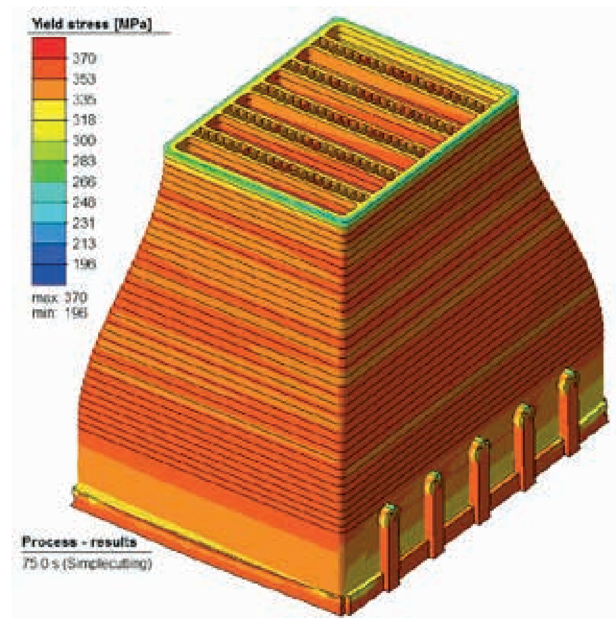
The internal annual funding of "Novel Emerging Concepts" (NEC) helps to strengthen innovation at the centre and allows for the development and testing of new ideas. The R&D partners can propose projects together with industry if possible, based on established criteria. 1.5 MNOK / year has been allocated for this scheme. So far, FME HighEFF has launched 3 new NEC projects.

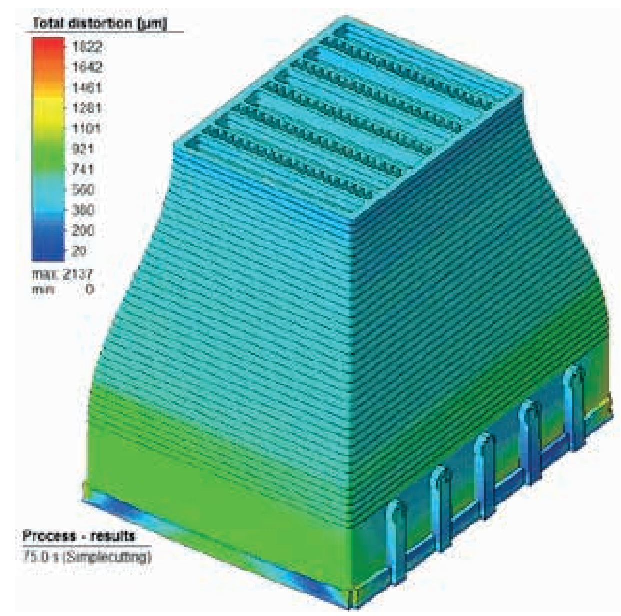
Novel Emerging Concepts

To further emphasize innovation in HighEFF, and make room for new ideas, the yearly funding of Novel Emerging Concepts (NEC) will continue. In 2019 HighEFF funded two more NEC projects; (1) *Using additive manufacturing for developing and testing novel heat exchanger concepts* (HighEx), and, (2) *Developing a tool that allow to consider complex trade-offs between energy savings and investment costs for energy storage* (CETES).

In HighEx researchers develop and validate a new workflow that combines design and production modelling to allow accurate additive manufacture of advanced heat exchanger geometries. The outcome of HighEx will be to validate the new workflow by producing smaller samples and compare to the original design and production models. This work will provide input and inspiration for ongoing and future HighEFF activities on developing new heat exchanger concepts, as well as enabling manufacture of functional prototypes for lab-scale experimental validation.

In CETES researchers develop a methodology for finding the most optimal thermal energy storage technology for storing steam in process industry.





The ultimate goal is to promote the usage of fluctuating renewable energy sources in steam production by utilizing thermal storage in combination with a suitable power-to-heat technology (electric boiler or high-temperature heat pump). The storage technologies considered include steam accumulator, latent heat storage, molten salt storage, and concrete storage. The expected result from CETES is a methodology realized in Python for finding the optimal heat-to-power and storage technologies for a given application with specific steam demand and electricity prices.

Open innovations 2019

From 2016 to 2019 HighEFF has produced 36 innovations. Here we present two open innovations from 2019.

Pre-heating of anodes in production of primary aluminium

Currently, new anodes are inserted into the cell at room temperature, while spent anodes are removed and allowed to cool down. Newly inserted anodes will not produce metal before they reach an adequate temperature, consuming energy from the cell. New anodes have in this study been pre-heated using spent anode material in an industrial setting.

1 %	0.2 %	7.8 TWh
Increased current efficiency, corresponding to 0.15 kWh/kg-Al	Achieved reduced energy consumption, corresponding to 0.02 kWh/kg-Al	Potential global energy savings per year, not including productivity increase

Increased productivity is based on literature data (Fortini et al., Light Metals 2012, pp. 595-600) achieved over a longer operating period. Achieved reduced energy consumption is based upon successful heating to 150 °C using spent butts, while the global potential of 7.8 TWh requires heating up to 960 °C, assuming an average energy consumption of 12 kWh/kg-Al and 65000 metric tonnes produced.

Steam-producing heat pump

We have conducted a case study targeting surplus heat upgrading for steam production in a nickel refinery plant. The objective was to perform an initial evaluation of several heat pumps concepts, with focus on energy efficiency, to form a basis for further work and discussions with vendors.

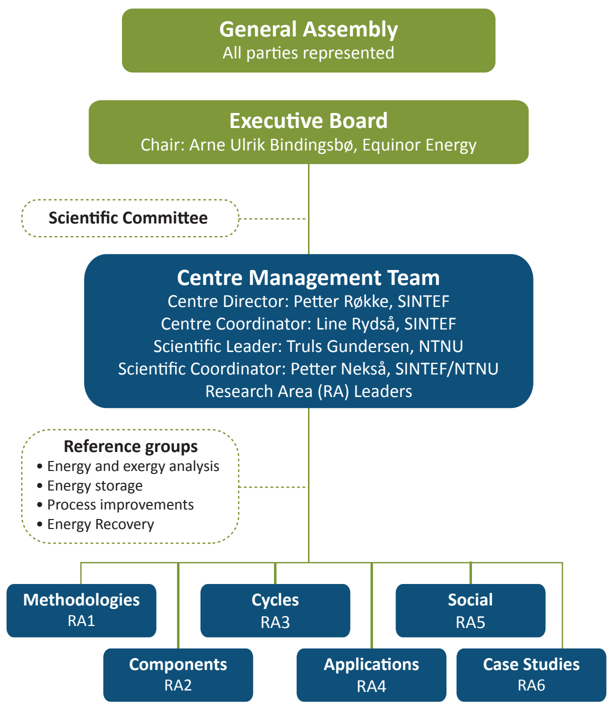
Potential savings compared to electric boiler:

3.8 MW or 75 %	630 ton or 75 %
Lower energy consumption	Lower yearly CO_2-emissions

Four environmentally friendly concepts were proposed, differing mainly in the refrigerant used and compressor technology applied. Potential savings in electricity demand, compared to the existing electric boiler, ranges between 50% and 75%.

The concept using water as refrigerant and blowers as compression technology showed the highest saving. The lowest savings were seen for a gas refrigeration cycle (reversed Brayton) with CO_2 as refrigerant. But, this concept offers the most compact and less complex system.

Organizational Structure



FME HighEFF is hosted by SINTEF Energy Research and the Centre Director is Petter E. Røkke. The General Assembly (GA) where all 28 industry partners, 13 research partners and the Excecutive Board Chair are represented, makes decision 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.

The GA approved the members of the Executive Board (EB) and Arne Ulrik Bindingsbø (Equinor Energy) was appointed Chair of the EB at the first GA meeting in June 2017, and the members have not changed since then. In addition to Arne Ulrik Bindingsbø, the other members of the EB are Ivar Valstad (Hydro Aluminium), Edin Myrhaug (Elkem/FFF*), Terje Lillebjerka (Mo Industripark), Kaia Andresen (REMA 1000 Norge), Anders Sørhuus (GE Power 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.

The HighEFF Scientific Committee is now set up with 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 (is HighEFF research world class or not). Based on this, they will provide strategic advises on scientific focus and priorities based on information received on the scientific performance in 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).

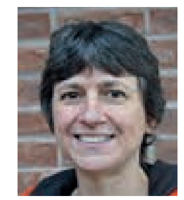
The Centre Management Team (CMT) consists of the Centre Director Petter E. Røkke (SINTEF Energy Research), Centre coordinator Line Rydså (SINTEF Energy Research), the Scientific Leader Truls Gundersen (NTNU), Scientific Coordinator Petter Nekså (SINTEF Energy Research), and the six RA leaders. The RA 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 Monika Nikolaisen (SINTEF Energy Research). The CMT is responsible for the strategic and executive centre management, including issues relating to coordination between work packages, and centre performance. CMT arrange regular meetings as required for coordinating the activities in the Centre. The Centre management reports on scientific, technical and financial matters as well as actual progress relating to EB.

* FFF: The Norwegian Ferroalloy Producers Research Association

SCIENTIFIC COMITTEE

ROBERT C. ARMSTRONG
Director MIT Energy Initiative

IGNACIO E. GROSSMANN
Former Director CAPD at CMU



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TRULS GUNDERSEN
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Partners

Research & education institutes

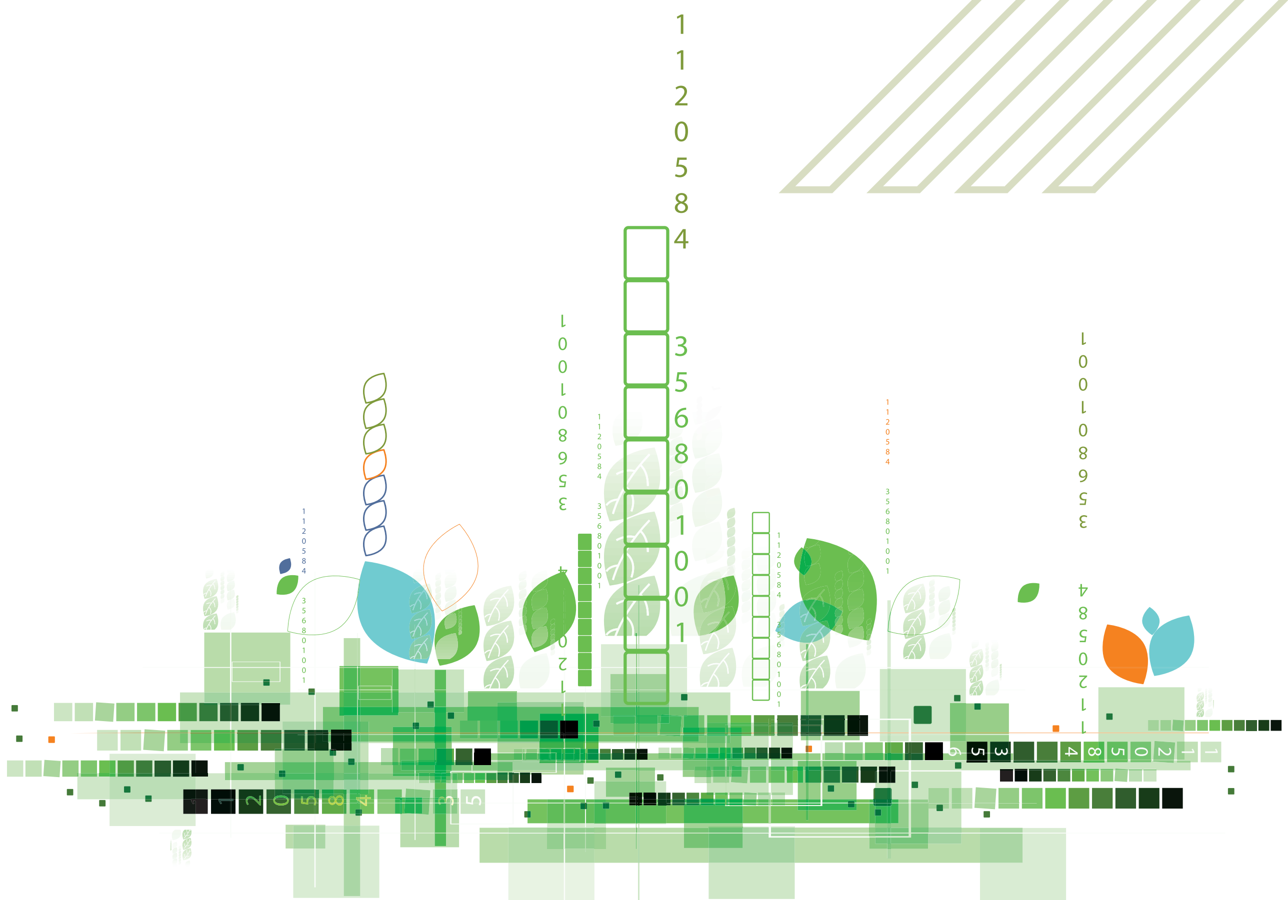
SINTEF Ocean, SINTEF Industry, SINTEF Energy Research, NTNU, NTNU Samfunnsforskning

Vendors & technology providers

User industry

Enablers

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.

All partners can contribute to the technical discussions and take part in research activities and affect the direction and ambitions for the next year's work plan. There are many arenas for technical discussions and initiating new activities.

In addition to all the meetings for specific sectors, research areas, topics, activities or tasks, 2019 saw the following larger meeting places and workshop open for all partners:

- Annual Consortium meeting held in Trondheim on 8 and 9 May
- Cross-sector Workshop, highlighting communication and Centre results, and as usual discussions about the research planned for 2020 held on 23-24 October

To ensure that all suggestions and input to research tasks are taken into consideration, the Scientific Coordinator will have the overall overview of the process.

Following a tradition that was started in March 2018, the annual Internal PhD/Postdoc Seminar was organised on Monday 25 February, hosted by NTNU. The main objectives of the seminar were to exchange ideas across Research Areas (RAs) and Work Packages (WPs), get to know each other and build networks. Current PhDs and Postdocs in HighEFF, as well as a few invited speakers, held presentations at this event. A total of 17 presentations were given.

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 neccessary interaction and input required to focus activities towards 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 have 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. Further, 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 also have 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.

Due to the global spread of partners, regional meetings are also arranged. A workshop arranged at Doshisha university in 2019 is a good example of this. Academic partners from Japan and China, industrial partners from Japan and representatives from NTNU and SINTEF took part.

International partners were also well represented at two major annual HighEFF meetings, indicating that they find these to be a good arena for the exchange of knowledge and networking.

Five Research Highlights from 2019

#1

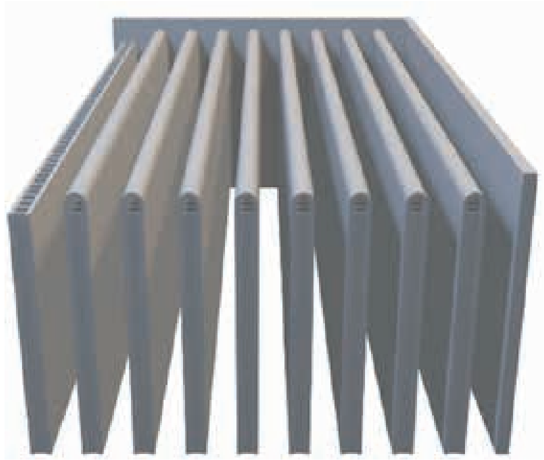
New heat exchanger concept for aluminium smelter off-gas

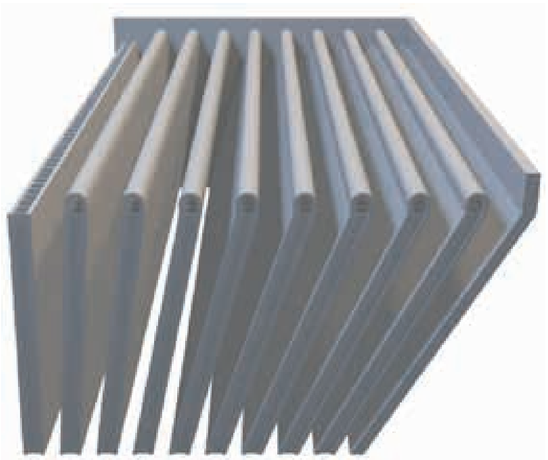
Vidar Torarin Skjervold, Research Scientist, SINTEF Energy Research

Significant amounts of surplus heat between 100-150 °C is available at aluminium production plants. The larger plants in Norway each reject around 1 TWh each year through the off-gas, but due to a lack of internal and external heat demands this heat is commonly not utilised. In addition to energy recovery, efficient heat exchangers are required for further process improvements on efficiency and emissions reductions. Aluminium smelter off-gas contains particles and fines from the electrolysis that can form solid layers on surfaces, a phenomenon often referred to as scaling. In order to avoid scaling and ensure operational stability, additional considerations must be made in the heat exchanger design.

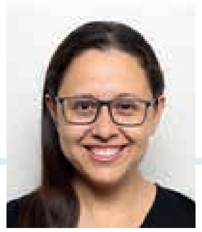
Heat exchangers that are designed to cool clean, particle-free gases often apply surface enhancements to increase the heat transfer. However, such concepts are not suitable for aluminium off-gas due to the risk of scaling. By drawing inspiration from clean gas concepts, we have investigated a modified plate-type heat exchanger without any fins on the gas side. Two variations of the concept were investigated: a straight exchanger and an exchanger with a gradual contraction along the heat exchanger length (see pictures below). Detailed heat exchanger simulations were performed, and results were compared to a clean gas reference exchanger. The analysis revealed that the proposed concepts are competitive both in terms of weight and compactness compared to the clean gas concept.

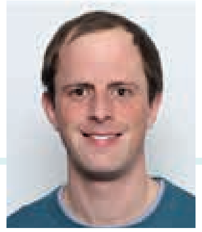
We will develop these heat exchanger concepts further in 2020. In collaboration with industry partners we are seeking opportunities for testing and validating our new concepts in an industrial environment.





Straight plate-type concept (left) and variable geometry plate-type concept (right).





#2

Utilizing low temperature surplus heat for food production

Adriana Reyes Lua, Research Scientist, SINTEF Energy Research, Goran Durakovic, Master of Science, SINTEF Energy Research, Julian Straus, Research Scientist, SINTEF Energy Research

Norwegian industry produces a large amount of low temperature surplus heat that is not utilized today due to a lack of local users of the heat. This is especially pronounced in the metal production industry in Norway due to significant magnitude of rejected heat and a limited number of people living in the neighbourhood of the production plants. Finding a user for the surplus heat can drastically increase the overall energy efficiency of an industrial process, similar to the concept of combined heat and power. Unfortunately, district heating as the standard approach is typically not an option in the metals industry because of limited local heat demand. Hence, a key aspect of improving the overall energy efficiency is the identification and development of local users of low temperature surplus heat.

A preliminary study in 2018 showed that the food production sector, in which the heat is used for space and water heating, is the most promising sector for utilization of low temperature surplus heat. This study was in 2019 extended with a focus on

1. greenhouse production of **tomatoes**,
2. warmwater **fish** production in recirculating aquaculture systems (RAS),
3. and **insect** production for both feed and food.

Greenhouse production of tomatoes using surplus heat is already applied in Norway and other countries. Our study showed that it is possible to utilize 100 GWh of surplus heat for the production of 1809 t tomatoes per year, corresponding to 5 % of the total Norwegian tomato consumption. Alternatively, warmwater fish production requires low temperature heat input for heating freshwater and to compensate for heat losses. For this application, a potential market has to be developed in Norway and Europe. The production of insects is another alternative currently with a niche demand in Europe. However, both the application of insects as food and in feed production is expected to grow drastically in the next couple of years.

There are obviously many other alternatives than food production for the utilization of surplus heat. However, different applications in food production are promising processes that can utilize a large share of the surplus heat. Furthermore, such applications reduce the dependency of Norway on food imports.


#3

The role of proximity dimensions and mutual commitment in shaping the performance of university-industry research centres

Thomas Lauvås, Associate Professor, Nord University, Marianne Steinmo, Associate Professor, Nord University

Ref: https://doi.org/10.1080/14479338.2019.1662725

It is well established that university-industry collaboration (UIC) can generate important and central contributions for firms and universities through the development of innovations, patents, licences and academic publications. However, in practice, these potential benefits are not always realized, as firms and university partners often find it challenging to collaborate effectively in UICs. Such challenges often relate to the divergent goals of industrial innovations and academic publications, which are difficult to leverage conjointly. These differences are often ascribed to a dichotomy between the opposing logics involving the academic publishing system and industrial commercialization.

This work seeks to address these gaps through a longitudinal study of two university-industry research centres in Norway. We examine how proximity along the dimensions of social and cognitive proximity and mutual commitment enables partners to comply with the research centres' goals of developing academic publications and innovations. We propose that social and cognitive proximity are equally important for complying with the goals, and we identify how these proximities co-evolve with actors' activities and interactions over time. By illustrating *key activities* for the development of social and cognitive proximity, we extend prior research that has shown that commitment is important for successful UIC but provided limited evidence regarding how such commitment should be put into action. Further, our main contributions are linked to the relationships among these proximities where repeated contact (social proximity) and mutual commitment are found to be key enablers for developing mutual understanding (cognitive proximity) between firms and university partners.

Our findings imply that formalizing UIC through a research centre does not in itself automatically lead to increased interaction. Hence, research partners should be motivated to involve industry partners early on and during the collaboration. To develop the proximity needed to support academic research and innovations, industry and university partners might be made aware of the value of forging relationships and mutual understanding, which can be developed through repeated interaction and commitment from both parties.

#4

Computational fluid dynamics for improved components in refrigeration systems

Knut Emil Ringstad, PhD Candidate at NTNU

The use of natural refrigerants in modern refrigeration systems has seen large growth in recent years, boosting high efficiencies without impacting the environment. To facilitate this transition, development of efficient systems and components is necessary.

Today, state-of-the-art computational tools, such as computational fluid dynamics (CFD), can give insight into the local flow behaviors inside these components. In our work, we focus on two-phase ejectors for CO_2 refrigeration systems, a critical component for large scale adoption of CO_2 systems, especially in warm climates.

The two-phase flow in these components is highly complex due to phenomena such as super-sonic flow, bubble/droplet interactions, non-equilibrium thermodynamics and two-phase turbulence. Therefore, an extensive review of current knowledge in the field has been conducted and is set to be published in 2020.

Currently, development of a novel model which can achieve accurate results with low computation time is under way. The model under development is based on a Two-Fluid multiphase model, which will give new insights into CO_2 ejectors.

Furthermore, an algorithm for automatic meshing of generic ejector geometries has been developed. This algorithm dramatically reduces the development time of novel ejector designs. Based on this, an optimization algorithm using automation of the CFD workflow and machine learning is under development. This will allow for better and faster design processes for ejectors, which will improve efficiency for CO_2 based refrigeration systems.

Further work will be in cooperation with Danfoss to investigate next generation CO_2 two-phase ejectors.

#5

Pinch analysis of a fish meal production process

Sverre Foslie, Research Scientist, SINTEF Energy Research

Fishmeal and fish oils are used worldwide as feed or omega 3 fatty acids, playing an increasingly important role as the world's population increases and the available land area for production of food is decreasing. Utilizing the sea for food production is one of the solutions for increasing food supply, and the focus on sustainability in the sea food production chain is increasing. Fishmeal and oil are mainly produced from waste from other fish products, and are important for utilizing as much as possible of the captured fish.

The fish meal production process is quite standardized and has not changed much in the last decades. Within energy efficiency, the main developments have focused on evaporation of water, where mechanical vapor recompression (MVR) has significantly reduced the energy consumption of the process. When it comes to drying technologies, the hot air dryer still dominates the market even though more energy efficient technologies exist, such as superheated steam dryers.

However, as the fish meal production has a long history, several facilities exist where the evaporation is still based on older technologies, such as the less energy efficient multi-stage evaporation. In contrast to the MVR evaporators which are electricity-driven, these use heat as the driving force. The heat is either delivered by steam from fossil fired boilers or from waste heat from the dryers.

In this case study, a pinch analysis methodology has been used to identify energy efficiency measures in a fish meal processing plant which currently uses a multi-stage evaporator heated by a combination of waste heat and process steam. The study was based on an energy analysis carried out in 2018, identifying process streams suitable for heat integration or heat upgrade.

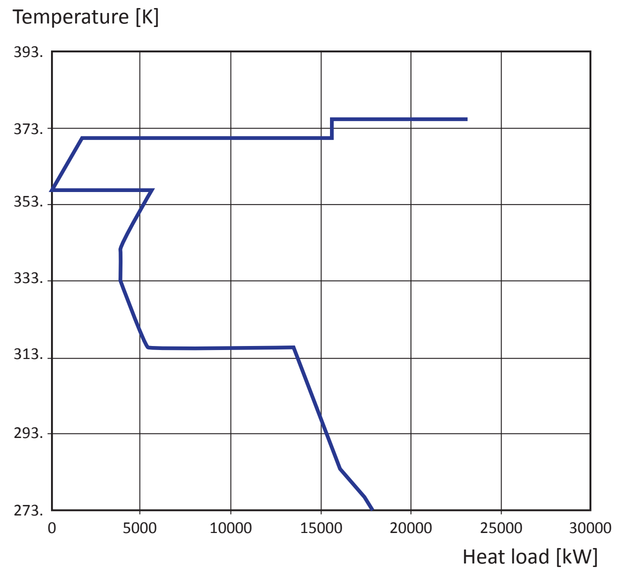
Two different options were evaluated, one where the process is kept more or less as it is today, and one option where the multi-stage evaporator is replaced by a modern MVR evaporator. In both options, several different cases are evaluated. The pinch analysis identified the pinch temperature of the two different processes and the minimum external heating requirement. The pinch temperature is the temperature for which no external heating is required below, and no external cooling above, if full heat integration of the streams is achieved. The pinch temperature therefore also tells us which temperature range a heat pump should operate in.

17-39 %
Lower energy consumption per year

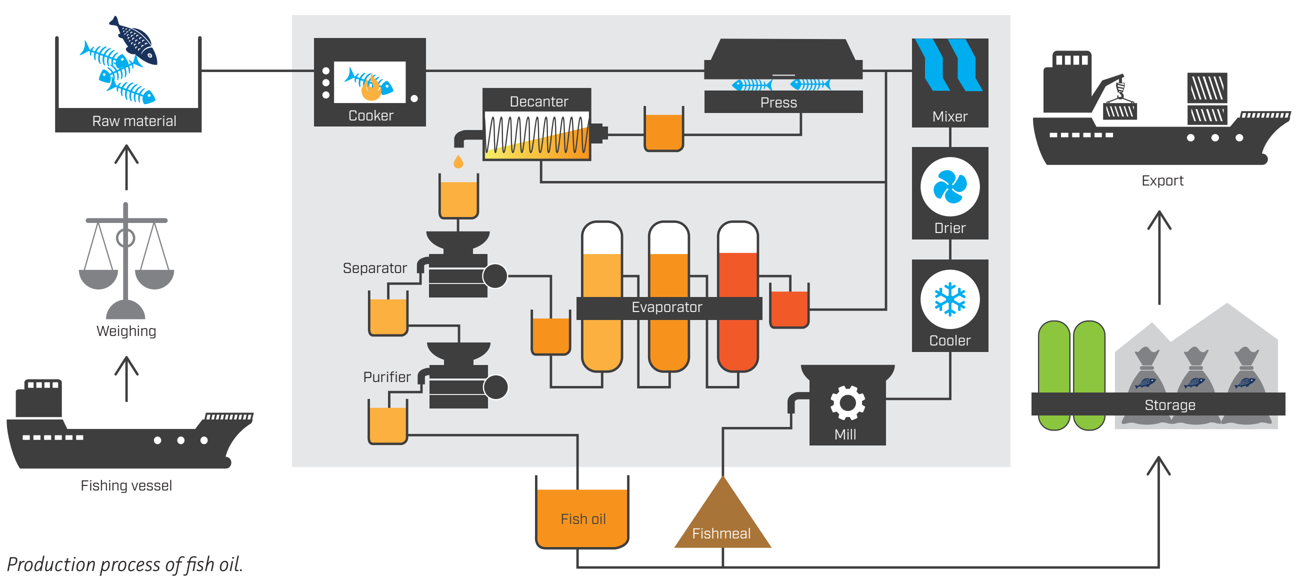
18-41 %
Less CO_2-equivalents emitted per year

#5

The main finding of the study was that implementation of a heat pump utilizing the waste heat from the existing multi-stage evaporator can provide nearly as high energy saving as replacing the evaporator with a new MVR evaporator. This is likely to have a significantly lower cost than replacing the evaporator entirely, with much smaller changes of the process. The energy saving potential ranged from 17% to 39% with reduction in CO_2 emissions of 18% to 41%.



Grand composite curves of the existing process.



Production process of fish oil.

Methodologies

RA**1**

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 are better drivers of innovation 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.

KPIs, Energy and Exergy Analyses/ Process Systems Engineering

One important task for RA1 is to use relevant KPIs for energy and resource efficiency. Alternative Key Performance Indicators (KPIs) have been tested and evaluated for an industrial case at Mo Industripark (MIP). Process data has been collected to describe the energy flows between industrial clients located at MIP.

The annual energy flow (in GWh) has been visualised in the form of Sankey diagrams while the quality of the available energy is presented in the form of a grand composite curve which describes the amounts of latent energy available at different temperature levels. High temperature flue gas from ferrosilicon (FeSi) production at Elkem Rana represent the largest heat source available for utilisation. A theoretical assessment of potential applications for this energy is presented and includes:

- electricity production via a steam Rankine cycle
- biocarbon production, where surplus heat is utilised for drying of wood chips produced at MIP
- carbon capture via amine-based post-combustion technology, where surplus heat is utilized for amine solvent regeneration.

The theoretical studies indicate that the MIP ambition from 2016 of increasing the energy recovery from 400 GWh to 640 GWh is realistic and may contribute both to increasing the energy recovery and facilitate overall reductions in the carbon footprint of the activities at MIP.

PhD Vikse and Postdoc Yu further developed Work and Heat Integration (WHI). Two review papers were published in 2019. WHI is now established as a new research field in HighEFF with considerable potential for industrial applications.

The main difference from established heat integration methods is that heat from compression and cooling from expansion are added to the basic heat recovery problem. Early results indicate considerable improvement to industrial energy systems. By making modest sacrifices in mechanical energy (work), significant savings can be obtained in thermal energy (heating and cooling). This has close connection to heat pumping, however, regular process streams are used as working fluids.

Considerable work was done on using Organic Rankine Cycles (ORCs) for power production from low temperature Waste Heat. The disadvantage with ORCs is their low efficiency in traditional applications, however, when combined with low temperature heat sinks (such as LNG regasification), the efficiency and economy can be quite good. The collaboration with Prof. Barton at MIT on developing a new paradigm for simulation and optimization has progressed. The methodology is referred to as Non-smooth Analysis and has been applied to LNG processes (multi-stream heat exchangers) and distillation columns.

Future Process Framework

Aluminium electrolysis by the Hall-Héroult process is energy intensive. In Norway, 18 TWh of electric power is consumed (12-13 % of the Norwegian production) for manufacturing about 1.2 Mton aluminium. The process emits around 2.1 Mt CO_2-equivalents.

Earlier we evaluated alternative processes to today's Hall-Heroult (inert anode technology and chlorination route). We also intended to evaluate new concepts and solutions for use in today's HH- process, creating a basis for continued research on methods and means for decreased energy consumption and environmental footprint.

In 2019 we had a detailed study of recycling of flue gas in Al electrolysis cells. We want to recycle flue gas because this will give higher concentration of CO_2 (today it is around 1 vol%), thereby enabling carbon capture technologies in the future. Another advantage is to increase the energy recovery potentials by introducing heat exchangers in the gas-system However, it is several challenges to be solved and therefore this will be followed up by a workshop in 2020 with industry partners and SINTEF.

Components

RA2

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, methods and tools required for designing components are developed. Focus is given to cycles with natural working fluid mixtures; thermodynamic properties, system optimization, and experimental development. The research area also performs design, support integration and maintains flexible component test facilities for the HighEFFLab infrastructure.

Research Activities and Results

Dry ice sublimation

We are developing a refrigeration system with heat absorption below –56˚C. The challenge is that CO_2 exists in an equilibrium between dry ice and gas at temperatures below -56 ˚C. Thus, in order to realize a refrigeration system with heat absorption below this temperature, one needs to develop a heat exchanger concept that enables sublimation of dry ice and to understand the phenomena related to this.

A tapered evaporator/sublimator with a swirl promoter, which induces a swirling flow of solid (dry ice)-gas two-phase flow, was designed and constructed and installed into a CO_2 ultra-low temperature cascade refrigeration system. By means of the heat transfer of solid (dry ice) -gas two-phase flow is investigated. Based on the measurement of heat transfer characteristics, it was verified that the CO_2 refrigeration system can operate continuously and stably without dry ice blockage in the evaporator/sublimator. It was understood that dry ice particles are uniformly distributed along the inner wall of the evaporator/sublimator by installing the swirl promoter, where the heat transfer coefficient is largely improved.

LT-Compressor replacement ejector

Decreasing the complexity of R744 commercial refrigeration systems for supermarkets could substantially reduce their cost, promoting worldwide spreading. Typically, the share of the low-temperature (LT) load in the total load for supermarkets is low. Nevertheless, significant investments must be made to

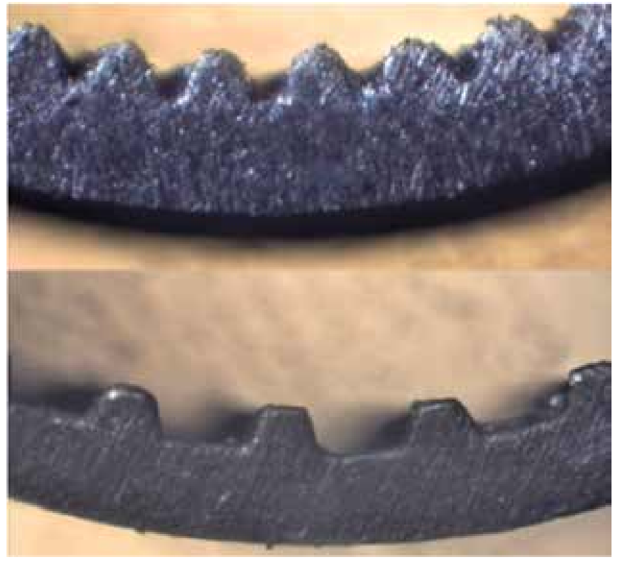
The team from HighEFF contributed to 35 presentations at the ICR2019 (International Congress of Refrigeration) in Montreal, Canada. Photo: Armin Hafner.

cover the LT demand, including dedicated compressors, inverter, desuperheater, and oil management equipment.

A new concept development based on high-pressure lift ejector to support LT evaporators reduces the system cost by replacing the whole LT compressor section with a fixed geometry ejector. In addition, elimination of the compressor(s) allows overfeeding operation of LT evaporators.

Propane evaporation in smooth and microfinned tubes

A new test section has been developed in order to measure the heat transfer coefficient and pressure drop of hydrocarbons in small diameter tubes. Following a study of different methods, a model was analysed and then a prototype built. The preliminary tests were positive and will be the basis for the final test section.

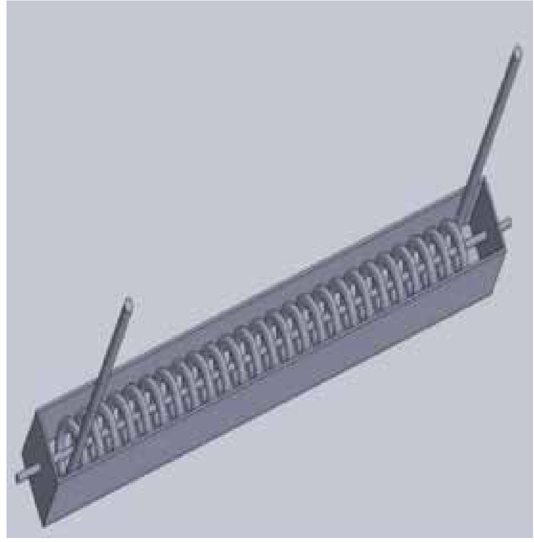


Cross section of the two tubes to be tested.

Humid gas

The work on humid gas in 2019 includes the modelling of two heat transfer scenarios using the thermodynamic model for humid gas implemented in 2018. The first scenario is to simulate the heat transfer of humid gas on a cold flat plate, where the calculation of heat transfer is based on the traditional method for dehumidification process. The second scenario is to simulate a tube-intube heat exchanger with humid gas flowing in the inner tube and cooling water flowing in the annulus. The method treats the humid gas as normal mixtures and uses the thermodynamic libraries for mixtures.

It requires further validation of the results based on experimental data, which is not available at present. Regarding the future work on modelling, it is suggested to find a suitable case relevant to the practical applications, such as the flue gases containing Sulphur components. The differences between using the dehumidification method and method of general mixtures should be further investigated.



Test section for heat transfer investigation of small tubes.

Cycles

RA3

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 emphasized.

Energy-to-power conversion

The energy recovery system at a silicon smelting plant has been analysed using a new dynamic model developed in HighEFF. Furnace off-gas energy recovery systems are subject to rapid changes in thermal load which is challenging with respect to both equipment safety and energy efficiency. The new model was applied to identify a new control strategy that can simultaneously boost electricity generation and improve thermal stability in the off-gas system. The model was developed and validated using data and measurements from the actual system.

Energy recovery concepts for practical energy recovery from metal casting have been evaluated. The thermal energy contained in the liquid metal in ferroalloy production makes it an interesting heat source for energy recovery. The starting temperature is typically in the range of 1500 °C which gives great potential for heat-to-power conversion. This heat is released during casting as the metal solidifies, but not utilized today. There are also some safety and environmental concerns related to common processes for Ferroalloy casting today. An initial new-concept evaluation that included a heat capture structure, thermal storage and power conversion was completed with promising results. A successful technical solution will not only improve the plant's energy efficiency, but also enable significant reductions in dust emissions and improved safety.

High temperature heat pumps, cooling and drying

Upgrading industrial waste heat with high temperature heat pumps (HTHP) is a popular alternative for many industries. However, there are limits in both supply temperature and availability. For now, the industry standards can deliver supply temperatures of around 90 °C, while ongoing research projects and a few smaller heat pump companies can deliver supply temperatures up to 160 °C

Last year, two promising concepts for higher supply temperatures were analysed in depth. The investigated concepts were a 3-stage turbo compressors system using water as refrigerant, and a reversed Brayton cycle using CO_2 as refrigerant. The systems were found technically and economically feasible solutions for process heat supply of up to 280 °C. These solutions are using large-scale equipment from oil and gas industries for applications in energy-intensive industries.

A pair of newly developed oil-free turbo compressors being tested at SINTEF Energy Lab.

The suggested systems benefitted from the economy of scale and access to low electricity prices. The concepts outperformed a biogas-based solution, and they were competitive with biomass or natural gas

Cycles

systems with respect to economic performance. It was concluded that an electricity-based heat supply is possible for a wide range of industrial applications and accordingly represents an important contribution to fulfilling the objectives of lower climate impact of energy supply in industry. The results were published in the journal "Energy Conversion and Management."

In addition, an international conference on high temperature heat pumps in Copenhagen was organized by SINTEF and approximately 100 delegates from 13 different countries were present to discuss the most recent developments.

Shanghai Jiao Tong University experimentally investigated the performance of a 280 kW high temperature heat pump with water as refrigerant using a single stage screw compressor prototype.

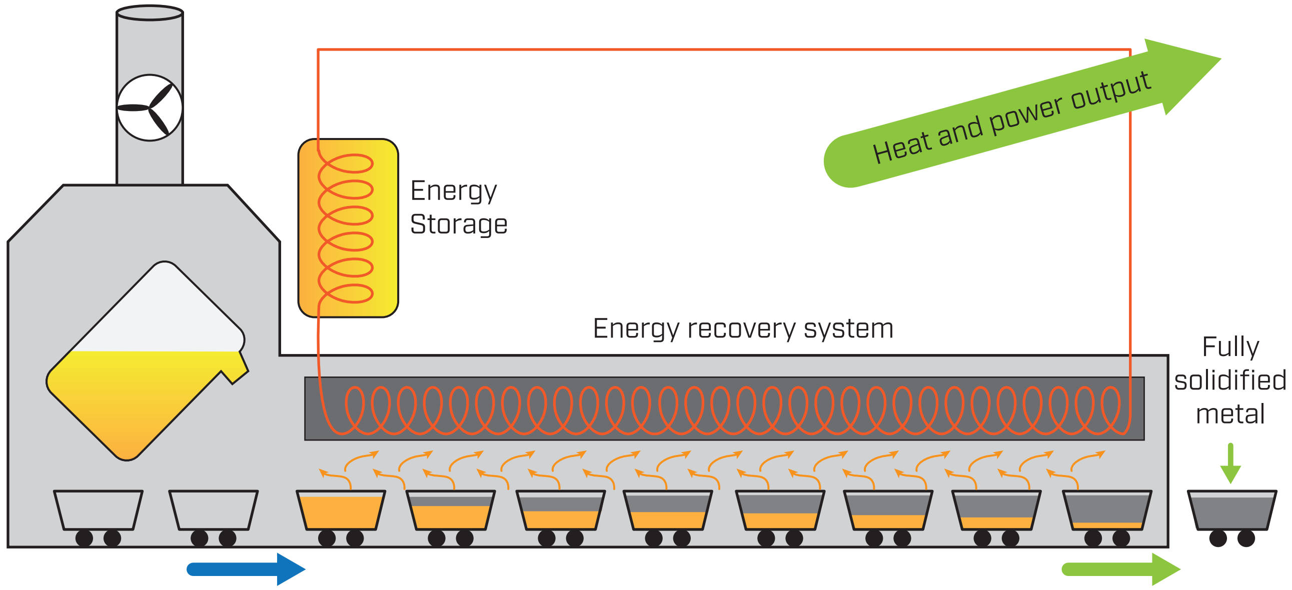
Water is an excellent refrigerant for high temperature heat pumps because of the high critical temperature which theoretically enables condensation up to 373 °C. However, water requires a high evaporating temperature, around 70°C or more, because of the low steam density at low temperatures. The heat pump from Shanghai Jiao Tong University demonstrated a saturated temperature increase of 65 °C, and a maximum heat supply of 150 °C. The results were published in the prestigious journal "Energy".

Energy storage

Different thermal energy storage (TES) concepts suited for storing steam in industrial applications have been evaluated, with focus on four technologies: steam accumulator, latent heat storage, molten salt storage, and concrete storage. Industrial steam demand is enormous, and most of the demand worldwide is still covered by fossil fuels. Utilizing TES in combination with concentrated solar power or power-to-heat technologies (electric boiler or high-temperature heat pumps) opens up the possibility for steam production based on renewables, thus cutting emissions related to steam production. While a steam accumulator is currently the only off-the-shelf technology available for storing steam, it is only suitable for storage on very short time scales, and alternative technologies are required to facilitate the green shift in industrial steam production.

In addition to such short-term, high-temperature TES systems, a study on the technologies suited for seasonal storage of industrial waste heat has been carried out. Vast amounts of industrial waste heat is dumped into the fjords especially in the summer. Seasonal thermal storage may result in this heat being available for use in the winter. The outlet temperatures available from such storages are however moderate.

At the low-temperature end, PhD candidate Håkon Selvnes (NTNU) has continued his work on developing a novel cold TES technology based on phase change materials (PCM) for applications in the food industry. The construction of a prototype unit in the SINTEF/NTNU laboratory at Gløshaugen was completed in mid-July, and tests have been carried out since August. This cold TES technology will potentially be implemented at a large poultry processing plant being under construction in Orkanger. The plant has a large and varying cooling demand and integrating cold TES in the refrigeration system may enable load shifting and a reduction in the required cooling system capacity by up to 20%, thus reducing both operational and investment costs.



Investigated concept for energy recovery from metal casting.

Applications RA4

We perform examination of applications that will integrate basic research and concepts, components, and cycles developed in other RAs into specific industry settings. This is done to generate more energy-efficient processes and to improve heat capture and utilisation concepts.

The primary focus is on process improvements within ferroalloys. Recovery of surplus heat has a focus on high utilisation of significant industrial sources. With an existing industry park as a scenario, the potential of "green" industry clusters and local thermal grids on a Nordic scale are developed.

Process Improvements

Work on efficient energy recovery from flue gases from smelters has been continued, and concepts for energy cascading were developed in 2019. These concepts have been presented to the industry and show potential for energy integration across industries.

The potential includes combined electricity recovery by Combined Heat & Power (CHP)-systems, biocarbon and biochemical production, integration towards carbon capture and storage (CCS) and at the lowest temperature ranges fish nurseries and green houses. The conceptual integration potential is large, the obstacles are more on the organizational level.

Modelling of the Submerged Arc Furnace (SAF) process has been studied for several decades. However, few of these models are integrated and show/represent the entire "picture" of the furnace. Initially a review of the work performed within The Norwegian Ferroalloy Producers Research Association (FFF)-companies has been performed to systematize the information available and start work to develop an understanding of the gaps. Two workshops with strong industrial involvement have been arranged. The results are compiled to form a basis for a Roadmap which shows the needs for further development of models. The models shall be used to improve the understanding of the mechanisms inside a furnace and how to influence/control it to minimize energy and carbon consumption, which in turn leads to cost savings.

Surplus heat recovery

Investigation of a novel heat exchanger concept for aluminium smelter off-gas was a key activity in 2019. By drawing inspiration from clean gas heat exchangers, a modified plate-type concept without fins on the gas side was developed. We hypothesize that such a concept can efficiently recover energy from the off-gas while simultaneously being able to avoid problems with scale formation, which will be important in order to avoid increased operational costs. Detailed heat exchanger simulations were performed, and results were compared to a clean gas reference exchanger. Results indicate that the developed concept can be competitive both in terms of weight and compactness compared to the reference case. Reduced weight will give lower capital costs and compactness is important because available space is often limited at aluminium plants. Increasing energy efficiency in the industry will be a key step towards reaching our climate ambitions. We will continue developing the plate-type concept in 2020.

Transferring knowledge to industry and sharing knowledge between academic and industrial partners is key for HighEFF to maximise its impact. In collaboration with the work package on energy-to-power conversion, a seminar entitled "Practical vs. Academic approach to Energy Recovery" was held within the Energy Recovery reference group. The seminar was well attended by both research and industry partners from HighEFF. Elkem and Finnfjord shared their practical experiences with operating industrial ferroalloy furnace off-gas energy recovery systems, and researchers from NTNU and SINTEF presented on improvement potentials, alternative technologies, novel ideas and concepts. In addition, Alcoa, Alfa Laval, Equinor, Eramet, GE Power, Hydro and KTH were present at the meeting. The workshop facilitated good disussions between researchers and industry and new potential topics for collaboration were identified.

Industry clusters and technology integration

A methodology for optimal Thermal Energy Storage (TES) tank dimensioning as well as an operation strategy for improved utilization of waste heat for district heating have been developed, in close collaboration with Mo Industripark/Mo Fjernvarme. The objective of the study has been to find an optimal TES size that minimizes investment costs while maximizing savings of peak heating costs, taking into account the actual dynamics of the heat central and impact of optimal control of the TES at the time of investment decision. The proposed methodology enables MFV to evaluate the potential economic, environmental and energy savings of TES relative to the investment costs.

Society

RA**5**

The overall aims are to manage the innovation activities and handle dissemination, communication and 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 will include research on internal and external interaction, as well as on the barriers and enablers for innovation and realization of HighEFF technologies and concepts.

Society

Innovation, barriers and enablers

The realization of energy efficient clusters might be one of key factors in order to reach the goals in HighEFF. Barriers for such inter-organizational interaction of industrial rhythms imposes dependencies and uncertainties for the companies involved. A study based on case studies in three industry clusters in Norway looked into how formal and informal aspects of inter-organizational collaborations can add resilience to socio-technical-economic systems for energy exchange that face uncertainties to the flow of operations and the viability of the systems.

The research on how energy efficiency is used in media, for policies directed to mitigate climate change and competitiveness, and to answer the question: *what do we talk about when we talk about energy efficiency?* was performed to give us an overall status and a hint on the future communication on energy efficiency in the industry. Energy efficiency is often framed generically without explicit or implicit assumption about reduction in consumption. Producing goods and services that are useful for society in a more energy-efficient way can be a valuable contributor to reducing carbon emissions and cost, and improving competitiveness. However, this two-fold benefit is only viable to the extent that it is coupled with absolute reductions and/or de-carbonization of energy production and use. These considerations are rarely addressed in the media discourse, and sometimes are not even the intention of the participating actors.

Novel Emerging Concepts (NEC)

Novel Emerging Concepts (NEC) is the HighEFF funding scheme for projects related to the HighEFF research and innovation objectives within emerging, energy efficient and cross-sectorial technologies. NEC is available for all industry partners. The goal of NEC is to make room for new ideas and to increase the innovation potential in HighEFF.

In 2019 HighEFF granted funding for two new NEC-projects; HighEx and CETES. HighEx researches how we can use additive manufacturing to develop and test novel heat exchanger concepts. If successful, the impact will be of high importance for the world´s energy footprint, since heat exchangers are crucial industrial components utilized in countless thermal processes in both industry and everyday life. New design, improved efficiency and performance can be the result when utilizing the design-freedom from artificial manufacturing.

CETES is developing a tool that allow us to consider complex trade-offs between energy savings and investment costs for energy storage, which can help the decision-makers in the industry to transition towards renewable-based steam production and, at the same time decrease their energy costs.

Dissemination and Communication

HighEFF's communication strategy for 2019 followed up the 2018 strategy on how the Centre will increase the visibility and knowledge among the partners and society, increasing the positive reputation of the Centre and how to improve the internal engagement within the Centre, to achieve the FME goals. The communication action plan was set up to meet the Dissemination, Exploitation and Communication (DEC) goals for the period by setting deadlines for the different activities.

During the annual HighEFF cross-sector workshop held in Trondheim in October 2019, communication staff from HighEFF partners gathered together with invited speakers. This successful event was designed to pinpoint the knowledge gained during HighEFF and make the Centre and its results more visible throughout the partner organisations.

For more details see the Communication chapter.

Case Studies

RA**6**

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 20-30 % reduction in specific energy use and/or 10 % reduction in CO_2 emissions through implementing technologies and solutions.

Metals & Materials

Dust is a commonly encountered problem in silicon and ferroalloy smelters. Thermal processes where liquid metal comes into contact with air typically generates a form of dust, known as fume. The fume is unwanted for several reasons, one of them being the occupational health of the operators of the plant. Other issues include dust emissions to the outdoor environment, material loss (decreased yield) and various challenges with respect to ventilation and gas cleaning systems, including off gas energy recovery units. One of the processes where fuming is substantial is the casting of the alloys, a process which also holds significant potential for improved energy efficiency and recovery.

In 2019, the effect of steam/water vapor on the fume generation from silicon during casting was studied. Overheated steam has proven useful in heat exchangers for the drying of aluminium alloys and was shown to improve the efficiency of the energy recovery.

Ingeborg Solheim, Research Scientist, SINTEF Industry, and Jonas Einan Gjøvik, Senior Engineer, SINTEF Industry, working in the Metallurgy Lab at NTNU Campus Gløshaugen.

However, the casting of silicon alloys takes place at a much higher temperature (>1500 °C) than the drying operations (200-250 °C). Also, previous studies have shown that air humidity and moisture increased the fuming from liquid silicon which, a priori, would be detrimental for the heat recovery.

The results from this study suggest that there may be less fume formation from liquid silicon under an atmosphere with a water partial pressure over 30%, compared to the fuming in humid air and moist atmospheres (with lower water partial pressures). Hence, the use of superheated steam atmospheres in energy recovery systems for the casting processes for silicon-rich alloys cannot be ruled out based on these results and it may constitute an interesting option for further investigations. In the future, smelters will need improved dust abatement methods as well as efficient energy recovery units for the casting processes. The two aspects will, however, need to be co-developed to avoid suboptimal solutions.

Oil, Gas & Energy

Case studies in 2019 evaluated high temperature heat pumps as a means of improving energy efficiency in industry. Three different industries were studied, including an electrified offshore oil and gas platform, a nickel refinery plant and an alumina production plant. All cases demonstrate a significant potential for improvement in energy efficiency using high temperature heat pumps. For instance, results show that implementation of heat pumps for steam production at the nickel refinery plant could reduce energy consumption by approximately 75 % compared to direct electric heating. Heat pump implementation could also reduce emission of CO_2-equivalents by approximately 630 tons in this case due to the emissions associated with electricity consumption.

Potential savings by implementing heat pumps for steam production at a nickel refinery plant:

3.8 MW or 75 %	630 ton or 75 %
Lower energy consumption	Lower yearly CO_2-emissions

Food

The TINE dairy production site in Bergen went into production in summer 2019. The production site is based on a HighEFF case study which outlined that the heat demand of the factory can be covered with its own excess heat when using high temperature heat pumps. TINE Bergen is the first dairy in the world which does not use fossil fuel or direct electric heating. The primary energy consumption is therefore reduced by 40%. TINE was the winner of the Norwegian Heat Pump Award 2019 from "Norsk Varmepumpeforening" and the Heat Pump City of the Year Award 2019 in the DeCarbIndustry category from the European Heat Pump Association. The heat pump system was supplied by Hybrid Energi AS and supported by ENOVA.

TINE receiving the Norwegian Heat Pump Award 2019.

Industry Parks

Case studies within Industry parks are so far focusing on identifying promising users of low temperature industrial surplus heat. Identifying promising users forms the basis of developing successful and efficient industry parks. Based on the results of an initial screening of potential surplus heat users in 2018, three promising cases were investigated in 2019: tomato production in greenhouses, warmwater fish production in recirculating aquaculture systems, and production of insects for both food and feed. Tomato production in greenhouses can be considered the easiest to implement as it is already done both in Norway and Europe. It can potentially lead to reductions in CO_2-emissions of around 75 %, but only utilizes half of the available energy due to different heat losses to the environment in summer and winter. Warmwater fish production is the second most promising case and it is already utilized in several countries. Due to lower water temperatures, heat utilization is improved compared to the greenhouse case, but it requires the development of a Norwegian or European market. Insect production is the market with the highest growth, but is currently limited to niche applications.

Research Infrastructure

HighEFF Lab 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, ensuring close collaboration between students and researchers from institutes and university. 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 the partners in HighEFF- and others.

HighEFFLab consists of six laboratories, with a total of 12 experimental rigs and 8 analysis instruments. They are supported by local infrastructure such as heating, cooling, power and ventilation. 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

A complete renovation of several laboratory areas was completed in 2019, and a brand new analytical and calibration laboratory is ready for use. The structural upgrading at VATL includes the extension of the cooling water supply, installation of a new transformer together with distribution cabinets, and ATEX approved ventilations. The available area has been expanded by building a mezzanine of approximately 60m2 to house the new heat excanger rig and the expander test rig. These two installations are still under construction, but onsite assembling is planned during 2020 and ready for testing late 2020, early 2021.

New equipment arrivals in 2019:

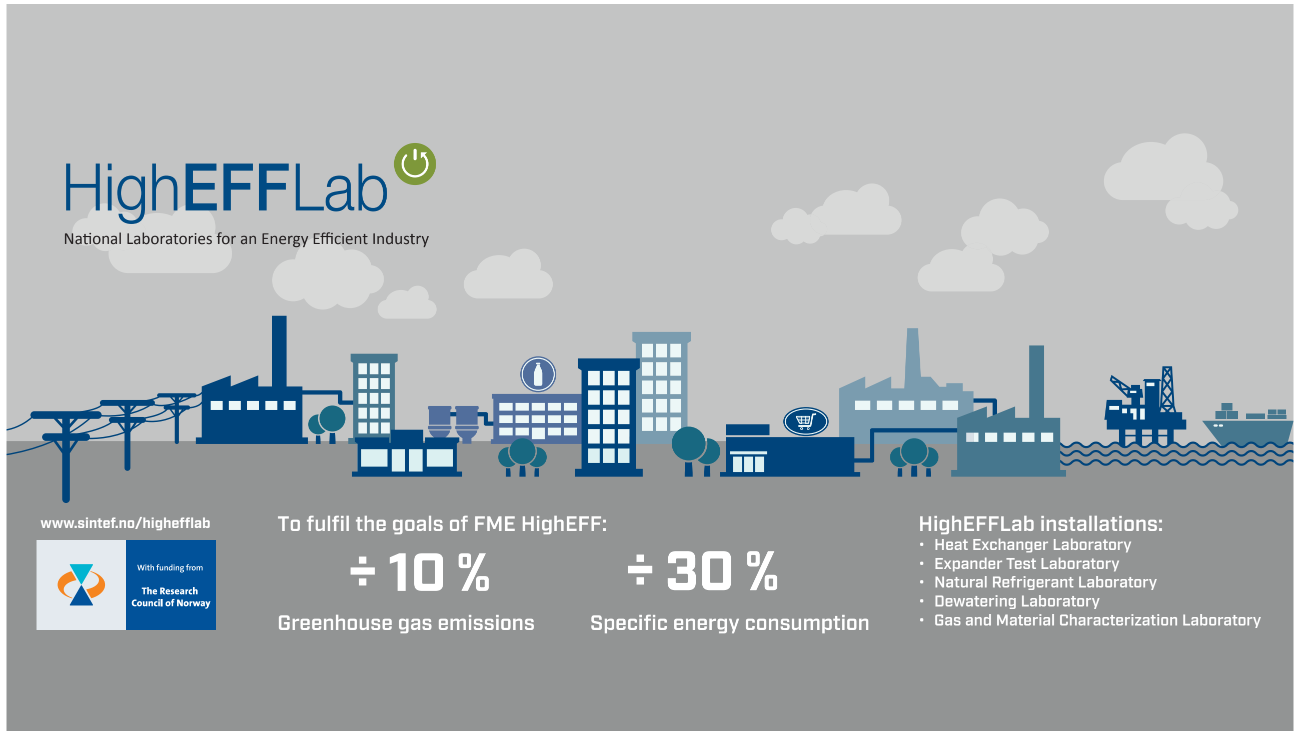
1. **Modified atmosphere dryer** (microwave vacuum dryer) with 3 kW capacity, freeze drying option and inert gas drying possibilities.
2. **Heat pump dryer** with thermal capacity up to 30 kW and product load up to 100 Kg. This system can demonstrate recovery and thermal upgrade of drying energy and fossil fuel free drying. The heat pump system uses natural refrigerant (R744). This closed-loop heat pump assisted drying process has the potential to reduce the energy demand by around 50-70% compared to conventional open-loop drying processes with fossil resources as energy source.
3. **Multifunctional test facility** for accurate testing of circuit components for high efficient R744 commercial and industrial units, such as heat exchangers, ejectors, expanders and expansion devices.
4. **Leco CS844 analyser** for determination of carbon and sulphur in primary steels, ores, finished metals, and other inorganic materials.

For further information on available instruments and test facilities, please visit the website: www.sintef.no/highefflab

Modified atmosphere dryer.

Heat pump dryer.

Leco CS844 analyser.



Education, researcher training and recruitment

Developing knowledge and expertise at various levels is a main objective and major task in HighEFF. The focus is on energy efficiency in industrial processes, and the main sub-activities are (i) methodologies for analysis, design and optimization, (ii) improved equipment and cycles, and (iii) systems integration including industrial parks (clusters). The education activity takes place at different levels such as 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.

By the end of 2019, HighEFF had recruited a total of 23 candidates (18 PhDs, four Postdocs and one researcher). One PhD will start in January 2020, and the last PhD position will be announced early 2020. One PhD and one Postdoc finished in 2019. We also have had eight associated PhDs (i.e. working on HighEFF related topics), and two of these finished in 2018.

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), two in the US (MIT and CMU) and two in Asia (Shanghai Jiao Tong University in China and Doshisha University in Japan), a total of eight universities.

The considerable number of recruited candidates has resulted in a large number of publications and conference presentations. HighEFF had 36 journal publications and 43 conference presentations in 2019 (both are "all time high") with at least one of the recruited candidates as author/co-author. One of the publications (PhD Cristina Zotica) received Best Paper Award among 250 papers on the ESCAPE'29 Conference in Eindhoven, The Netherlands, June 2019.

Selected PhDs and Postdocs

PhD SAIF RAHAMAN KAZI

What are you researching?
My research involves process flowsheet optimization with detailed equipment designs. Our focus is on the heat exchanger network (HEN) problem which has been a research topic for more than 50 years. Optimal design of HENs not only requires minimizing operating costs like steam and cold water utilities, but also reducing capital costs of added exchangers for exchanging heat between process streams. My research focuses on incorporating detailed designs for heat exchangers into the optimization model. Further work would be directed towards extending this to work and heat exchanger networks (WHEN) and multi-stream heat exchanger systems.

Who is involved in your research?
I am part of RA4-Applications, specifically involved in WP4.3.2 working on applications of new process technology in industrial case studies. This project is also collaborated with Prof. Michael Short from University of Surrey with the supervision of Prof. Lorenz Biegler of Carnegie Mellon University.

Why is your research important?
Future plants would be required to minimize their energy consumption and maximize their production simultaneously. This project will aid in practical design of energy efficient and optimal design of heat exchanger systems including refrigeration cycles and heat-to-power cycles. As detailed design of exchangers are intrinsically modeled inside these networks, the results from this strategy will be more realistic and practical in real life applications as compared to previous studies. Optimal design of multi-stream heat exchangers will also reduce energy cost for natural gas liquefaction and transportation processes.

Tell us about an interesting result.
We have developed a mathematical dynamic model for optimal design of heat exchangers using first principles-based heat and mass balances. This was used in detailed designing of heat exchangers in the HEN problem using a two-step hybrid strategy. Using our strategy, we encountered that including the detailed design of heat exchangers did not just change the operating cost but also resulted in a different network of exchangers as compared to the case which did not consider detailed designs. The results of our strategy on three examples from literature were compared and have been submitted in American Institute of Chemical Engineers (AIChE) Journal.

Alternatively, we have also developed a phase change model for flooded heat exchangers used in water cooled chillers. The non-smoothness of phase changes modelled using complementarity constraints which are then reformulated into non-linear programming (NLP). The results were presented and published in a conference paper in 9th FOCAPD conference held in Copper Mountain Resort, Colorado from 14th-18th July 2019.

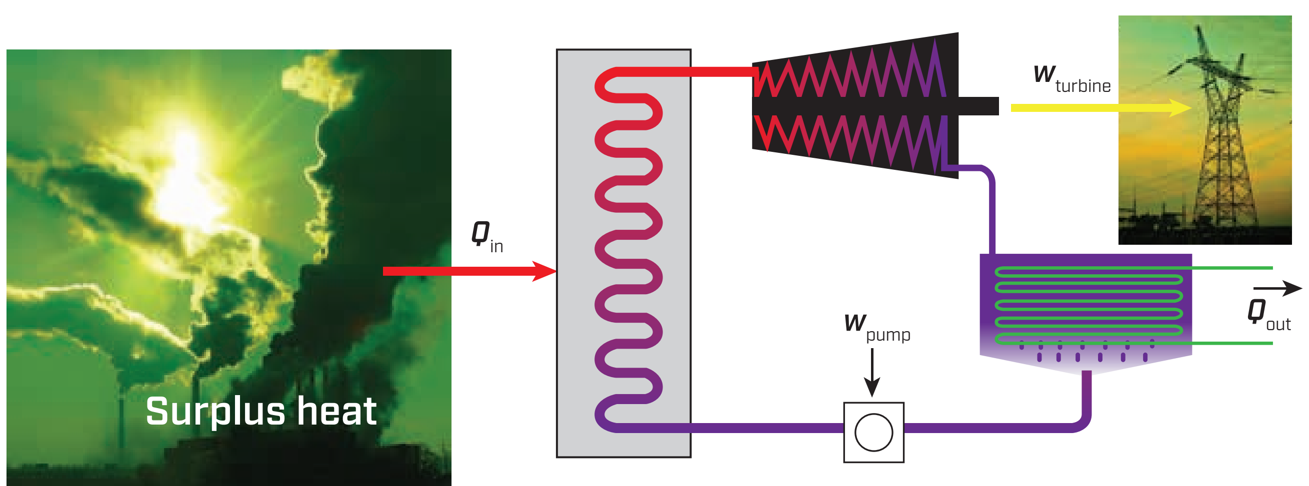
DR. ÁNGEL ÁLVAREZ PARDIÑAS

What are you researching?
My research activities in HighEFF are linked to the design of the experimental setup EXPAND (https://www.sintef.no/projectweb/higheflab/equipment/). Our main objective with EXPAND (Flexible Expander Test Rig) is to record experimental data of turbines/expanders operating with natural working fluids in the 100 kWe range.

Why is your research important?
This research is aligned with the HighEFF goals for the increase of energy efficiency and reduction of greenhouse gas emissions through waste heat recovery, i.e. converting unused thermal energy from industrial processes or thermal engines into useful power.

Organic Rankine Cycles (ORC) are an efficient and cost-effective technology to convert waste heat into power. Arguably, the two most important factors affecting the performance of the Rankine cycle are the choice of working fluid and type of expander. Surprisingly, there is a lack of experimental data available in the open literature concerning the working fluids and flow conditions encountered in small-scale expanders and therefore the performance estimation and design methodologies adopted in the field rely on models that have not been validated.

The purpose of the EXPAND project is to develop a flexible test rig that will allow to measure expander performance data. We hope that this data will be a valuable resource that will help to validate some of the small-scale expander models currently in use in the ORC community.



Organic Rankine Cycle

Tell us about an interesting result.
There are no experimental results at the moment, since EXPAND is still in the construction phase. However, the construction and commissioning of the system will be a big achievement that we expect for 2020. The schematic of EXPAND is indicated in the picture below and it was presented in the Organic Rankine Cycle Conference 2019 at Athens (Greece), attracting the attention of many of the participants. The focus of our research will be the expander/turbine, which will be conveniently instrumented to have accurate measurements of its overall performance (angular speed, mass flow rate, thermodynamic states at inlet and outlet and isentropic efficiency).

Who is involved in your research?
NTNU is leading this project and is responsible for the test rig. Even if there are no other industrial and research partners involved, this setup is a perfect opportunity for ORC and expander manufacturers or different end-users (metal industry) to join research projects and improve the efficiency of their units or processes.

MANDAR THOMBRE

What are you researching?
My research is primarily about improving energy-efficiency in thermal energy storage (TES) systems with potential uses in industrial clusters and district heating networks. To this end, I employ mathematical optimization methods on large-scale nonlinear models that describe the dynamics of the TES system. The use of TES in industrial systems requires consideration of two problems: a) Optimal Design: to find the best size of the TES for installation, keeping in mind capital investment costs and long-term operating costs; and b) Optimal Operation: once the TES is installed, to find the best operating strategy for it on a daily/weekly basis. A key aspect of my research is to investigate optimization methods that can efficiently handle uncertainty in the supply and demand of heat in the TES. As such, my work focuses on techniques such as stochastic optimization, bilevel programming and robust model predictive control to solve the above problems.

Who is involved in your research?
I am supervised by Prof. Johannes Jäschke in the Department of Chemical Engineering at NTNU. I am part of WP4.3 of HighEFF – Industrial Clusters and Technology Integration, within RA4 – Applications. I have collaborations with Brage Rugstad Knudsen and Hanne Kauko, who are HighEFF colleagues from SINTEF Energy Research. Through them, I have a small collaboration with Mo Fjernvarme, a HighEFF industrial partner. As part of my PhD program, I am spending 6 months at Carnegie Mellon University in the US, where I am working with Prof. Larry Biegler at the Center for Advanced Process Decision-making.

Why is your research important?
Chemical and process industries are responsible for releasing large quantities of waste heat to the environment. To improve the overall energy-efficiency, it is important to recover, store and reuse this surplus heat. By using TES, it is possible to store energy when the surplus heat supply exceeds demand, and to use the stored energy when the demand goes high. By using advanced optimization methods to solve the optimal design and optimal operation problems for the TES, my research aims to provide significant cost savings to industrial clusters, while also eliminating the wastage of surplus heat. The developed optimization techniques are also designed to be robust against uncertainty in heat supply and demand in the TES, which is often not the case with conventional design and operation strategies used in such systems.

Tell us about an interesting result
We investigated the optimal operation of a TES system with uncertain heat supply and demand. We found that using conventional control strategy like the standard model predictive control (MPC) resulted in the system violating some critical temperature bounds. To rectify this, we then employed a robust MPC strategy to handle the uncertainties. The new method was able to prevent the system from violating the critical bounds but turned out to be relatively expensive in terms of energy costs. To further improve on this, we analyzed the available historical data on heat supply and demand, sourced from Mo Fjernvarme. By doing statistical multivariate analysis on this data, we found some underlying interdependencies between the heat supply and demand. We exploited these interdependencies by integrating the data-driven analysis into the robust MPC strategy. The new strategy was still able to prevent the system from violating the temperature bounds, but now with much lower energy costs.

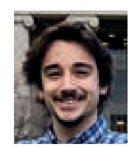
One important task of HighEFF is to educate masters and doctoral students to become the next generation energy researcher and employees for the industry. During 2019 2 PhD students have been recruited, bringing the total number of candidates to 23, 18 PhDs and 5 Postdocs. In addition, 7 master students have completed their theses related to HighEFF in 2019.

PhD Students and Postdocs (PDs) active in 2019

ÀNGEL ÀLVAREZ PARDINAS, PD
Expander Test Laboratory
Supervisor: Professor Lars O. Nord

BREDE A. L. HAGEN, PhD
Power production from medium temperature heat sources
Supervisor: Adjunct professor Petter Nekså

CRISTINA ZOTICA, PhD
Optimal Operation and Control of flexible Heat-to-Power Cycles
Supervisor: Professor Sigurd Skogestad



DAVID PÉREZ PIÑEIRO, PhD
Optimal operation and control of energy storage systems
Supervisor: Professor Sigurd Skogestad

EHSAN ALLYMEHR, PhD
Heat transfer and pressure drop in small diameter pipes for natural working fluids and mixtures - Measurement and modelling
Supervisor: Professor Tryggve M. Eikevik

HAOSHUI YU, PD
Thermodynamic Approach to Work and Heat Exchange Networks
Supervisor: Professor Truls Gundersen

HÅKON SELVNES, PhD
Cold Thermal Energy Storage for Industrial Applications
Supervisor: Professor Armin Hafner

IRINA NIKOLAYEVNA ISAEVA, PhD
Industry/University collaboration for environmental innovations
Supervisor: Professor Einar Rasmussen

JENS PETTER JOHANSEN, PhD
Barriers and enablers for energy- efficiency and exchange
Supervisor: Professor Per Morten Schiefloe

JUEJING SHENG, PhD
Exergy Analysis of Offshore Oil & Gas Processing Systems
Supervisor: Professor Ivar Ståle Ertesvåg

PhDs and Postdocs

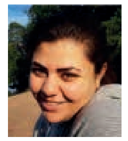
JULIA JIMENEZ ROMERO, PhD
Reduction of Industrial Energy Demand through Sustainable Integration of distributed Energy Hubs
Supervisor: Professor Robin Smith

KNUT EMIL RINGSTAD, PhD
CFD based calculation tools for improving components of R744 vapor compression units
Supervisor: Professor Armin Hafner

MANDAR THOMBRE, PhD
Optimization of Energy Efficiency in large-scale Industrial Systems under Uncertainty
Supervisor: Professor Johannes Jäschke

MARCIN PILARCZYK, PD
Compact and efficient bottoming Cycles for offshore Power Production
Supervisor: Professor Lars Olof Nord

MATIAS VIKSE, PhD
Development of Optimization Models for Work and Heat Exchange Networks
Supervisor: Professor Truls Gundersen



MINA SHAHROOZ, PhD
Low Temperature Power Cycles for Waste Heat utilization with Mixtures of natural Fluids
Supervisor: Professor Per G. Lundqvist

SAIF RAHAMAN KAZI, PhD
Optimization of Multi-Stream Heat Exchangers with Phase Change
Supervisor: Professor Lorenz T. Biegler

SUZANE CAVALCANTI, PhD
Nonsmooth Approaches for Process Flowsheet Simulation and Optimization
Supervisor: Professor Paul I. Barton

TRINE ASKLUND LARSSEN, PhD
Energy Distribution in Mn-alloy Furnaces
Supervisor: Professor Merete Tangstad

ZHONGXUAN LIU, PhD
Modeling and Optimization for Design and Operation of a Network of Distributed Energy Hubs
Supervisor: Professor Truls Gundersen

Master, Internship and Summer Scientists

SIMON BIRGER BYREMO SOLBERG
Spring 2019, WP1.1, Male, Norway
Supervisor: Signe Kjelstrup, NTNU, Dept. of Chemistry
Thesis: Energy-Efficient Designs of Systems – From Nature to Chemical Engineering

HÅKON HELLAND
Spring 2019, WP1.2, Male, Norway
Supervisor: Truls Gundersen, NTNU, Dept. of Energy and Process Engineering
Thesis: Modeling and Optimization of an Organic Rankine Cycle

ESKILD AAS
Spring 2019, WP1.2, Male, Norway
Supervisor: Johannes Jäschke, NTNU, Dept. of Chemical Engineering
Thesis: Optimization of Heat Exchanger Networks using Aspen Energy Analyser and SeqHENS

MARTIN GRIMSTAD
Spring 2019, WP6.1/6.4, Male, Norway
Supervisor: Kristian Etienne Einarsrud, NTNU, Dept. of Materials Science and Engineering
Thesis: Using surplus heat to pre-heat carbon anodes for aluminium electrolysis

SIMON LINGAAS
Spring 2019, WP3.1, Male, Norway
Supervisor: Petter Nekså, NTNU, Dept. of Energy and Process Engineering
Thesis: Energy recovery from batchwise metal casting

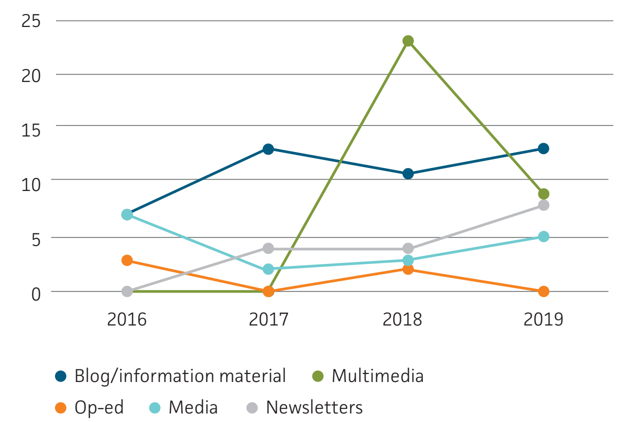
IDA ANDERSSKOG
Spring 2019, WP1.2, Female, Norway
Supervisor: Sigurd Skogestad, NTNU, Dept. of Chemical Engineering
Thesis: Plantwide control of thermal power plants

ZAWADI MDOE
Spring 2019, WP1.2, Male, Norway
Supervisor: Johannes Jäschke, NTNU, Dept. of Chemical Engineering
Thesis: Optimal control of thermal energy storage under supply and demand uncertainty

Communication

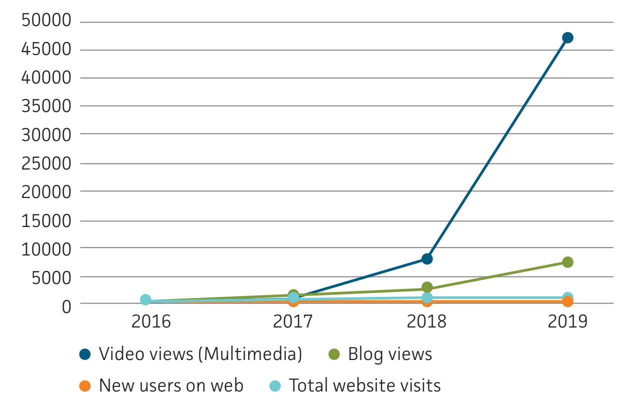
Reaching HighEFF's vision of making Norway the world's cleanest industry requires sharing new knowledge and information to industry, industrial and political willingness as well as public acceptance. Therefore, communication is a core strategic activity in HighEFF.

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



Visibility

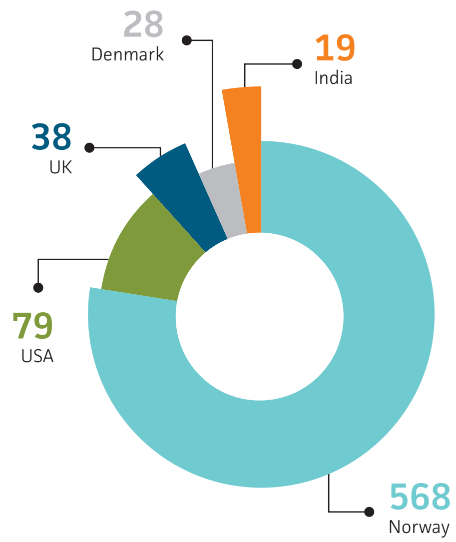
In order to reach a wide audience (both within and outside of the consortium) HighEFF has contributed to media coverage of energy efficiency in industry. In total, HighEFF had 5 media clips, 13 blogs and information material, several videos and other multimedia products in 2019.



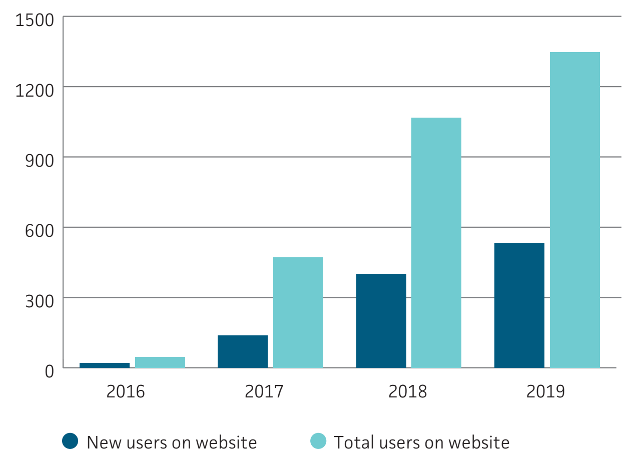
Web

The HighEFF webpage provides information about the Centre, its research and other activities like events and conferences. Towards the end of 2019 it was updated to a more modern look with better user friendliness.

The top 5 countries to visit higheff.no in 2019 were



Website development since Centre-start



Newsletter

In 2019, 8 newsletters were sent out. In 2018 and 2017 only had 4 newsletters each.

The newsletters contain the latest blogposts on SINTEFBlog, events and news from HighEFF.

- desember 18, 2019 HighEFF Newsletter Fornybar oppvarming og kjøling - PhD student Mandar Thombre
- oktober 8, 2019 HighEFF Day, -Lab and -Workshop
- september 16, 2019 HighEFF Newsletter # 6 2019
- juni 24, 2019 HighEFF Newsletter 5-2019
- mai 31, 2019 HighEFF Newsletter 4-2019
- april 25, 2019 HighEFF Newsletter 3-2019
- april 3, 2019 HighEFF Newsletter 2-2019
- januar 25, 2019 HighEFF Newsletter 1-2019

Twitter

The HighEFF Twitter account (@HighEFF_FME) was established in January of 2019 to share news about Centre activities, popular science publications like videos, posts on #SINTEFBlog and conference news. The target groups of the account are consortium members, potential partners, researchers, policy makers (domestic and international) and the "interested public".

After 2019, HighEFF had:

94 followers

25 600 Twitter views

12 tweets

The most popular tweet of 2019 was the annual report video with Centre Director Petter Røkke where he looks back at the highlights of 2018.

The tweet had:
- 7 300 views
- 380 video views
- 75 engagements (I.e. retweets, likes, etc.)

Blogs

HighEFF published 14 blogposts on the SINTEFBlog in 2019 (10 in 2018). Towards the end of 2018 the strategy for blogposts changed to allow blogpost to go more in-depth on HighEFF science and research, where the previous strategy was to only "stay on the surface". Blogpost are preferably a spin-off product from a scientific publications. They are aimed at other researchers (both within and outside the research-field of the blogpost), policy makers and people working in areas connected to energy efficiency.

This strategy was carried out through the whole year of 2019, resulting in 7200 readers where 2018 only had 2450 readers.

Top three blogpost of 2019 were:

#ENERGY / ENERGY EFFICIENCY

Is aluminium electrolysis using inert anodes a blind alley?

The Hall-Héroult process, patented in 1886, is currently used universally for the smelting of primary aluminium. Since then, of course, many improvements have...

946 readers

#ENERGY / ENERGY EFFICIENCY

Could the chloride process replace the Hall-Héroult process in aluminium production?

At present, the Hall-Héroult process is universally used in the production of aluminium. It is an electrolytic process in which aluminium oxide is...

552 readers

#ENERGY / #MANUFACTURING / ENERGY EFFICIENCY

Additive manufacturing of heat exchangers (How would it work?)

Today, heat exchanger design and possibilities are limited by current production processes. But what new potential could be realised if heat exchanger design...

454 readers

Media

In addition to attending and presenting at important conferences, political meetings etc, HighEFF always aims at reaching a wide audience through the media in order to affect both political and public acceptance. Here are two snippets of media cases from HighEFF in 2019.

HighEFF Scientific Coordinator Petter Nekså commented on the energy efficiency of the AC-facilities at the Athletics World Championship stadium.

HighEFF Senior Research Scientist Michael Bantle was interviewed about SINTEF's new heat pump which can produce steam up to 160 °C. It can therefore be used in process-, chemical and food industry. Traditionally heat pumps can only deliver heat up to 60-70 °C, which is too low for the aforementioned purposes.


VM-stadionet forurenser like mye hver dag som å kjøre bil 20 ganger rundt ekvator

Arrangøren lovet at Khalifa stadion skulle være klimavennlig, til tross for verdens kanskje største air condition-anlegg. Sånn ble det ikke.


VARME TIL NÆRINGSMIDDELINDUSTRIEN

Sintefs nye varmepumpe kan lage 160 grader varm damp

Sjokoladegiganten Mars er pilotkunde.

Appendices

Appendix 1 Personnel involved in the centre in 2019

Key researchers		
Name	**Institution**	**Main research area**
Adriana Reyes Lua	SINTEF Energy Research	Industry clusters
Afaf Saai	SINTEF Industry	FEM modelling, WP2.2
Alexis Sevault	SINTEF Energy Research	High-temperature TES for industrial processes
Ángel Pardiñas	NTNU	Expander test laboratory
Anton Beck	Austrian Institute of Technology	Steam thermal storage
Armin Hafner	NTNU	Hight temperature heat pumps, cold thermal storage
Arne Petter Ratvik	SINTEF Industry	Novel emerging concepts
Asbjørn Solheim	SINTEF Industry	Chloride Al processes, inert anode, HH improvement, Case study Al
Aud Nina Wærnes	SINTEF Industry	Process improvements
Balram Panjwani	SINTEF Industry	Process improvements
Bernd Wittgens	SINTEF Industry	Process improvement
Bin Hu	Shanghai Jiao Tong University	Steam high temperature heat pump
Brage Knudsen	SINTEF Energy Research	Thermal energy storage potential for the industry, modelling and optimization of energy exchange in clusters
Brede Hagen	NTNU	Surplus heat-to-power conversion
Catharina Lindheim	NTNU Social Research	Society
Cecilia Gabrielii	SINTEF Energy Research	Low temperature cooling
Christian Schlemminger	SINTEF Energy Research	High temperature heat pumps and thermal energy storage for industrial processes
Cristina Zotica	NTNU	Optimal Operation and Control of flexible Heat-to-Power Cycles
Daniel Rohde	SINTEF Energy Research	Energy-to-power conversion, and Industry clusters and technology integration
David Perez Pineiro	NTNU	Optimal operation and control of energy storage systems
Egil Skybakmoen	SINTEF Industry	RA1 Methodologies leader
Ehsan Allymehr	NTNU	Heat transfer and pressure drop in small diameter pipes for natural working fluids and mixtures

Key researchers		
Name	**Institution**	**Main research area**
Einar Jordanger	SINTEF Energy Research	Management
Einar Rasmussen	Nord University	Supervisor Irina Isaeva
Espen Verpe Halvorsen	SINTEF Energy Research	Heat pumps, cooling and drying
Geir Skaugen	SINTEF Energy Research	Heat exchangers
Gerwin Drexler-Schmid	Austrian Institute of Technology	High-temperature thermal energy storage, High Temperature heat pumps
Goran Durakovic	SINTEF Energy Research	Surplus heat-to-power conversion, RA6 case studies; industry clusters
Gudveig Gjøsund	NTNU Social Research	Organizational analysis
Halvor Dalaker	SINTEF Industry	Process improvements
Han Deng	SINTEF Energy Research	Heat exchangers, natural working fluids
Hanne Kauko	SINTEF Energy Research	Thermal energy storage (TES) potential in industry clusters, High-temperature TES for industrial processes
Haoshui Yu	NTNU	Thermodynamic Approach to Work and Heat Exchange Networks
Helle Børset Eidissen	SINTEF Energy Research	Heat exchangers
Hiroshi Yamaguchi	Doshisha University	Refrigeration technology
Håkon Fyhn	NTNU Social Research	Future success factors of industrial clusters
Håkon Selvnes	NTNU	Cold thermal storage for industrial applications
Ida Kero	SINTEF Industry	Metallurgy, materials science, process improvements
Ingeborg Solheim	SINTEF Industry	Casting case study
Ingrid Camilla Claussen	SINTEF Energy Research	Dissemination, society
Irina N. Isaeva	Nord University	Industry/University collaboration for environmental innovations
Ivar S. Ertesvåg	NTNU	Exergy Analysis of Offshore Oil & Gas Processing Systems
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
Johannes Jäschke	NTNU	Optimization of Energy Efficiency in large-scale Industrial Systems under Uncertainty
Juejing Sheng	NTNU	Exergy Analysis of Offshore Oil & Gas Processing Systems

Key researchers		
Name	**Institution**	**Main research area**
Julia Jimenez Romero	The University of Manchester	Reduction of Industrial Energy Demand through Sustainable Integration of distributed Energy Hubs
Julian Straus	SINTEF Energy Research	RA6 case studies; industry clusters
Kai Tang	SINTEF Industry	Process improvements Si
Karl Erik Artur Lindqvist	SINTEF Energy Research	Heat exchangers
Knut Emil Ringstad	NTNU	CFD for improving components of R744 vapor compression units
Krisitan E. Einarsrud	NTNU	Cluster modelling, materials science
Kristian Leonard Aas	SINTEF Industry	Thermo electric generation
Kristina Norne Widell	SINTEF Ocean	HTHP, Cooling and Drying and Case studies food
Lars O. Nord	NTNU	Supervisor
Leiv Kolbeinsen	NTNU	Industrial clusters
Line Rydså	SINTEF Energy Research	Management
Lorenz T. Biegler	Carnegie Mellon University	Supervisor Siaf Kazi
Mandar Thombre	NTNU	Optimization of Energy Efficiency in large-scale Industrial Systems under Uncertainty
Marcin Pilarczyk	NTNU	Compact bottoming cycles for offshore power production
Marianne Therese Steinmo	Nord University	Industry/research collaboration in FME centres
Matias Vikse	NTNU	Development of Optimization Models for Work and Heat Exchange Networks
Merete Tangstad	NTNU	Energy Distribution in Mn-alloy Furnaces
Michael Bantle	SINTEF Energy Research	High temperature heat pump (HTHP), low temp cooling next gen drying systems, case studies
Michael Jokiel	SINTEF Energy Research	Seasonal thermal energy storage
Michael Lauermann	Austrian Institute of Technology	High Temperature Heat Pump
Mina Shahrooz	KTH Royal Institute of Technology	Low temperature waste-heat-to-power conversion
Monika Nikolaisen	SINTEF Energy Research	Surplus heat-to-power conversion, oil, gas and energy case studies
Morten Dahle Selfors	Nord University	Society

Key researchers

Name	Institution	Main research area
Olaf Trygve Berglihn	SINTEF Industry	KPIs, energy & exergy analyses, process improvements
Ole H Meyer	SINTEF Energy Research	RA2 Components
Paul I Barton	Massachusets Institute of Technology	Supervisor Suzane Cavalcanti
Per Lundqvist	KTH Royal Institute of Technology	Supervisor Mina Shahrooz
Per M. Schiefloe	NTNU Social Research	Innovation
Petter Nekså	SINTEF Energy Research/NTNU	Energy efficiency in industry
Petter Røkke	SINTEF Energy Research	Management
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 Industry	HH improvement, Gas recycling Al cells.
Signe Kjelstrup	NTNU	Establish KPIs with Focus on Energy Efficiency in HighEFF
Sigurd Skogestad	NTNU	Process systems engineering
Suzane Cavalcanti	Massachusets Institute of Technology	Nonsmooth Approaches for Process Flowsheet Simulation and Optimization
Sverre Foslie	SINTEF Energy Research	High temperature heat pumps and thermal energy storage for industrial processes
Tom S. Nordtvedt	SINTEF Ocean	HTHP, Cooling and Drying and Case studies food
Torbjørn Pettersen	SINTEF Industry	Case study modelling in report KPIs
Trine Asklund Larssen	NTNU	Energy Distribution in Mn-alloy Furnaces
Trond Andresen	SINTEF Energy Research	Surplus heat-to-power conversion
Truls Gundersen	NTNU	Pinch analyses
Trygve Eikevik	NTNU	Natural refrigerants
Vidar Skjervold	SINTEF Energy Research	Surplus heat recovery
Zhongxuan Liu	NTNU	Modeling and Optimization for the Design and Operation of a Network of Distributed Energy Hubs
Åsmund Ervik	SINTEF Energy Research	RA2 components, work recovery and compression

Visiting researchers

Name	Affiliation	Nationality	Sex	Duration	Topic
Diego Kingston	Universidad de Buenos Aires	Argentina	M	Sep-Nov 2019	Distillation Column for Air Separation
Nataliya Kizilova	Warsaw Univ. of Technology	Ukraine	F	Apr-Jun 2019	Nature inspired Design in Fuel Cells
Ruiqi Wang	China Univ. of Petroleum	China	M	Oct-Dec 2019	Layout Design of Plants and Industrial Parks

Postdoctoral researchers with financial support from the Centre budget

Name	Nationality	Period	Sex	Topic
Haoshui Yu	China	04 2017 - 03 2019	M	Thermodynamic Approach to Work and Heat Exchange Networks
Àngel Àlvarez Pardinas	Spain	05 2018 - 05 2020	M	Expander Test Laboratory
Marcin Pilarczyk	Poland	07 2018 - 07 2021	M	Compact and efficient bottoming Cycles for offshore Power Production

PhD students with financial support from the Centre budget

Name	Nationality	Period	Sex	Topic	Completed?
Brede A. L. Hagen	Norway	08 2018 - 07 2021	M	Power production from medium temperature heat sources	No
Cristina Zotica	Romania	08 2017 - 08 2021	F	Optimal Operation and Control of flexible Heat-to-Power Cycles	No
David Pérez Piñeiro	Spain	09-2019 - 08-2022	F	Optimal operation and control of energy storage systems	No
Ehsan Allymehr	Iran	07 2018 - 05 2022	M	Heat transfer and pressure drop in small diameter pipes for natural working fluids and mixtures	No
Håkon Selvnes	Norway	08 2017 - 07 2020	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 - 08 2020	M	Barriers and enablers for energy-efficiency and exchange	No
Juejing Sheng	China	09 2017 - 06 2021	F	Exergy Analysis of Offshore Oil & Gas Processing Systems	No

PhD students with financial support from the Centre budget					
Name	**Nationality**	**Period**	**Sex**	**Topic**	**Completed?**
Julia Jimenez Romero	Ecuador	10 2017 - 03 2020	F	Reduction of Industrial Energy Demand through Sustainable Integration of distributed Energy Hubs	No
Knut Emil Ringstad	Norway	08 2018 - 08 2021	M	CFD based calculation tools for improving components of R744 vapor compression units	No
Mandar Thombre	India	08 2017 - 08 2020	M	Optimization of Energy Efficiency in large-scale Industrial Systems under Uncertainty	No
Matias Vikse	Norway	08 2016 - 06 2020	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	No
Suzane Cavalcanti	Brazil	06 2017 - 05 2021	F	Nonsmooth Approaches for Process Flowsheet Simulation and Optimization	No
Trine Asklund Larssen	Norway	08 2017 - 07 2020	F	Energy Distribution in Mn-alloy Furnaces	No
Zhongxuan Liu	China	09 2018 - 09 2021	F	Modeling 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						
Name	**Funding**	**Nationality**	**Period**	**Sex**	**Topic**	**Completed**
Adriana Reyes Lúa	NTNU (NV Faculty)	Mexico	09 2016 - 12 2018	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 (IV Faculty)	India	09 2017 - 08 2020	M	Optimal Design and Operation of Polygeneration Production Chains	No
Daniel Rohde	KPN INTERACT	Germany	09 2016 - 11 2018	M	Dynamic Simulation of Future Integrated Energy Systems	Yes

PhD students working on projects in the centre with financial support from other sources						
Name	**Funding**	**Nationality**	**Period**	**Sex**	**Topic**	**Completed**
Roberto Agromayor	KPN COPRO	Spain	01 2017 - 07 2020	M	Turbomachinery for Waste Heat Recovery Applications	No
Silje Marie Smitt	NTNU (NV Faculty)	Norway	08 2017 - 08 2020	F	Design and Control of Energy Efficient, Integrated Vapor Compression Units for HVAC and Sanitary Hot Water Systems in high performance Building	No
Marcel Ulrich Ahrens	NTNU Energy / xx	Germany	10-2017 - 09-2021	M	Development of a combined absorptioncompression heat pump test facility at high temperature operation	No
Stefanie Blust	IV fac / NTNU	Germany	06-2019 - 02-2023	F	Large Hadron Collider (LHC) detector cooling with R744 refrigeration technology	No

Master's degrees		
Name	**Funding**	**Nationality**
Simon Birger Byremo Solberg	M	Energy-Efficient Designs of Systems – From Nature to Chemical Engineering
Håkon Helland	M	Modeling and Optimizastion of an Organic Rankine Cycle
Eskild Aas	M	Optimization of Heat Exchanger Networks using Aspen Energy Analyser and SeqHENS
Martin Grimstad	M	Using surplus heat to pre-heat carbon anodes for aluminium electrolysis
Simon Lingaas	M	Energy recovery from batchwise metal casting
Ida Andersskog	F	Plantwide control of thermal power plants
Zawadi Mdoe	M	Optimal control of thermal energy storage under supply and demand uncertainty

Appendix 2 Statement of accounts 2019

(All figures in 1000 NOK)

Costs	Amount
Host institution (SINTEF Energy Research)	22 851
Research partners	33 284
User partners	4 341
Equipment	1
Total	**60 477**

Funding	Amount
Research Council of Norway	28 529
Host institution (SINTEF Energy Research)	6 300
Research partners	9 383
User partners	13 766
Total *)	**57 978**

*) The missing funding (kNOK 2 499) will be balanced on the 2020 accounts

Appendix 3

HighEFF publications 2019

Peer reviewed Journal publications

From: 2019 *To:* 2019 *sub-category:* Academic article *sub-category:* Academic literature review *sub-category:* Short communication *All publishing channels*

1. **Agromayor, Roberto; Müller, Bernhard; Nord, Lars O. One-Dimensional Annular Diffuser Model for Preliminary Turbomachinery Design.** *International Journal of Turbomachinery, Propulsion and Power* 2019 ;Volume 4.(3) p. -. NTNU
2. **Agromayor, Roberto; Nord, Lars O. Preliminary Design and Optimization of Axial Turbines Accounting for Diffuser Performance.** *International Journal of Turbomachinery, Propulsion and Power* 2019 ;Volume 4.(3) p. - NTNU
3. **Andreasen, Glenn; Stoustrup, Jakob; Izadi-Zamanabadi, Roozbeh; Pardiñas, Ángel Á.; Hafner, Armin.** *Data-driven modeling of a CO_2 refrigeration system.* American Control Conference (ACC) 2019 ;Volume 2019-July. p. 5385-5390 NTNU
4. **Bamigbetan, Opeyemi Olayinka; Eikevik, Trygve Magne; Nekså, Petter; Bantle, Michael; Schlemminger, Christian. Experimental investigation of a prototype R-600 compressor for high temperature heat pump.** *Energy* 2019 ;Volume 169. p. 730-738. ENERGISINT NTNU
5. **Bamigbetan, Opeyemi Olayinka; Eikevik, Trygve Magne; Nekså, Petter; Bantle, Michael; Schlemminger, Christian. The development of a hydrocarbon high temperature heat pump for waste heat recovery.** *Energy* 2019 ;Volume 173. p. 1141-1153. ENERGISINT NTNU
6. **Durakovic, Goran; Skaugen, Geir. Analysis of Thermodynamic Models for Simulation and Optimisation of Organic Rankine Cycles.** *Energies* 2019 ;Volume 12.(17). ENERGISINT
7. **Jakobsen, Siri; Lauvås, Thomas Andre; Steinmo, Marianne Terese. Collaborative dynamics in environmental R&D alliances.** *Journal of Cleaner Production* 2019 ;Volume 212. p. 950-959. NORD
8. **Knudsen, Brage Rugstad; Kauko, Hanne; Andresen, Trond. An Optimal-Control Scheme for Coordinated Surplus-Heat Exchange in Industry Clusters.** *Energies* 2019 ;Volume 12.(10) p. 1-22. ENERGISINT
9. **Larssen, Trine Asklund; Kero, Ida; Tangstad, Merete. Energy Distribution in HC FeMn and SiMn - Energy vs Exergy Analyses.** *The Southern African Journal of Mining and Metallurgy* 2019 ;Volume 119.(12) p. 1071-1076. NTNU SINTEF
10. **Lauvås, Thomas Andre; Steinmo, Marianne Terese. The role of proximity dimensions and mutual commitment in shaping the performance of university-industry research centres.** *Innovation: Organization and Management* 2019. NORD
11. **Magnanelli, Elisa; Solberg, Simon Birger Byremo; Kjelstrup, Signe. Nature-inspired geometrical design of a chemical reactor.** *Chemical engineering research & design* 2019 ;Volume 152. p. 20-29 ENERGISINT NTNU
12. **Mastrowski, Mikolaj; Smolka, Jacek; Hafner, Armin; Haida, Michal; Palacz, Michal; Banasiak, Krzysztof. Experimental study of the heat transfer problem in expansion devices in CO2 refrigeration systems.** *Energy* 2019 ;Volume 173. p. 586-597. ENERGISINT NTNU
13. **Reyes-Lúa, Adriana; Andreasen, Glenn; Larsen, Lars F.S.; Stoustrup, Jakob; Skogestad, Sigurd. Control structure design for a CO2-refrigeration system with heat recovery.** *Computer-aided chemical engineering* 2019 ;Volume 46. p. 1243-1248. NTNU
14. **Reyes-Lúa, Adriana; Skogestad, Sigurd. Multiple-Input Single-Output Control for Extending the Steady-State Operating Range—Use of Controllers with Different Setpoints.** *Processes* 2019 ;Volume 7.(12) p. - NTNU
15. **Reyes-Lúa, Adriana; Skogestad, Sigurd. Systematic Design of Active Constraint Switching Using Classical Advanced Control Structures.** *Industrial & Engineering Chemistry Research* 2019 ;Volume 56.(6) p. 2229-2241. NTNU
16. **Reyes-Lúa, Adriana; Zotica, Cristina Florina; Forsman, Leif Krister; Skogestad, Sigurd. Systematic Design of Split Range Controllers.** *IFAC-PapersOnLine* 2019 ;Volume 52.(1) p. 898-903. NTNU
17. **Rohde, Daniel; Knudsen, Brage Rugstad; Andresen, Trond; Nord, Natasa. Dynamic optimization of control setpoints for an integrated heating and cooling system with thermal energy storages.** *Energy* 2019 ;Volume 193. ENERGISINT NTNU
18. **Schlemminger, Christian; Monsås, Atle; Lovås, Kim Andre; Jenssen, Sigmund; Dallai, Mauro. Hydrocarbon Heat Pumps with Combined Process Cooling and Heating at 115°C.** *Book of presentations of the 2nd Symposium on High-Temperature Heat Pumps* 2019 p. 134-145. ENERGISINT
19. **Straus, Julian; Skogestad, Sigurd. A new termination criterion for sampling for surrogate model generation using partial least squares regression.** *Computers and Chemical Engineering* 2019 ;Volume 121. p. 75-85. NTNU
20. **Vikse, Matias; Watson, Harry AJ; Barton, Paul I; Gundersen, Truls. Nonsmooth Formulation for Handling Unclassified Process Streams in the Optimization of Work and Heat Exchange Networks.** *Industrial & Engineering Chemistry Research* 2019 ;Volume 58.(22) p. 9526-9539. NTNU
21. **Yu, Haoshui; Kim, Donghoi; Gundersen, Truls. A study of working fluids for Organic Rankine Cycles (ORCs) operating across and below ambient temperature to utilize Liquefied Natural Gas (LNG) cold energy.** *Energy* 2019 ;Volume 167. p. 730-739. NTNU
22. **Yu, Haoshui; Kim, Donghoi; Hu, Xiangping; Gundersen, Truls. Organic Rankine Cycle with Pure and Mixed Working Fluids for LNG Cold Energy Recovery.** *Chemical Engineering Transactions* 2019 ;Volume 76. p. 607-612. NTNU
23. **Yu, Haoshui; Vikse, Matias; Anantharaman, Rahul; Gundersen, Truls. Model reformulations for Work and Heat Exchange Network (WHEN) synthesis problems.** *Computers and Chemical Engineering* 2019 ;Volume 125. p. 89-97. ENERGISINT NTNU
24. **Zotica, Cristina Florina; Nord, Lars O.; Kovács, Jenő; Skogestad, Sigurd. Optimal Operation and Control of Heat-to-Power Cycles: a New Perspective using a Systematic Plantwide Control Approach.** *Computer-aided chemical engineering* 2019 ;Volume 46. p. 1429-1434. NTNU
25. **Zühlsdorf, Benjamin; Bühler, F.; Bantle, Michael; Elmegaard, Brian. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C.** *Energy Conversion and Management* 2019 ;Volume 2. p. 1-20. ENERGISINT

Presentations

From: 2019 *To:* 2019 *Main category:* Conference lecture and academic presentation *All publishing channels*

1. **Agromayor, Roberto; Pilarczyk, Marcin; Pardiñas, Ángel Á.; Nord, Lars O. Design of an Experimental Expander Setup Using Natural Working Fluids. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU**

2. Ahrens, Marcel Ulrich.
Compressors for ammonia-water hybrid absorption-compression heat pumps. Annual Consortium Meeting - HighEFF; 2019-05-08 - 2019-05-09. NTNU
3. Ahrens, Marcel Ulrich; Hafner, Armin; Eikevik, Trygve Magne.
Development of a combined absorption-compression heat pump test facility at high temperature operation. Cross-sector Workshop - HighEFF; 2019-10-23 - 2019-10-24. NTNU
4. Ahrens, Marcel Ulrich; Hafner, Armin; Eikevik, Trygve Magne.
Development of a combined absorptioncompression heat pump test facility at high temperature operation. HighEFF Cross-sector workshop; 2019-10-23 - 2019-10-24. NTNU
5. Andreasen, Glenn; Stoustrup, Jakob; Izadi-Zamanabadi, Roozbeh; Pardiñas, Angel A.; Hafner, Armin.
Data-Driven Modeling of a CO_2 Refrigeration System. American Control Conference, Philadelphia, USA, July 2019; 2019-07-01 - 2019-07-03. NTNU
6. Andresen, Trond.
RA3 - Cycles. HighEFF Cross-sector workshop; 2019-10-23 - 2019-10-24. ENERGISINT
7. Andresen, Trond; Skjervold, Vidar T.
Energy Recovery in FME HighEFF - past and future activities. Reference Group Energy Recovery meeting; 2019-05-09 - 2019-05-09. ENERGISINT
8. Andresen, Trond; Skjervold, Vidar T.
Practical vs. Academic approach to Energy Recovery - an introduction. Practical vs. Academic approach to Energy Recovery; 2019-10-22. ENERGISINT
9. Berglihn, Olaf Trygve; Kauko, Hanne; Andresen, Trond.
Information about reference group meetings. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09 SINTEF ENERGISINT
10. Claussen, Ingrid Camilla.
Status from RA5. HighEFF Cross-sector workshop; 2019-10-23 - 2019-10-24. ENERGISINT
11. Ervik, Åsmund; Saai, Afaf; Meyer, Ole; Nekså, Petter.
Dynamic modelling of compressor ring plate valve behaviour with CFD and FEM. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. ENERGISINT NTNU SINTEF
12. Gundersen, Truls.
Education in HighEFF Status. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
13. Hafner, Armin.
Why natural working fluids are a smart choice for energy efficient heat pumps and refrigeration units. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
14. Hagen, Brede.
Optimization of Rankine cycles operating under time-variable conditions. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
15. Hagen, Brede.
Optimization of Rankine cycles operating under time-varying conditions. HighEFF Annual Consortium Meeting; 2019-05-08 - 2019-05-09. NTNU
16. Jäschke, Johannes; Thombre, Mandar.
A Data-driven approach for robust operation of energy storage systems. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
17. Kauko, Hanne; Drexler-Schmid, Gerwin.
Thermal storage for improved utilization of renewable energy in steam production. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. ENERGISINT
18. Larssen, Trine Asklund; Tangstad, Merete; Kero, Ida.
Experimental study of the initial stages of manganese ferroalloy prereduction. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU SINTEF
19. Lauvås, Thomas Andre.
Duelling or dancing? How firms steer the research agenda in big science centres. The Future of Conducting and Publishing Research in Entrepreneurship, Innovation Management and Strategy; 2019-05-22 - 2019-05-24. NORD
20. Lindheim, Catharina; Gjøsund, Gudveig; Liste, Lucia; Gauteplass, Asle.
Organizing shared resources and alternative business models. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. SAMFORSK
21. Liu, Zhongxuan; Gundersen, Truls.
Distributed Energy Hubs - Liquid Air Energy Storage (LAES). HighEFF consortium; 2019-05-08 - 2019-05-09. NTNU
22. Nikolaisen, Monika.
Highlights and plans - RA6 Case studies. HighEFF Cross-sector workshop; 2019-10-23 - 2019-10-24. ENERGISINT
23. Nikolaisen, Monika; Skjervold, Vidar T.; Andresen, Trond.
Academic analysis of improvement potential at Elkem Thamshavn. Practical vs. Academic approach to Energy Recovery; 2019-10-22. ENERGISINT
24. Panjwani, Balram; Pettersen, Torbjørn.
Controlling flue gas temperatures in silicon furnaces. Practical vs. Academic approach to Energy Recovery; 2019-10-22. SINTEF
25. Pardiñas, Ángel Á.; Pilarczyk, Marcin; Agromayor, Roberto; Nord, Lars O.
Design of an Experimental ORC Expander Setup Using Natural Working Fluids. 5th International Seminar on ORC Power Systems (ORC 2019); 2019-09-09 - 2019-11-09. NTNU
26. Pardiñas, Ángel Á.; Pilarczyk, Marcin; Agromayor, Roberto; Nord, Lars O.
Design of an Experimental ORC Expander Setup Using Natural Working Fluids. Annual Consortium Meeting; 2019-05-08 - 2019-05-09. NTNU
27. Pilarczyk, Marcin.
Thermo-mechanical fatigue of componentns exposed to pressure and temperature variations. Practical vs. Academic approach to Energy Recovery; 2019-10-22. NTNU
28. Pilarczyk, Marcin; Nord, Lars O.
A tensometric method for studying of stress at elevated temperatures. Annual Consortium Meeting; 2019-05-08 - 2019-05-09. NTNU
29. Pilarczyk, Marcin; Nord, Lars O.
Monitoring the working conditions of components in Heat Recovery Steam Generators (HRSG). PhD/PD Seminar (HIGH-EFF); 2019-02-25 - 2019-02-25. NTNU
30. Reyes-Lúa, Adriana; Zotica, Cristina Florina; Skogestad, Sigurd.
Split range control. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
31. Ringstad, Knut Emil; Allouche, Yosr; Hafner, Armin.
Investigation of CFD models for ammonia ejector design. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
32. Rohde, Daniel.
Mitigation of furnace Dynamics in Energy Recovery. Practical vs. Academic approach to Energy Recovery; 2019-10-22 ENERGISINT.
33. Rydså, Line.
Poster session FME HighEFF Annual Consortium Meeting 2019. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. ENERGISINT
34. Røkke, Nils Anders.
The Role of Energy Efficiency – Global View. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09 ENERGISINT
35. Røkke, Petter Egil.
Energy Efficiency - Research Center. HighEFF Cross-sector workshop; 2019-10-23 - 2019-10-24. ENERGISINT
36. Røkke, Petter Egil.
Energy Efficiency - Research Center. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. ENERGISINT
37. Røkke, Petter Egil.
Information from the Research Council of Norway ENERGIX programme. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. ENERGISINT
38. Schlemminger, Christian; Bamigbetan, Opeyemi Olayinka; Svendsen, Eirik; Bantle, Michael; Dallai, Mauro; Pisano, Giacomo.
Hydrocarbon Compressor Technology for High temperature heat Pumps. Norsk Kjøleteknsik Møte 2019; 2019-04-04 - 2019-04-05. ENERGISINT NTNU
39. Schlemminger, Christian; Monsås, Atle; Lovås, Kim Andre; Jenssen, Sigmund; Dallai, Mauro.
Hydrocarbon heat pumps with combined process cooling and heating at 115°C. 2nd Conference on High Temperature Heat Pumps; 2019-09-09 - 2019-09-09. ENERGISINT
40. Selvnes, Håkon.
CFD modeling of ice formation and melting in horizontally cooled and heated plates. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
41. Selvnes, Håkon; Allouche, Yosr; Sevault, Alexis; Hafner, Armin.
CFD modeling of ice formation and melting in horizontally cooled and heated plates. Eurotherm Seminar 112 - Advances in Thermal Energy Storage; 2019-05-15 - 2019-05-17 ENERGISINT NTNU
42. Selvnes, Håkon; Allouche, Yosr; Sevault, Alexis; Hafner, Armin.
CFD modeling of ice formation and melting in horizontally cooled and heated plates. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. ENERGISINT NTNU
43. Sheng, Juejing.
Advanced exergy analysis of the oil and gas processing on a North Sea oil platform. HighEFF Annual Consortium 2019; 2019-05-08 - 2019-05-09. NTNU
44. Sheng, Juejing; Voldsund, Mari; Ertesvåg, Ivar Ståle.
Advanced exergy analysis of the oil and gas processing plant

on a North Sea platform. ECOS 2019 - 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems; 2019-06-23 - 2019-06-28. ENERGISINT NTNU

45. **Skjervold, Vidar T.; Andresen, Trond; Skaugen, Geir; Nekså, Petter.**
Novel heat recovery concept development. Practical vs. Academic approach to Energy Recovery; 2019-10-22 ENERGISINT
46. **Skybakmoen, Egil; Skogestad, Sigurd; Berglihn, Olaf Trygve; Senanu, Samuel.**
RA1 Methodologies. HighEFF Crosse sectorial workshop; 2019-10-23 - 2019-10-24. NTNU SINTEF
47. **Steenstrup-Duch, Anne.**
Why you matter more than ever in the era of fake news. HighEFF Cross-sector workshop; 2019-10-23 - 2019-10-24. ENERGISINT
48. **Tranell, Gabriella.**
The Norwegian «Process21», Vision and Strategy for the Norwegian Process Industry. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
49. **Wærnes, Aud Nina.**
SFI Metal Production Interaction with the industry partners and FME. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. SINTEF
50. **Yu, Haoshui.**
ORCs for LNG cold energy recovery Working fluid screening and process optimization. HighEFF Annual Consortium Meeting 2019; 2019-05-08 - 2019-05-09. NTNU
51. **Zotica, Cristina Florina; Skogestad, Sigurd.**
A New Perspective on Optimal Operation and Control of Heat-to-Power Cycles. Young Professionals Conference on Process Engineering; 2019-03-18 - 2019-03-20. NTNU
52. **Zotica, Cristina Florina; Skogestad, Sigurd.**
Transformed Manipulated Variables for Decoupling and Perfect Disturbance Rejection. Nordic Process Control Workshop; 2019-08-21 - 2019-08-23. NTNU

Peer-reviewed papers

From: 2019 *To:* 2019 *sub-category:* Academic chapter/article/Conference paper *All publishing channels*

1. **Ahrens, Marcel Ulrich; Hafner, Armin; Eikevik, Trygve Magne.**
Compressors for ammonia-water hybrid absorption-compression heat pumps. I: *8th Conference on Ammonia and CO2 Refrigeration Technologies, Proceedings*. International Institute of Refrigeration 2019 ISBN 978-2-36215-034-0. p. 366-373. NTNU
2. **Banasiak, Krzysztof; Pardiñas, Ángel Á.; Kriezi, Ekaterini E.**
Modelling and development of high-pressure-lift ejector for low temperature evaporators in R744 refrigeration systems for supermarkets. I: *Proceedings of the 25th IIR International Congress of Refrigeration. Montréal, Canada, August 24-30, 2019*. International Institute of Refrigeration 2019 ISBN 978-2-36215-035-7. p. 3327-3334. ENERGISINT NTNU
3. **Barton, Paul I; Gundersen, Truls; Nielsen, Caroline J.; Vikse, Matias.**
Nonsmooth Analysis In Process Modeling, Design And Optimization. I: *Proceedings of the 9th International Conference on Foundations of Computer-Aided Process Design*. Elsevier 2019 ISBN 978-0-12-818597-1. p. 7-16. NTNU
4. **Durakovic, Goran; Nikolaisen, Monika.**
Performance Comparison of Different Rankine Cycle Technologies Applied to Low and Medium Temperature Industrial Surplus Heat Scenarios. I: *Proceedings of the 5th International Seminar on ORC Power Systems*. Athens, Greece: The National Technical University of Athens (NTUA) 2019 ISBN 978-90-9032038-0. ENERGISINT
5. **Nekså, Petter; Bantle, Michael; Schlemminger, Christian; Bamigbetan, Opeyemi Olayinka.**
High temperature industrial heat pumps utilising natural working fluids. I: *Proceedings of the 25th IIR International Congress of Refrigeration. Montréal, Canada, August 24-30, 2019*. International Institute of Refrigeration 2019 ISBN 978-2-36215-035-7. p. 4729-4736. ENERGISINT NTNU
6. **Pardiñas, Ángel Á.; Pilarczyk, Marcin; Agromayor, Roberto; Nord, Lars O.**
Design of an Experimental ORC Expander Setup Using Natural Working Fluids. I: *Proceedings of the 5th International Seminar on ORC Power Systems*. Athens, Greece: The National Technical University of Athens (NTUA) 2019 ISBN 978-90-9032038-0. p. - NTNU
7. **Rammohan Subramanian, Avinash Shankar; Kim, Donghoi; Adams, Thomas; Gundersen, Truls.**
Modeling and Simulation of a Waste Tire to Liquefied Synthetic Natural Gas (SNG) Plant. I: Proceedings of the 9th International Conference on Foundations of Computer-Aided Process Design. Elsevier 2019 ISBN 978-0-12-818597-1. p. 397-402. NTNU
8. **Ringstad, Knut Emil; Allouche, Yosr; Gullo, Paride; Banasiak, Krzysztof; Hafner, Armin.**
CO2 ejector modelling using CFD: current status. I: *Proceedings of the 25th IIR International Congress of Refrigeration. Montréal, Canada, August 24-30, 2019*. International Institute of Refrigeration 2019 ISBN 978-2-36215-035-7. p. 2813-2822. ENERGISINT NTNU
9. **Ringstad, Knut Emil; Hafner, Armin; Allouche, Yosr.**
Investigation of CFD models for ammonia ejector design. I: *8th Conference on Ammonia and CO2 Refrigeration Technologies, Proceedings*. International Institute of Refrigeration 2019 ISBN 978-2-36215-034-0. p. 94-100. NTNU
10. **Schlemminger, Christian; Kopp, Christian Andre; Banasiak, Krzysztof; Drexler-Schmid, Gerwin; Lauermann, Michael; Windholz, Bernd; Zauner, Christoph; Baumhakel, Alexander.**
Hochtemperatur Wärmepumpe mit Ejektor. I: *Deutsche Kälte- und Klimatagung 2019, Ulm*. DKV - Deutscher Kälte- und Klimatechnischer Verein 2019 ISBN 978-3-932715-52-5. ENERGISINT
11. **Schlemminger, Christian; Svendsen, Eirik Starheim; Foslie, Sverre Stefanussen; Bantle, Michael; Bamigbetan, Opeyemi Olayinka; Nekså, Petter.**
Performance of high temperature heat pump for simultaneous and efficient production of ice water and process heat. I: *Proceedings of the 25th IIR International Congress of Refrigeration. Montréal, Canada, August 24-30, 2019*. International Institute of Refrigeration 2019 ISBN 978-2-36215-035-7. p. 4632-4639 ENERGISINT NTNU
12. **Selvnes, Håkon; Allouche, Yosr; Sevault, Alexis; Hafner, Armin.**
A CFD analysis for the performance assessment of a novel design of plates-in-tank latent storage unit for freezing applications. I: *8th Conference on Ammonia and CO2 Refrigeration Technologies, Proceedings*. International Institute of Refrigeration 2019 ISBN 978-2-36215-034-0. p. 303-310. ENERGISINT NTNU
13. **Selvnes, Håkon; Allouche, Yosr; Sevault, Alexis; Hafner, Armin.**
CFD modeling of ice formation and melting in horizontally cooled and heated plates. I: *Eurotherm Seminar #112 - Advances in Thermal Energy Storage*. Lleida, Spain: Edicions de la Universitat de Lleida 2019 ISBN 978-84-9144-155-7. p. 837-847 ENERGISINT NTNU
14. **Selvnes, Håkon; Hafner, Armin; Kauko, Hanne.**
Design of a cold thermal energy storage unit for industrial applications using CO2 as refrigerant. I: *Proceedings of the 25th IIR International Congress of Refrigeration. Montréal, Canada, August 24-30, 2019*. International Institute of Refrigeration 2019 ISBN 978-2-36215-035-7. p. 1879-1886. ENERGISINT NTNU
15. **Smitt, Silje Marie; Hafner, Armin; Hoksrød, Erik.**
Presentation of the first combined CO2 heat pump, air conditioning and hot tap water system for a hotel in Scandinavia. I: *8th Conference on Ammonia and CO2 Refrigeration Technologies, Proceedings*. International Institute of Refrigeration 2019 ISBN 978-2-36215-034-0. p. 220-226. NTNU
16. **Yu, Haoshui; Chen, Zhichao; He, Chang; Gundersen, Truls.**
Modeling and Optimization of Simultaneous Waste Heat Utilization and Wastewater Treatment Processes. I: *Proceedings of the 9th International Conference on Foundations of Computer-Aided Process Design*. Elsevier 2019 ISBN 978-0-12-818597-1. p. 29-34. NTNU

Report/thesis

From: 2019 *To:* 2019 *Main category:* Report/thesis
All publishing channels

1. **Andresen, Trond; Senanu, Samuel; Solheim, Asbjørn.**
System impact of recycling aluminium electrolysis off-gas. : SINTEF Energi AS 2019 6 p. SINTEF ENERGISINT NTNU
2. **Bantle, Michael.**
Status of the dairy case implementation in Bergen. TRONDHEIM: SINTEF Energi AS 2019 8 p. ENERGISINT
3. **Einarsrud, Kristian Etienne.**
Case study 1-pager for Martin Grimstad's MSc. TRONDHEIM: SINTEF Energi AS 2019 1 p. NTNU
4. **Gabrielii, Cecilia H.**
Case study 1-pager for steam production at Glencore Nikkelverk. TRONDHEIM: SINTEF Energi AS 2019 1 p. ENERGISINT
5. **Gabrielii, Cecilia H.**
Heat pump concepts for steam production at Glencore Nikkelverk. TRONDHEIM: SINTEF Energi AS 2019 22 p. ENERGISINT

6. **Grimstad, Martin.**
   Using surplus heat to pre-heat carbon anodes for aluminium electrolysis. TRONDHEIM: SINTEF Energi AS 2019 97 p. SINTEF NTNU
7. **Jokiel, Michael.**
   Seasonal Storage of Industrial Waste Heat. : FME HighEFF 2019 34 p. ENERGISINT
8. **Kauko, Hanne; Sevault, Alexis; Beck, Anton; Drexler-Schmid, Gerwin.**
   Thermal storage for improved utilization of renewable energy in steam production. : SINTEF Energy Research 2019 28 p. ENERGISINT
9. **Kero, Ida; Einarsrud, Kristian Etienne; Kauko, Hanne.**
   Case plan 2020: Sustainable industrial clusters. TRONDHEIM: SINTEF Energi AS 2019 3 p. SINTEF ENERGISINT NTNU
10. **Kvalsvik, Karoline.**
    Food case Orkla: How to enhance energy efficiency at Nidar chocolate production. Trondheim: SINTEF Energi AS 2019 38 p. NTNU
11. **Lindqvist, Karl Erik Artur; Skaugen, Geir.**
    A CFD model for a tube-in-fin heat exchanger using OpenFoam. : SINTEF Energy Research 2019 12 p. ENERGISINT
12. **Nikolaisen, Monika.**
    Case study 1-pager for industrial heat pump. TRONDHEIM: SINTEF Energi AS 2019 1 p. ENERGISINT
13. **Nikolaisen, Monika.**
    Performance evaluation of an industrial heat pump. TRONDHEIM: SINTEF Energi AS 2019 12 p. ENERGISINT
14. **Pettersen, Torbjørn; Dæhlin, Emil; Eidem, Per Anders; Berglihn, Olaf Trygve.**
    Energy utilisation at Mo Industripark. : SINTEF Industri 2019 30 p. SINTEF
15. **Skaugen, Geir.**
    Documentation of HX models used in HighEFF case studies-Variable geometry heat exchanger model. : SINTEF Energy Research 2019 32 p. ENERGISINT
16. **Skaugen, Geir.**
    Initial experience with WEB-interfaced modelling tools - report from summer intern work. : SINTEF Energy Research 2019 9 p. ENERGISINT
17. **Solheim, Asbjørn.**
    Recycling of the Flue Gas in Aluminium Electrolysis Cells. Trondheim: SINTEF Industry 2019. SINTEF
18. **Solheim, Asbjørn; Gudbrandsen, Henrik.**
    Aluminium case study. TRONDHEIM: SINTEF Energi AS 2019 8 p. SINTEF
19. **Solheim, Asbjørn; Gudbrandsen, Henrik.**
    Aluminium case study 1-pager. TRONDHEIM: SINTEF Energi AS 2019 1 p. SINTEF
20. **Solheim, Asbjørn; Gudbrandsen, Henrik.**
    Pre-heating of alumina. Weight of rafts at different temperatures. Trondheim: SINTEF Industry 2019 8 p. SINTEF
21. **Straus, Julian.**
    Case study 1-pager for utilization of waste heat. TRONDHEIM: SINTEF Energi AS 2019 1 p. ENERGISINT
22. **Straus, Julian.**
    Cross-industry exploration for external utilization of waste heat. Trondheim: SINTEF Energi AS 2019 27 p. ENERGISINT
23. **Straus, Julian; Mazzetti, Marit Jagtoyen.**
    Cross-industry exploration for external utilization of waste heat. Trondheim: SINTEF Energi AS 2019 27 p. ENERGISINT
24. **Straus, Julian; Reyes, Adriana; Durakovic, Goran.**
    Cross-industry exploration for external utilization of waste heat - Tomato greenhouse, fish production, and insect production. TRONDHEIM: SINTEF Energi AS 2019 44 p. ENERGISINT

Media contributions

From: 2019 *To:* 2019 *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*

1. **Bantle, Michael.**
   Lars Hansens varmepumpe skal være «minst» 35 prosent mer effektiv enn nærmeste konkurrent. Har fått avtale med Panasonic. Polar Energi [Internet] 2019-12-17. ENERGISINT
2. **Bantle, Michael.**
   Sintefs nye varmepumpe kan lage 160 grader varm damp. TU [Business/trade/industry journal] 2019-01-22. ENERGISINT
3. **Kauko, Hanne.**
   Dette kan være løsningen på verdens enorme vind- og solproblem. Nettavisen.no [Internet] 2019-11-26 ENERGISINT
4. **Nekså, Petter.**
   VM-stadionet forurenser like mye hver dag som å kjøre bil 20 ganger rundt ekvator. NRK [Internet] 2019-10-04. ENERGISINT
5. **Røkke, Petter Egil.**
   Fra blomstereng i hagen til løsninger for en bedre verden. NOBIO [Internet] 2019-08-16. ENERGISINT

Media contributions not in Cristin

These media contributions involve FME HighEFF, but does not mention any HighEFF researchers or staff.

1. Ny varmepumpeløsning kuttet energiforbruket i meieriet med 40 prosent, Teknisk Ukeblad, 2019-05-21, https://www.tu.no/artikler/ny-varmepumpelosning-kuttet-energiforbruket-i-meieriet-med-40-prosent/465500?key=liywZuvH
2. **Kyllingfabrikk med ai og spillvarme, Teknisk Ukeblad, 2019-10-22**
3. Bidrar i verdens største forskningssenter innen energieffektivisering, forskning.no, 2019-11-07, https://forskning.no/nord-universitet/bidrar-i-verdens-storste-forskningssenter-innen-energieffektivisering/1587477,

Blogs and information material

From: 2019 *To:* 2019 *Main category:* Information material(s) *All publishing channels*

1. **Aarhaug, Thor Anders.**
   Online monitoring of perfluorcarbon (PFC) emissions from aluminium industry. SINTEF
2. **Andresen, Trond.**
   Additive manufacturing of heat exchangers (How would it work?). ENERGISINT
3. **Bantle, Michael.**
   Prestisjetung pris til HighEFF industripartner: Reduserte klimagassutslipp og energibehov med 40%. ENERGISINT
4. **Bantle, Michael.**
   Successful 2nd Conference on High Temperature Heat Pumps (HTHP). ENERGISINT
5. **Claussen, Ingrid Camilla.**
   HighEFF at workshop: The Future of Conducting and Publishing Research in Entrepreneurship, Innovation Management and Strategy.
   ENERGISINT
6. **Kauko, Hanne.**
   Industrial energy consumption is massive, but thermal storage can boost energy efficiency. ENERGISINT
7. **Kauko, Hanne.**
   Termisk lagring for økt energieffektivitet. ENERGISINT
8. **Nikolaisen, Monika.**
   Utnytte industriell overskuddsvarme med termisk lager. ENERGISINT
9. **Røkke, Petter Egil.**
   HighEFF Annual report. ENERGISINT
10. **Skreiberg, Øyvind.**
    Kun fornybar oppvarming og kjøling i Europa innen 2050 er mulig. ENERGISINT
11. **Solheim, Asbjørn.**
    Er aluminiumelektrolyse med inerte anoder en blindvei? SINTEF
12. **Solheim, Asbjørn.**
    Is aluminium electrolysis using inert anodes a blind alley? SINTEF
13. **Øye, Bjarte Arne.**
    Kan kloridprosessen erstatte Hall-Héroult for aluminiumproduksjon? SINTEF
14. **Øye, Bjarte Arne.**
    Could the chloride process replace the Hall-Héroult process in aluminium production? SINTEF

Multimedia products

From: 2019 *To:* 2019 *sub-category:* Multimedia product *All publishing channels*

1. **Andresen, Trond; Zotica, Cristina; Skjervold, Vidar T.**
   Energy efficiency in industry - value from research. SINTEF Energi 2019. ENERGISINT NTNU
2. **Røkke, Nils Anders; Rydså, Line; Hafner, Armin (SINTEF).**
   HighEFF Consortium meeting 2019. SINTEF Energi 2019 ENERGISINT
3. **Røkke, Petter Egil.**
   Cross sector workshop 2019. SINTEF Energi 2019. ENERGISINT
4. **Røkke, Petter Egil.**
   Effektstudien higheff. SINTEF Energi 2019. ENERGISINT
5. **Røkke, Petter Egil.**
   Energy Efficiency in industry - value from research. SINTEF Energi - HighEFF 2019. ENERGISINT
6. **Røkke, Petter Egil.**
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Multimedia products not in Cristin

These multimedia products involve FME HighEFF, but does not mention any HighEFF researchers or staff.

1. **Gassifiseringsreaktor SINTEF ENergy Lab,** https://www.facebook.com/755592304507539/videos/301036120830893/
2. **HighEFF annual Consortium Meeting throwback. More Videos come soon!** https://twitter.com/HighEFF_FME/status/1133738404280246272

Other

From: 2019 *To:* 2019 *Main category:* Artistic result *sub-category:* Book review *sub-category:* Reader opinion piece *sub-category:* Letter to the editor *sub-category:* Popular scientific chapter/article *sub-category:* Abstract *sub-category:* Errata *sub-category:* Foreword *sub-category:* Introduction *sub-category:* Other *sub-category:* Chapter Translation *sub-category:* Book Translation *sub-category:* Digital learning tools *sub-category:* Model (architecture) *sub-category:* Music – recorded product *sub-category:* Software *sub-category:* Database *sub-category:* Other product *All publishing channels*

1. **Agromayor, Roberto; Nord, Lars O.**
   AnnularDiffuser1D: one-dimensional annular diffuser model implemented in MATLAB. NTNU 2019. NTNU
2. **Agromayor, Roberto; Nord, Lars O.**
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3. **Skaugen, Geir.**
   Variable geometry heat exchanger model. SINTEF Energy Research 2019. ENERGISINT

HighEFF – Centre for an Energy Efficient and Competitive Industry for the Future

HighEEF is a Centre for Environment-friendly Energy Research (FME). The objective of the FME-scheme is to establish time- limited research centres which conduct concentrated, focused and long-term research of high international calibre.

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