Sustainable Energy Systems 2050

NORDIC ENERGY RESEARCH PROGRAMME

Final Report

SUSTAINABLE SHIFT

Nordic energy systems towards 2050

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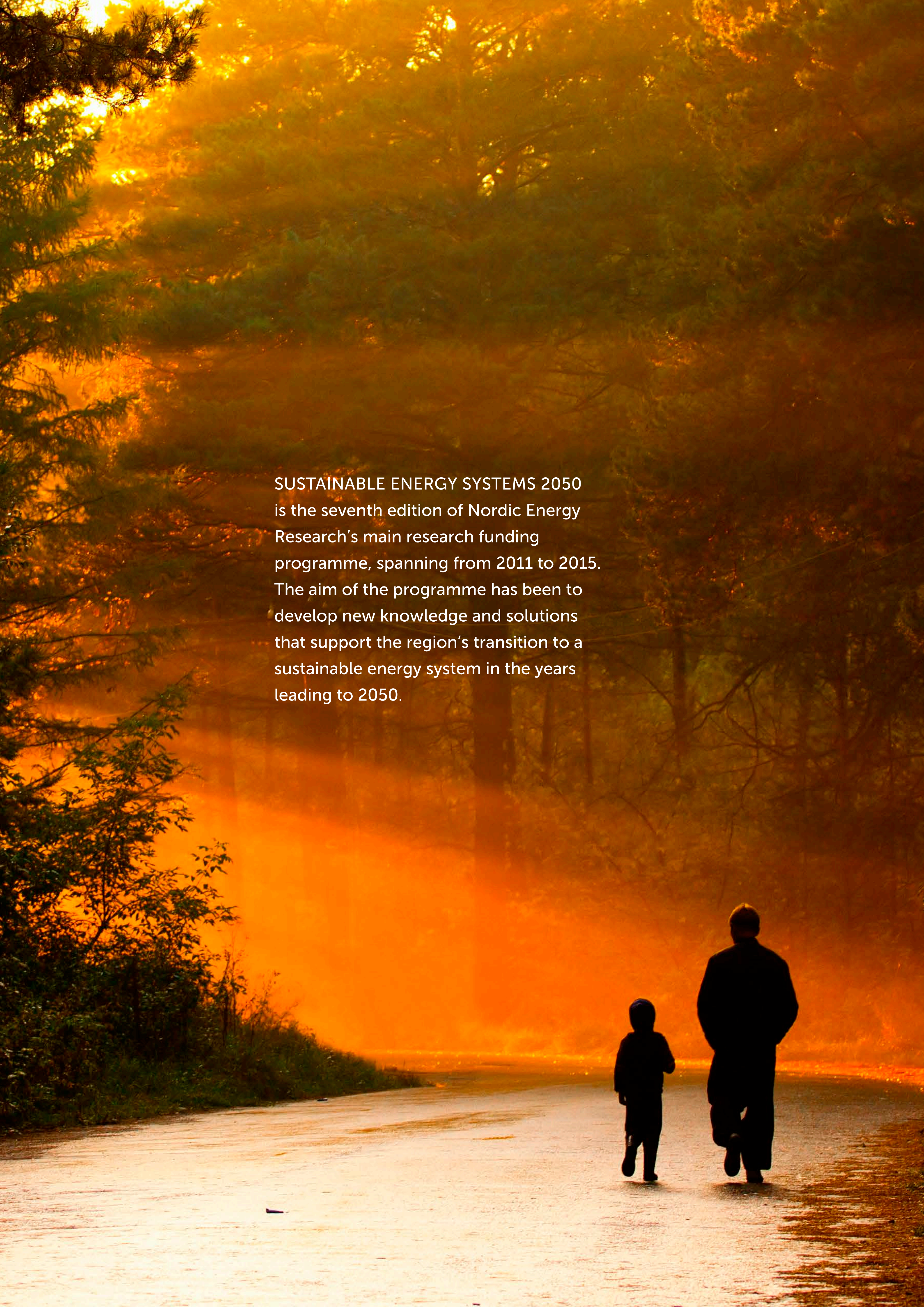
Nordic Energy Research
Nordic Council of Ministers



SUSTAINABLE ENERGY SYSTEMS 2050 is the seventh edition of Nordic Energy Research's main research funding programme, spanning from 2011 to 2015. The aim of the programme has been to develop new knowledge and solutions that support the region's transition to a sustainable energy system in the years leading to 2050.

Contents

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“While decarbonizing electricity is still a central challenge for much of the world, the Nordic case offers insight into how a clean electricity system can be achieved and how it can facilitate decarbonization of other sectors.”

THIS PUBLICATION marks the finalization and outcome of the research programme Sustainable Energy Systems 2050. An overarching goal was to develop solutions to reach the ambitious targets for reduction of greenhouse gas emissions in the Nordic countries. The main challenges in this respect lie within the three domains of electricity and heating, transport and industry. Cross-cutting targets have been to strengthen already ambitious efforts to increase energy efficiency and integrate large amounts of variable renewable energy into our supply and demand patterns.

The electricity system collaboration between the Nordic countries has been globally recognized as very successful, and the region has become the benchmark for well-functioning liberalized energy markets. The region has positioned itself as a leader in the development and deployment of competitive and sustainable energy solutions in well-functioning markets.

While decarbonizing electricity is still a central challenge for much of the world, the Nordic case offers insight into how a clean electricity system can be achieved and how it can facilitate decarbonization of other sectors. The Nordic collaboration has ensured that CO_2 emissions per unit of electricity generated is already at the level the rest of the world must reach by 2045 to limit global warming to less than 2°C above pre-industrial levels, according to the International Energy Agency (IEA).

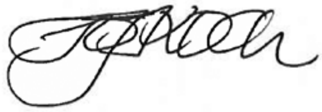
However, electricity and heat constitute only 30 per cent of Nordic energy related CO_2 emissions. The remaining 70 per cent come mainly from transport and industry. These sectors still have a long way to go to reach acceptable emission levels.

The 10 projects in the SES 2050 programme have investigated central challenges and provided key contributions towards reaching the region's ambitious climate goals. Great potential has been highlighted in several areas, for instance further electrification of our energy supply, biomass production and solar energy. The projects also offer policy advice.

The SES 2050 findings deliver important input on how to achieve the carbon-neutral scenario for 2050 as described in the publication Nordic Energy Technology Perspectives 2016 (NETP 2016) from IEA and Nordic Energy Research (NER). This publication was launched in the five Nordic capitals in May and June 2016. It offers neutral, unbiased analysis on how the Nordic countries can achieve carbon neutrality by 2050 in the most secure and cost-effective way.

The work done the SES 2050 programme and in NETP 2016 will be carried on through NER-funded networks for collaboration and information exchange between researchers and decision makers in industry and policy-making sectors. It will also be utilized in the Nordic cooperation on energy within the framework of the Nordic Council of Ministers. The findings will serve as input to considerations on long-term policy for cooperation on research, development and dissemination of clean technologies, and how to achieve ambitious energy and climate targets within a secure energy system that enables stable economic growth while minimizing environmental impacts.

Hans Jørgen Koch



Pioneers of the global energy future

ENERGY IS A KEY ISSUE for our global future. The demand for it is rising rapidly, in tandem with increasing concerns about global warming and greenhouse gas emissions. People, nations and markets still rely heavily on fossil fuels. Sustainable development is not conceivable without an extensive reform of energy systems worldwide, and research plays a significant role in bringing the reform forward.

Limiting global warming to less than 2°C above pre-industrial levels is the central target of the 2015 Paris Climate Agreement, adopted by 195 countries within the United Nations Framework Convention on Climate Change (UNFCCC). Several Nordic countries go beyond this, and some are aiming for a near carbon-neutral energy system in 2050.

SYSTEM-ORIENTED PERSPECTIVES

In most aspects, the Nordic power grid and electricity market is operated as an integrated system. Combined with substantial grid-balancing resources, this has made the region well equipped to handle renewable energy. Norwegian and Swedish hydropower balances the variable wind power from Denmark. Wind generated 42 per cent of Danish electricity in 2015. This is the highest share of wind power achieved by any one country, according to the recently published Nordic Energy Technology Perspectives (NETP 2016) by the International Energy Agency and Nordic Energy Research.

The Nordic region is blazing a trail towards future sustainable energy systems, enabled by cutting-edge research, as well as connections across borders.

The Nordic experience of transitioning energy systems and markets can provide valuable insights to the rest of the world. The 10 projects funded through the SES 2050 programme are particularly related to system perspectives. More specifically, Nordic researchers have explored how to integrate the developments in three important areas: renewables, markets and grids, and low-carbon transport.

EXPANDING NORDIC COOPERATION

The SES 2050 programme envisioned research that could both further the successful Nordic collaboration on the electricity market and bring the region forward in developing renewable energy and transport solutions for all parts of society.

The transition to sustainable energy systems will have a major effect on our communities, on how we use energy in our daily life, and on the general structure of industries and services. An important goal is securing and increasing Nordic competitiveness in this process.

There is a clear technological and economic pathway for the Nordic region to follow to reach a near carbon-neutral energy system in 2050, according to NETP 2016. Together, Nordic countries have the opportunity to send a strong signal to the global community that the ambitious aims of the Paris Climate Agreement are achievable.

Combined, the 10 research projects in the SES 2050 programme show that a goal of a near carbon-neutral energy system in the Nordic region is well within reach. In fact, it can be achieved in different ways, so decision makers should be aware of multiple paths to a green future.

LONG-TERM SUSTAINABILITY

Decision makers are encouraged to consider the possibilities for a transition to renewable energy sources and to ensure incentives for investors and consumers. At the same time, decision makers need to keep long-term sustainability in mind. For instance, certain renewable energy solutions might introduce complications for natural environments and communities. Increasing the share of biofuels can affect soil, land use and biodiversity. Centralizing and speeding up decision-making processes challenges local democracy. Environmental considerations for future energy solutions should be based on perspectives that encompass more than tackling the current challenge of carbon emissions.

(Photo: Shutterstock)

Nordic added value

The future is sustainable. Developing Nordic technology for renewable energy systems makes the region more competitive and ensures dissemination of Nordic solutions.

THE SES 2050 PROGRAMME was funded by the Nordic countries and administered by Nordic Energy Research (NER). NER is an institution that operates under the auspices of the Nordic Council of Ministers, the intergovernmental body that is operated by Denmark, Finland, Iceland, Norway and Sweden, and that also includes the autonomous areas of the Faeroe Islands, Greenland and the Åland Islands.

The overarching programme question was how to greatly accelerate the rate of technological development needed to make the complex transition to a sustainable energy system. The Nordic countries have different but complementary energy systems, competences, resources and innovation capacities within the field. The success of the common electricity grid clearly demonstrates that cooperation facilitates synergies between countries.

STRONGER TOGETHER

Individually, the Nordic countries have limited influence. Together, they comprise the twelfth largest economic region in the world. The region is highly competitive in the global perspective. The advancement of sustainable energy systems would benefit from increased efforts to align the countries' positions, despite differences in technological emphasis and choices.

For SES 2050 projects, the ability to provide Nordic added value was a requirement from the start. This means providing more than the sum of what researchers in the individual countries would have been able to deliver alone. The focus has been on solutions that are relevant for the whole region and that tap into the advantages of cooperation.

DIFFERENTIATED BUT COORDINATED

Project findings from the SES 2050 programme emphasize the importance of Nordic collaboration on long-term policy. Recommendations include an inter-Nordic strategy on further development of the electricity transmission grid based on coordinated regulations and shared investments. Depending on geographical resource variations, the project findings suggest differentiated but coordinated commitments to harvesting solar energy, wind power and the production of biomass and biofuels.

Smart policy can drive the Nordic transformation process and benefit the global climate, and also promote welfare and Nordic competitiveness.

INTEGRATION

As stated in, for instance, the TOP-NEST project, there is strong evidence that the transition to meeting the 2050 goals must entail increased integration. This needs to happen between the different parts of the national energy systems, as well as between the Nordic countries. Joint and coordinated approaches to technology and system development, as well as integrated and coherent policy, is essential.

All SES 2050 projects have built cross-border research networks, as well as competencies within the development of sustainable energy solutions. The SES 2050 programme has made a significant contribution towards enhancing Nordic integration and facilitating network-building and information exchange in this important area. Achieving national climate goals requires Nordic solutions because of the integrated energy system. SES 2050 findings go beyond the national level and benefit the whole region.

(Photo: Shutterstock)

Project highlights

Huge potential

MOST OF THE NORDIC electricity production is already carbon neutral, and the potential for additional renewable power is huge, according to the **NORSTRAT** project. The region could become an important exporter in the future European system. In fact, less than a third of the new wind power projects registered in 2012 would be enough to replace the region's remaining fossil-fuel-based electricity production. With some upgrades, the grid would be able to handle such a development. Swedish nuclear power production could also be phased out, but this would require major grid upgrades.

A totally electric private car fleet would only increase electricity consumption by 30 TWh/y or less than 10 per cent of the current electricity consumption. The central grid can probably manage this with some minor upgrades. Combined with electric heat pumps for private homes, this would be a resource for short-term grid balancing that largely exceeds the need, according to the **NORSTRAT** project.

NORSTRAT

Nordic power road map 2050: Strategic choices towards carbon-neutrality

Unified diversity

ELECTRICITY IS INDEED the most promising pathway for de-carbonizing road transport, according to the **TOP-NEST** project. The limitations of current battery technology imply that heavy transport will still rely on chemical fuels. In addition, the Nordic countries have differing strategies for decarbonizing road transport, related to available resources, infrastructure and institutional conditions. There is a relative focus on electricity and hydrogen in Norway, electricity in Denmark and biofuels in Sweden and Finland. The **TOP-NEST** prescription for Nordic road traffic is balancing electricity from renewable sources against hydrogen and advanced biofuels. The project suggests diversity and flexibility combined with an alignment of infrastructure, as well as a unified approach at the European level.

TOP-NEST

Technology Opportunities in Nordic Energy System Transitions

Biofuels from Nordic forests

TRANSPORT CURRENTLY accounts for almost 40 per cent of Nordic CO_2 emissions, according to NETP 2016. It presents a carbon-neutral scenario in which bioenergy surpasses oil as the largest energy carrier in 2050. Bioenergy is already the dominating form of renewable energy in the region, and increasing imports are expected to cover the growing demand, according to NETP 2016. Wood and woody biomass is already the most important source of bioenergy in the Nordic region. According to the **ENERWOODS** project, this production can be doubled at the forest stand scale, using well-known measures to increase growth. This includes nurse crops, non-native species and breeding programmes for genetically improved material. The project researchers consider it a realistic scenario to intensify management in parts of the Nordic forest area so that the region becomes self-sufficient with regard to biomass production, in spite of an expected and considerable growth in demand.

ENERWOODS

Wood-based energy systems from Nordic and Baltic forests

Converting electricity to fuels

THE LARGE AMOUNTS of electricity produced from renewable sources can also be used to boost the production of biofuels. Coupled with biomass conversion, advanced high-temperature electrolysing techniques can efficiently convert electricity into liquid or gaseous fuels that are suited for heavy-duty transport. The biomass potentials can be doubled or tripled without jeopardizing sustainability criteria, according to the **CO_2 Electrofuels** project. This could be another strategy to eliminate the need for biomass imports, and at the same time provide means for electricity storage and grid balancing. Biomass contains too much carbon compared to hydrogen, so large amounts of the CO_2 is currently wasted in biofuels production. Solid oxide electrolyser cells (SOECs) are fuel cells in reverse. They can efficiently produce hydrogen from water, CO_2 and electricity through synergies between SOECs and biofuel synthesis.

CO_2 Electrofuel

CO_2 Neutral Electrolysed Synthetic Fuels for Heavy Transportation and Electricity Load Balancing

Biofuels from algae

SECOND-GENERATION biofuels can also be harvested from new sources. Algae and cyanobacteria can be employed to produce biomass with a high sugar or starch content. The tiny organisms can also act as biological machines that produce hydrogen or other biofuels directly. Both pathways were explored in the **AquaFEED** project. A good hydrogen-producing Finnish cyanobacterial strain was identified and genetically sequenced. Biotechnological methods, mechanical methods and process methods were explored to improve hydrogen yield. Bigger breakthroughs are still needed before this strategy becomes relevant on an industrial scale.

AquaFEED

Conversion of solar energy to infrastructure-ready transport fuels using aquatic photobiological organisms as the hydrocarbon feedstock producer

Prediction for offshore wind farms

WIND POWER is the fourth largest carbon-neutral energy source in the region after bioenergy, nuclear power and hydropower, according to NETP 2016. In 2013, wind power provided 13 per cent of Nordic electricity. This is expected to increase to 30 per cent in 2050, according to the carbon-neutral NETP 2016 scenario. The new frontier of the wind industry is large-scale offshore wind farms, according to the **Offwind** project. Nordic countries have long coastlines and favourable wind conditions, but development depends on proper tools for planning and prediction of expected power output to estimate profitability. The **Offwind** open-access prediction tool can lead to optimized location and layout of offshore wind farms, as well as improved wind turbine design.

Offwind

Prediction tools for offshore wind energy generation

Solar power in cold climates

IT IS A WIDESPREAD NOTION that the Nordic region seems less likely to see the solar boom other countries are experiencing. In 2013, solar power accounted for 0.13 per cent of the Nordic electricity mix, according to NETP 2016. The idea that northern regions are not very suitable for grid-connected photovoltaic (PV) systems is quite a common misconception, according to the **NorthSol** project researchers. Using solar tracking, they established Sweden's most effective PV system in Piteå – comparable to installations in southern Europe. They have no doubt that efficient PV in a cold climate is technically feasible. Depending on a range of factors, it can also be economically feasible.

NorthSol

Solar Power Plants in the North

Methanol from solar panels

NEW CONCEPTS for harvesting solar energy, and developments in electricity storage, can increase the competitiveness of solar power in the region. Ongoing technological developments make it too early to rule out a pathway in which this plays a prominent role.
In the **NISFD** project, researchers have been working towards producing methanol in solar panels. By using an artificial photosynthesis 10 times as efficient as its natural counterpart, catalytically active solar panels can directly transform solar energy to fuels, instead of delivering electricity. Panels could be connected to the electrical grid and could generate fuel even when there is no sunlight. In that way, the solution could contribute to balancing the grid as well as the issue of storing electricity.

NISFD

Nordic Initiative for Solar Fuel Development

Photovoltaic and thermal conversion combined

THERMAL CONVERSION is another pathway for harvesting energy from the sun. Existing solar thermal power plants concentrate the sunlight by using mirrors or lenses, and employ the energy as a heat source. If such plants also included a PV device operating at high temperatures, the efficiency potential would be very high. A theoretical photon-enhanced thermionic emission (PETE) device has been explored in the **HEISEC** project. It combines quantum and thermal mechanisms into a single physical process. Findings show that efficient PETE solar cells require materials that are not yet available. The properties of such super materials have been specified by the project researchers.

HEISEC

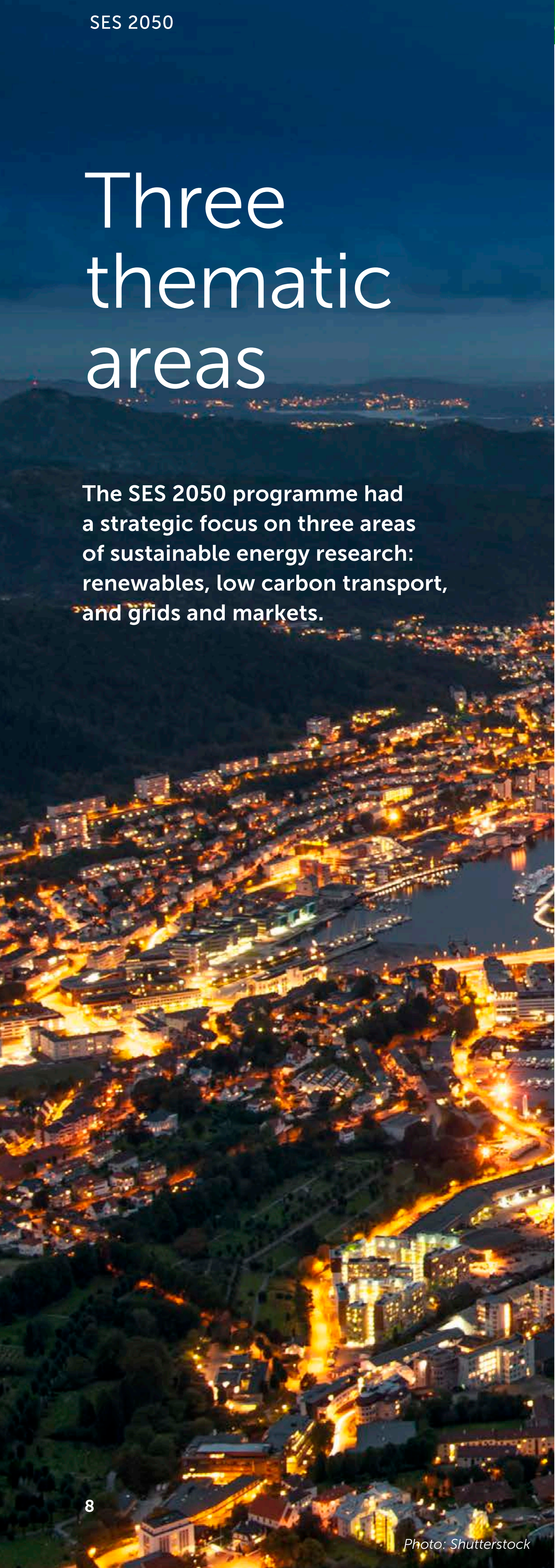
High Efficiency Integrated Solar Energy Converter

Smartgrid applications

INCREASING SHARES of wind and solar power challenge both the organization of the common Nordic electricity market and the electricity system operation. Increased variability and unpredictability require stronger diagnostics and faster responses. Emerging tools provide totally new system information and control possibilities. This can radically enhance power system operation and the ability to cope with a changing and less predictable system based on renewable energy sources. Phasor measurement units (PMUs) provide extremely high temporal resolution to wide-area grid diagnostics updating 50 times a second. Applications where this information stream can be channelled have been developed in the **STRONGrid** project. Cooperating Nordic universities have set up PMUs in their laboratories, creating a wide-area research platform. This has placed the region at the forefront of applying this technology.

STRONGrid

Smart Transmission Grid Operation and Control



Three thematic areas

The SES 2050 programme had a strategic focus on three areas of sustainable energy research: renewables, low carbon transport, and grids and markets.

Photo: Shutterstock

RENEWABLES

IN ORDER TO LIMIT greenhouse gas emissions from energy generation, a transition from fossil fuels to renewable energy sources is required. This calls for increased research and development efforts in several areas of common Nordic interest, including biomass and bioenergy, wind-power, solar-power and hydro-power.

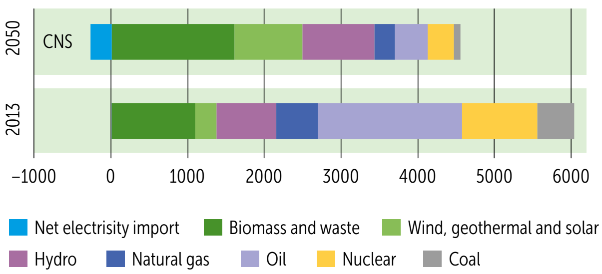
Most of the Nordic electricity production is already carbon neutral. Only 13 per cent of electricity was generated from fossil fuels in 2013, according to NETP 2016. About half of all electricity generated in 2014 came from hydropower.

Wind power is experiencing the largest growth of all renewable technologies. It accounted for 7 per cent of the Nordic electricity generation in 2013, and is projected to account for 30 per cent in the carbon neutral scenario for 2050.

Biomass pellets are compressed organic matter. (Photo: Shutterstock)

It is a widespread notion that the Nordic region seems less likely to see the solar boom other countries are experiencing. In 2013, solar power accounted for 0.13 per cent of the Nordic electricity mix, according to NETP 2016. However, several technological developments, including SES 2050 project findings, make it too early to rule out a pathway in which this plays a prominent role.

When it comes to bioenergy, this is already the dominating renewable energy source in the region, and increasing biomass imports are expected to cover the growing demand. Plans are in place to increase deployment of biomass technologies to decarbonize transport and industry, as well as electricity and heat generation. In the NETP 2016 carbon neutral scenario, biomass surpasses oil as the largest energy carrier in the years leading to 2050.



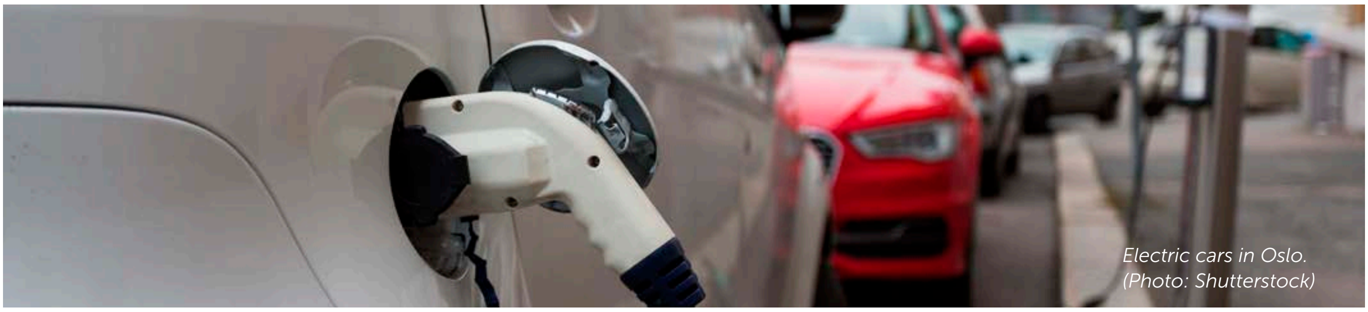
In the NETP 2016 carbon neutral scenario, Nordic primary energy supply decreases by 25 per cent in 2050 compared with 2013 (excluding net electricity exports). Fossil fuels and nuclear decrease, while bioenergy, wind and hydropower increase, as do net electricity exports. (Figure: IEA/NER/NETP 2016)

LOW-CARBON TRANSPORT

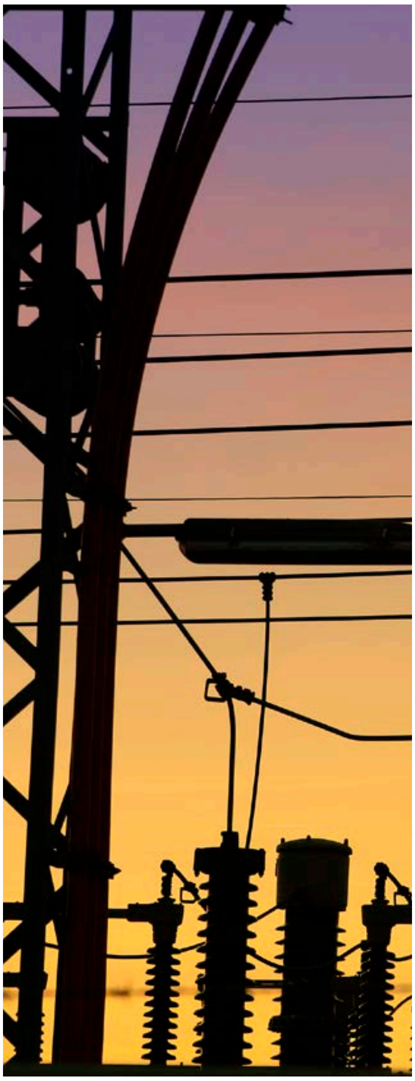
ONE OF THE MAIN CHALLENGES for the Nordic region is to substantially reduce emissions and increase energy efficiency in the transport sector. Transport currently accounts for almost 40 per cent of Nordic CO_2 emissions, according to NETP 2016. In the carbon-neutral scenario for 2050, this sector delivers the greatest emission reduction. With current battery technology, short-distance transport might see a broad electrification, but long-distance traffic is unlikely to be decarbonized without large volumes of biofuels. It is estimated that biofuels will comprise nearly two-thirds of total final energy use in Nordic transport in 2050.

Competing low-carbon fuels such as hydrogen, or highway electrification, bear higher investment risks and costs. At the same time, it is difficult to predict the impacts of potentially disruptive technologies like autonomous vehicles, or developments like shared mobility services.

The Nordic countries all have ambitious goals but somewhat different preconditions and strategies for developing cleaner road transport. There is a relatively strong focus on electricity and hydrogen in Norway, electricity in Denmark and biofuels in Sweden and Finland. Enabling a future low carbon transport system will require increased policy cooperation and coordination. The Nordic countries have strong traditions in the development and manufacture of transport technologies, and have already made significant advances in low-carbon transport. A joint Nordic region creates a larger market for international transport actors. Enabling the Nordic region to take a leading role in creating new sustainable transport solutions could give it a significant advantage in the development of this sector and the future development of the energy sector as a whole.



Electric cars in Oslo. (Photo: Shutterstock)



GRIDS AND MARKETS

INCREASED AMOUNTS OF ENERGY from fluctuating renewable energy sources, decentralized production and the expected electrification of the transport sector require intelligent grids and improved market solutions. The Nordic countries have a long tradition of collaboration to ensure a sufficient and stable energy supply and optimal utilization of energy resources. Together, the countries have built a truly liberalized and harmonized market with several cross-border interconnectors.

The Nordic power system will need upgrades to support the increasing share of renewable energy. Given the significant potential for new renewable energy in the Nordic region, important strategical choices need to be made to set the future course for this power system. There are significant benefits from supplying and balancing the European electricity grid.

The development and implementation of new solutions in markets and grids is very costly, time consuming and politically sensitive, and requires a high degree of policy coordination. Nordic knowledge on market and grid issues should be further exploited in order to stay at the forefront in this area.

Electric plant in Denmark. (Photo: Shutterstock)

Nordic hydropower will be increasingly valuable for regulating the North European power system, but it will not be enough. New and emerging tools for grid balancing will be needed. Electric cars and heating systems can be an important source for short-term grid balancing, as charging or heating can be remotely activated or deactivated if the frequency gets too low or too high. Combined with flexible demand from industry, there should be enough resources for this type of balancing.

As envisioned in the smartgrid concept, new and emerging tools provide totally new grid information and control possibilities with the potential to radically enhance power system operation and to cope with a changing and less predictable system based on renewable energy sources. The Nordic countries have an opportunity to become world leading in the use of such technology.

According to NETP 2016, better integration between electricity and district heating systems allows storage of excess electricity as heat. Better integration between electricity and gas by converting electric power to fuel allows storage of electricity as carbon-neutral gaseous or liquid fuels.

A long history of cooperation

The Nordic countries have worked together on energy research since the 1970s.

NORDIC ENERGY RESEARCH (NER) is a research funding institution that operates under the auspices of The Nordic Council of Ministers, which is the intergovernmental body operated by Denmark, Finland, Iceland, Norway and Sweden and that also includes the autonomous areas of the Faeroe Islands, Greenland and the Åland Islands. Individually, the five Nordic countries are too small to have a significant influence on an international level, but together their populations comprise 25 million people and the region is the twelfth largest economy in the world. The core function of NER is to fund energy research and policy development and to support transnational collaborations both in the Nordic and Baltic regions.

COOPERATION PLATFORM

In today's research, we can find building blocks for the future platform of Nordic cooperation. However, it may take 10 or 20 years before the results are implemented in society, and even longer before the full effects are achieved. From this perspective, research is of strategic importance and a precondition for future Nordic energy cooperation. To achieve the intended long-term effects, research results urgently need to be considered by decision makers. In this regard, the Nordic cooperation offers a unique platform for both the development of solutions and their launch onto the global market.

OIL CRISIS

Nordic governments initiated cooperation on energy research in the 1970s, in response to the oil crisis. By the mid 1980s, this cooperation was organized as a research-funding programme. The purpose was to increase competence and secure a leading international position for the Nordic region in the area of energy research.

In 1999, the organization Nordic Energy Research was established. Funds were granted in four-year research programmes, each covering several thematic areas.

CHANGE OF FOCUS

The year 2003 marks a thematic change in NER's funding programmes for applied research. Research on fossil fuels was phased out and replaced with research on sustainable energy technology, and this has been the underlying focus in the research-funding programmes that followed, including the SES 2050 programme and the current Nordic Flagship Projects.

Sustainable energy technology is a challenging topic that demands new energy technology solutions and knowledge. The change of direction has resulted in new sustainable energy technologies, policy development to support the alignment of Nordic energy solutions, and increased Nordic research collaboration.

RESEARCH CONTINUITY

Long-term research collaboration has paid off in the sense that research consortia have been able to continue successful research from one NER research programme to another. Nordic consortia that do research of such a quality that they are able to secure additional funding in subsequent programmes should be considered another form of Nordic added value.

In the global race towards sustainable production of hydrogen, Nordic and Latvian researchers had an international break-through in 2005 in a project called Renewable Production of Hydrogen Using Algae. The highly promising results were investigated further in the AquaFEED project under the SES 2050 programme.

DEVELOPING BIOFUEL PRODUCTION

NER-funded researchers also discovered that the cost of biofuel (ethanol) production can be dramatically reduced if the production is integrated with other types of industrial facilities, for instance oil refineries or paper factories. The project was called New, Innovative Pre-Treatment of Nordic Wood for Cost-Effective Fuel-Ethanol Production, and ran from 2007 to 2010. A factory producing 150,000 m^3 ethanol every year could cut costs by EUR 200-300 per m^3 by means of such integration.

The results indicated a way to organize forestry and biomass-based industry in order to achieve competitive advantages. The two SES 2050 projects CO_2 Electrofuels and ENERWOODS provide further insights into how Nordic biomass and biofuel production can be increased.

WIND FARM TOOLS

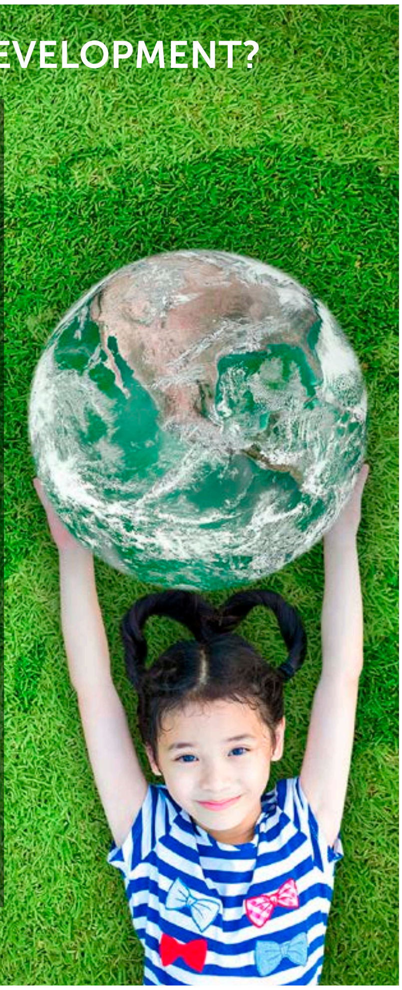
To speed up development of wind energy parks, the development of advanced analytical tools for wind farm planners was funded in the research programme from 2003 to 2006, in a project called Large-Scale Integration of Wind Energy into the Nordic Grid. Simulation systems were developed and transferred to industries. The systems enable more accurate planning of how to integrate wind energy into the power system. The analytical toolkit for wind farms has been further improved in the SES 2050 programme within the Offwind project. The Offwind tool can help determine optimal positioning and layout of offshore wind farms.


(Photo: NASA)

WHAT IS SUSTAINABLE DEVELOPMENT?

In the early 1980s, a United Nations commission was addressing growing concern with accelerating deterioration of the human environment and natural resources and the consequences for economic and social development. Its landmark report Our Common Future (1987) popularized the most commonly used definition of sustainable development: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Several definitions exist, and they usually include the idea of understanding and acting on the complex interconnections between the environment, the economy and society. Degrading or destroying the ecosystems on which our communities depend means living unsustainably.

Over the past 25 years, governments, businesses and civil society have committed to sustainable development goals.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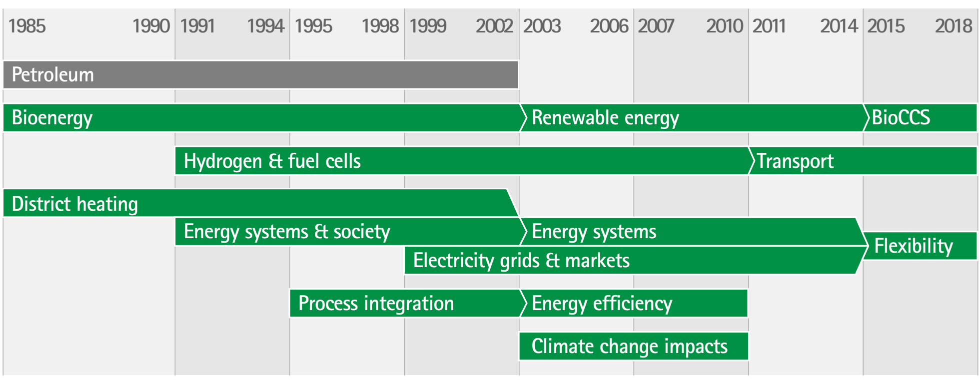


Development of the NER funding research areas since the initiation of NER as a research-funding programme. (Figure: NER)

Increasing the share of renewables

There is huge potential and multiple ways to increase the share of renewable energy in the Nordic region.

EXISTING ENERGY and transport systems are deeply embedded in industrial and societal structures, so the transition towards carbon neutrality will affect us all. Changes in one part of the system will affect other parts, and a lack of system consideration may jeopardize any kind of change. Smart policies and investments that facilitate the transition are needed.

Making a common effort to coordinate long-term policy development on a Nordic level can provide support for decision makers and make necessary and extensive changes less daunting. Such collaborations can also lower the cost of investments. Research findings from the SES 2050 programme reveal some of the possibilities and the significant potential that could be reached through a Nordic collaboration on the entire energy system.

ESTABLISHED TECHNOLOGY

There is no question that the electricity system can become carbon neutral. Put together, the SES 2050 projects demonstrate that the potential for additional renewable power is very high. This is true even when improvement and increased deployment of already established technologies is considered alone, in particular wind farms (NORSTRAT and Offwind), but also photovoltaics (NorthSol).

Possible benefits from exporting renewable power and balancing the wider European grid need to be further identified, and require increased transmission integration between the Nordic region and the rest of Europe. Strategical decisions related to this must be based on considerations of a wide range of factors, from renewable energy build-out to electricity and grid capacity (NORSTRAT).

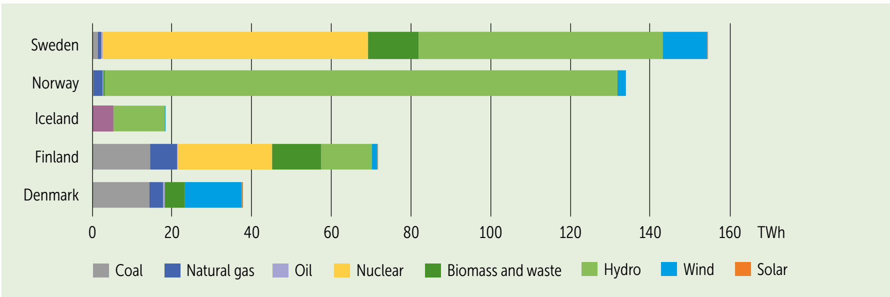
NEW SOLUTIONS

The SES 2050 research programme has also brought forward the development of several new and emerging renewable energy technologies that could become important in the future. Boosting biomass production with power-to-fuel technologies (CO_2 Electrofuel) and utilizing artificial photosynthesis (NISFD) or aquatic microorganisms to produce biofuel (AquaFEED) are all promising ways to increase the renewable share. Some of these solutions can even offer additional benefits to the energy system by means of grid balancing or electricity storage. Focusing on fuel production rather than direct generation of electricity, these pathways should interest decision makers who are facing one of the most pressing current challenges for the Nordic energy system: working out how to decarbonize the transport sector.

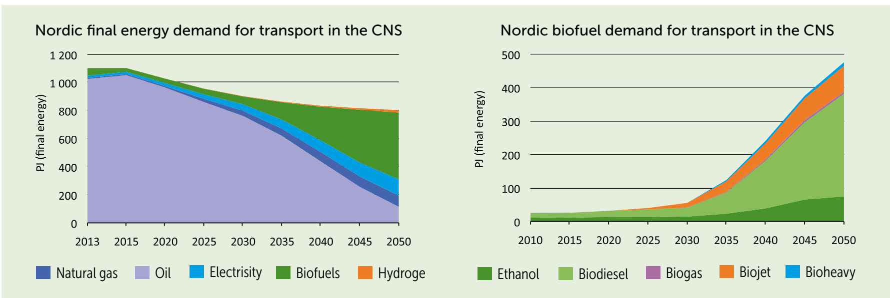
NORWEGIAN INCENTIVES

Nordic transport has much further to go than the electricity system, but could also become carbon neutral. Transport is the region's third largest sector in terms of energy demand and CO_2-emissions. The process of electrifying private transport can gain momentum by utilizing incentives similar to the ones that are already in play in Norway. Here, 24 per

Laboratory photobioreactors creating biofuel from algae. (Photo: Shutterstock)



At present, 83 per cent of the electricity production in the Nordic countries is carbon neutral, of which 63 per cent is renewable. (Figure: IEA/NER)



In the carbon-neutral scenario presented in NETP 2016, biofuels will play a critical role in phasing out oil used for transport in the Nordic countries. (Figure: IEA/NER) cent of all new cars sold are either an electric or chargeable hybrid car, while in Europe the market share is about 1 per cent. Developing the charging infrastructure is key for a fast transition of the passenger fleet (NORSTRAT).

Due to the somewhat diverging strategies for cleaner road transport in the Nordic countries, steps must be taken to avoid technological islands that make driving from one country to another in the same car impossible. Both technological diversity and infrastructure alignment is recommended, balancing electricity from renewable sources against hydrogen and advanced biofuels on Nordic roads (TOP-NEST).

BIOFUELS FOR HEAVY TRANSPORT

For long-distance transport by road, sea or air, biofuel is considered a very important part of the solution. NETP 2016 suggests that increasing imports of biomass could be a cost-effective means to secure the supply of such fuels. In addition to the new and emerging options to increase biofuel production, the SES 2050 programme also presents a strategy in which well-known and established methods could be sufficient. Boosting forest productivity to provide more woody biomass has the potential to make the region self-sufficient with bioenergy (ENERWOODS). Timber for construction and other climate-friendly uses is usually the prime product from forests. Increasing the use of such materials maximizes the forests' impact of climate mitigation. However, there will always be co-production of large quantities of woody biomass, for instance low-grade material to be used directly for energy.

A major advantage of biofuel and electricity-coupled biofuel is that it can replace fossil fuels with only slight adjustments to existing engines and by using the existing distribution system. It has also been tested and found suitable for ships and heavy goods vehicles.

STRENGTHENING DESIRED PATHWAYS

Strategic decisions must be made in many areas to put green policies and incentives in place. Research findings from the SES 2050 programme suggest that a clear and strategic Nordic long-term policy is a prerequisite to realizing the Nordic ambitions. It is critical for all policy measures to combine financial incentives with a stable, cross-border regulatory framework (TOP-NEST). Getting industrial actors interested in investing in new technology is crucial for the transition to sustainable energy systems. Policy strategies will play an important role in minimizing risks related to such investments.

Collaboration on smart policy and green industrial development will provide business opportunities for Nordic enterprises and increase the welfare of its communities. Nordic industries can also increase their competitiveness in a global market demanding efficient and low-carbon services. In turn, all of this will strengthen the desired renewable technology pathways.

CONTINUED RESEARCH EFFORT

In the SES 2050 research programme, the quality of the research and development work, as well as the broad variation in approaches and solutions, gives cause for optimism. However, it takes time for scientific findings and technological innovations to be implemented. In today's research, we find building blocks for the future platform of Nordic cooperation. It may take 10 or 20 years before the results are implemented in society, and even longer before the full effects are achieved. From this perspective, research is of strategic importance and a precondition for future Nordic energy cooperation, which can offer a platform for both the development of solutions and their launch onto the global market.

RESEARCH AND INDUSTRY

This implies a continued emphasis on both basic and applied research by Nordic consortia. The value of basic research cannot be overstated. History shows that

Current battery limitations prevent electrification of long-distance transport. (Photo: Shutterstock)

scientific breakthroughs often emerge in surprising ways. The thorough investigation of the theoretical proposal to combine photovoltaic and thermal conversion to increase the efficiency of solar-generated power (HEISEC) is an example of research that will not currently be translated into working technology. The required theoretical super materials might, however, become available in the future, so it is impossible to know how important this technology could become.

Connections between research and industry should also be reinforced and further developed. The SES 2050 projects with industrial partners boosted innovation and industrial development. Demonstration projects provide experience with applying technology, and increase market acceptance of new systems. Increased exchange of experiences across country borders will improve the learning effect of demonstration plants.

Integrating new energy solutions

Nordic cooperation has proved successful for electricity. The current challenge is to expand the collaboration to the entire energy system.

(Photo: Shutterstock)

IN ORDER TO INTEGRATE an increasing share of renewable energy into the power system, two major challenges must be overcome. These are technical development and Nordic collaboration on policy and market conditions. Integrating a sustainable energy system into our habits and expectations could be an even more complicated matter.

SMARTGRID

On the technological side, there will be a need to expand and upgrade the transmission grid in order to decarbonize the Nordic power system and private passenger transport, as described in the carbon neutral scenario in the NORSTRAT project. An even further expansion of the grid will be necessary if the Nordic region is to become a major exporter of green electricity to Europe, as envisioned in the European hub-scenario.

Also, a smart transmission grid is an important technological key to integrating more renewable energy, and there are high expectations for smartgrid solutions. The software and applications developed in the STRONGrid project give the Nordic transmission system operators (TSOs) an advantage. They are now in a better position to utilize the new smartgrid technology and new sources of grid balancing to operate the next-generation power system. The research also provides industrial actors with a leading edge in the market for new solutions in power system monitoring and control.

CONCESSION PROCEDURE

As for policy and markets, there is potential in developing shared Nordic strategies, standards, subsidies and regulations. For instance, a major barrier for expanding the Nordic electricity grid is the concession procedure for projects. This is the formal process that secures permission to develop and use a transmission line. The national procedures are lengthy processes involving multiple legal frameworks and stakeholders, and have to deal with conflicts of interest in different municipalities, according to the NORSTRAT project. While there is stated public support for decarbonization, the TOP-NEST project finds that in some jurisdictions, the construction of new power lines is often strongly resisted by the local public. A shared Nordic policy can simplify the concession procedure.

HABITS AND EXPECTATIONS

With regard to electrifying passenger transportation, the challenge is broader than changing technology and the infrastructure. The shift also challenges peoples' habits and expectations. We will have to accept cars that travel shorter ranges. Owners might appreciate lower running costs, but will need to accept long charging times. Consumer expectations for charging times are as low as 10 to 15 minutes. Currently, fast charging takes two times longer than that.

More fundamental changes in car ownership and how transport needs are met can also be envisioned. In the future, expectations could shift from individual car ownership to a preference for

access to transportation services. User norms and expectations among consumers are important aspects of the shift towards sustainable energy systems.

Breakthrough dynamics have been demonstrated in geographical pockets such as in Norway and in California. This may be driven by factors such as enthusiasts and early adopters in the market, or the regional presence of a car manufacturer.

SUSTAINABILITY IN A BROAD PERSPECTIVE

The renewable shift is motivated by the concern about global climate change. However, solutions suggested by the SES 2050 projects might also introduce complications for the natural environment in other areas, or complications for the Nordic communities. Nordic decision makers will have to deal with some dilemmas in this regard.

For instance, the ENERWOODS project highlights the Nordic potential for increased production of biomass. One of the measures that could be used to achieve this is introducing non-native species. This conflicts with existing regulations and understanding of sustainable nature management with regard to its effects on soil, land use and biodiversity. The forests' contribution to supporting the need for renewables such as timber and biomass must be balanced with the need for sustainable management of the forests themselves.

By using waste-based and lignocellulosic ethanol as suggested by the TOP-NEST project, change in land use should be a minor issue. However, these technologies still involve competition regarding the use of biomass resources in transport fuels and animal feed.

Local democracy is also challenged by the need for centralized and faster decision-making processes to expand the electricity grid, to plan for new power production and to establish restrictions on transport systems.

DRIVING THE TRANSFORMATION

Policy changes will enable transformation of the energy systems. Analysis provided by the TOP-NEST project suggests variation and experimentation in the early stages. Transition policy should consider specific local, regional or national resources, infrastructure and institutional conditions for transitions instead of policy mainstreaming.

At the same time, there is a need for better policy coordination between different policy domains and instruments, and between the Nordic countries. For instance, there is a need for coordinated subsidy systems in order for other countries to catch up with the development of Swedish solar energy and Norwegian electrification of the passenger fleet. There is also a need to develop a stable and cross-country regulatory framework, and to continue investments in long-term research and innovation, according to the NORSTRAT project.

The Nordic transformation must comply with EU regulations. Stronger EU policy signals are needed to show the way and create confidence for long-term investments for industry actors. European standards may not be the most favourable for Nordic resources and systems. In this respect, it is important for the Nordic countries to act and speak with one voice to the EU and to the rest of the world.

Photo: Shutterstock

Programme overview

This seventh edition of NER's main research funding programme spanned from 2011 to 2015. The project portfolio budget was NOK 134 million, including project co-funds.

THE AIM OF THE PROGRAMME has been to develop new knowledge and solutions, supporting the region's transition to a sustainable energy system in 2050. The programme supported 10 projects, each with research partners from three or more Nordic countries. The supported projects developed integrated solutions in the fields of renewables, low-carbon transport, and grids and markets. The direction taken by the Sustainable Energy Systems 2050 programme was directly founded in the Nordic Energy Research Strategy for 2011 to 2014.

FUNDS

The programme had a common-pot format, where national contributions not only financed researchers from that particular country but were shared among all applicants. Together, the five Nordic countries contributed with NOK 100 million over the 4 years of the programme. This financing was complemented through co-funding to reach a total budget of NOK 134 million. The projects' co-funds consisted of additional financing from project owners, private companies and public organizations etc.

PARTNERS

Project partners covered all five Nordic countries in addition to European partners, and came from universities, research institutions and industry. A total of 68 partners contributed to the projects, including 43 research institutes and 25 industry partners. This includes all the Nordic countries, the Baltic countries and northwest Russia.

PROPOSALS

The high number of proposals received gives an indicator of the significant interest there is for Nordic cooperation in energy research. All 90 proposals were evaluated by top international experts and the Board of Nordic Energy Research. In total, the applications' proposed financing totalled over NOK 1 billion. This application success rate was 10 per cent.

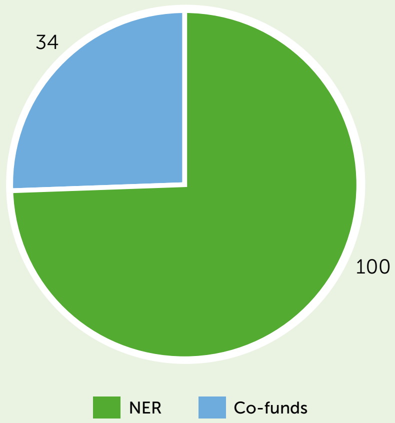
COMMUNICATED RESULTS

The programme educated 25 new Nordic researchers - 7 women and 18 men. A total of 493 scientific publications were produced. This includes 143 peer-reviewed articles in scientific journals, books and book chapters, etc. Output also included 350 non-peer-reviewed publications and other dissemination activities. These include reports, briefs, books and articles that are aimed at policymakers, industry or other end users. The results have also been communicated at a number of conferences and to the media. The SES 2050 programme findings are available for industry actors, politicians and the general public.

FINAL SEMINAR

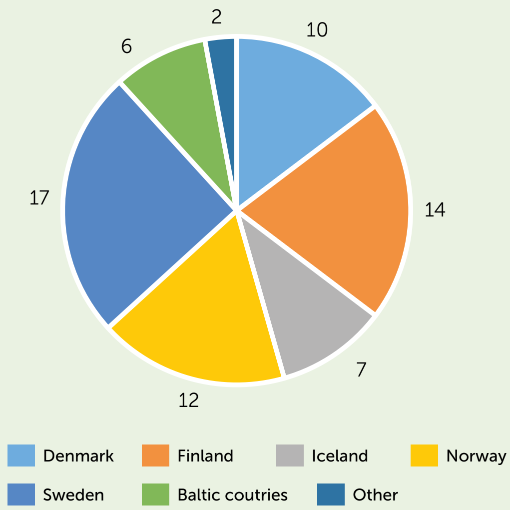
Nordic Energy Research hosted a final seminar for the research programme Sustainable Energy Systems 2050 on 21 and 22 October 2015. The seminar took place at the Norwegian Research Council in Oslo. A total of 65 representatives from energy research, authorities and industries in the Nordic countries gathered to share and learn from the results.

PROJECT FUNDS



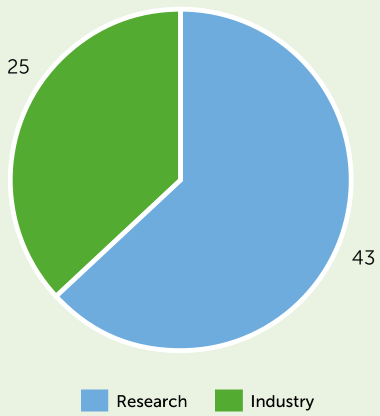
The total funding of the SES 2050 programme was NOK 134 million. NER was responsible for 75 per cent of the funding. The remaining 25 per cent of the funds came from other sources, such as universities, research institutes and industry.

PROJECT PARTICIPANTS BY COUNTRY OF ORIGIN



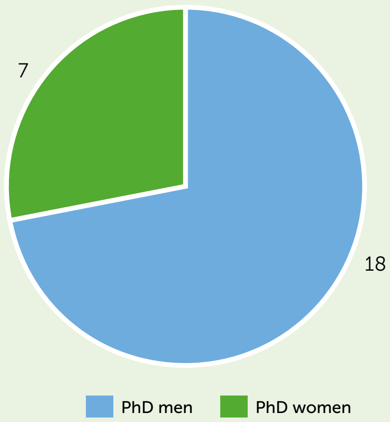
The total number of participating organizations.

TOTAL RESEARCH INSTITUTES AND INDUSTRY PARTICIPANTS



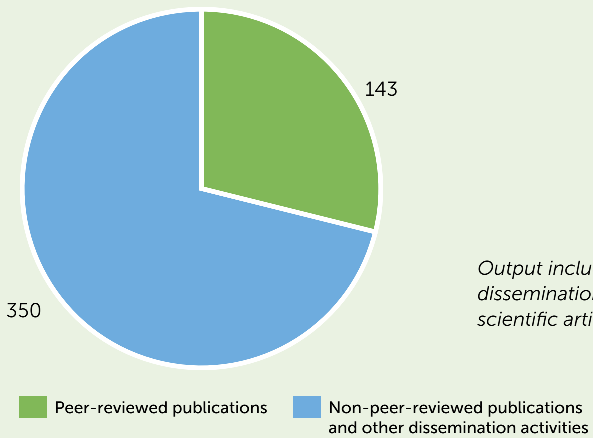
68 partners and 11 countries participated.

DOCTORAL STUDENTS



The SES 2050 programme supported 25 PhD graduates, of which seven were women.

SCIENTIFIC PUBLICATIONS



Output included 493 scientific publications and other dissemination activities. Peer-reviewed publications include: scientific articles, books and book chapters, etc.

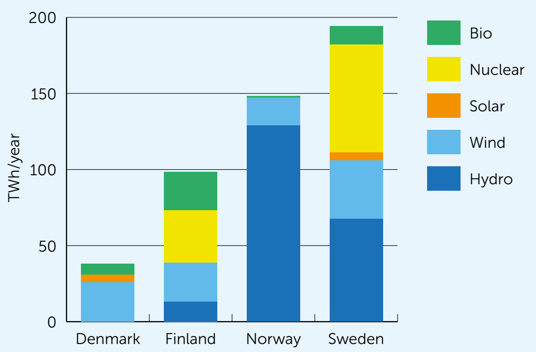
SES 2050
10 Nordic research projects

Together, the projects in the research programme Sustainable Energy Systems 2050 are a demonstration of extensive Nordic cooperation in world-class energy research and development. The findings and developed knowledge networks facilitate national ambitions of sustainability, economic development and competitiveness.

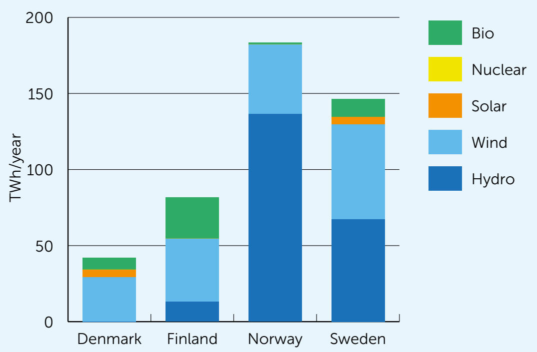
NORSTRAT

Empowering Nordic energy policy

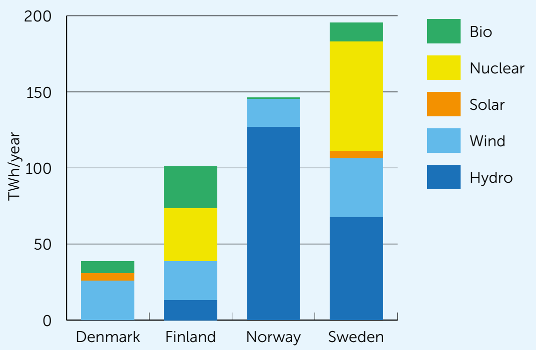
The Nordic region has more than enough renewable energy resources to phase out fossil power generation and cover the expected increase in power demand.



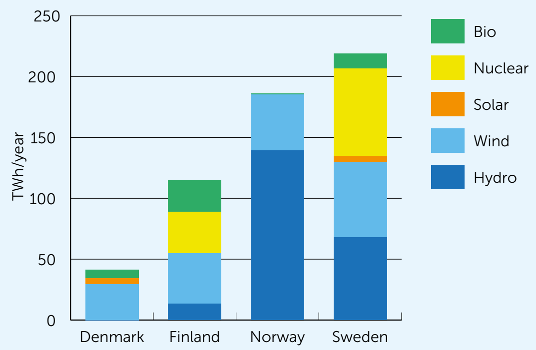
Carbon Neutral - power production from fossil fuels is phased out and substituted with nearly 150 TWh/y new power production from RES. The transmission connections between the Nordic region and the rest of Europe are limited to the 2015 level.



Purely RES - nearly 250 TWh/y new renewable energy source (RES) based power production is integrated and nuclear and fossil fuel based power production decommissioned. The transmission connections to the rest of Europe are limited to the 2015 level.



European Battery - nearly 150 TWh/y new power production from RES is integrated into the Nordic region and the capacity in the Norwegian hydropower system is increased by 11 GW. Transmission capacities to the rest of Europe are increased according to profitability criteria.



European Hub - nearly 250 TWh/y new power production from RES is integrated and the Norwegian hydropower system capacity is increased by 11 GW. Transmission capacities to the rest of Europe are increased according to profitability criteria.

In all scenarios power demand is increased by ca. 13 percent in 2050, compared to the present level. (Figures: NORSTRAT)

High-voltage pylon in Finland. (Photo: Shutterstock)

MORE THAN HALF of the Nordic power production is from renewable energy sources. Roughly 20 per cent is nuclear. Power production from fossil fuels is dwindling – already in 2010 it was less than 20 per cent of the total. To phase out the remaining power production from fossil fuel, Nordic countries do not have to look further than to new renewable energy projects that, in 2012, already were registered. Such production will mainly be based on onshore and offshore wind resources.

Depending on how many renewable energy projects are realized, and how much the transmission grid is expanded, the Nordic countries can also become an exporter of green power in the future European system. "There is huge potential for new renewable power production in the Nordic region," says Ingeborg Graabak.

WATER BALANCE

The NORSTRAT project leader explains how the region (Denmark, Finland, Norway and Sweden) is in a very fortunate position. "We have a lot of resources, like hydropower and other renewable energy sources. We also have hydropower reservoirs to balance variability in production from wind and solar resources. The rest of Europe is facing much bigger challenges in that respect."

All Nordic private cars can be battery electric vehicles by 2050 with only a 10 per cent increase in current power consumption. Graabak says the Nordic renewable resources can cover this as well. The power system can also handle it – with limited upgrades of the large transmission lines. Local distribution grids might need to be upgraded to a larger extent, and fast charging is not included in the analysis.

REPLACING NUCLEAR POWER

NORSTRAT findings also indicate that the region has enough renewable resources to decommission nuclear power production in Sweden – in addition to replacing the Nordic fossil fuel based production. A large increase in transmission capacities is necessary to accommodate this. The present Nordic grid has a capacity of 75 gigawatt (GW), and an increase of at least 22 GW would probably be needed. "Removing a large power production in one place has a larger impact than replacing fossil fuel based production in several places," Graabak says. In comparison, the analysis indicates that approximately 6 GW capacity increase would be required in the most basic scenario called "Carbon Neutral". Here, fossil fuel based power production is replaced by renewable resources, but nuclear production is kept at the 2012 level.

PROJECT AT A GLANCE:

Exploring possible carbon neutral futures for an integrated Nordic power system.

System development and emerging challenges also depend on the Nordic approach towards Europe. Becoming an electricity hub for Europe will require a stronger transmission infrastructure, and electricity prices will be more influenced by the European prices. According to the project leader, it is not clear whether a Nordic focus or major exports of green energy will yield the most benefits for the Nordic region.

FREQUENCY RESERVES

With increasing amounts of energy from renewable sources, more reserves will be required. In addition to hydropower reservoirs, both battery electric vehicles and heat pumps can contribute to balancing the grid. Assuming that all private cars are electric and all Nordic homes have heat pumps the potential for frequency reserves is huge. Cars and heat pumps would have to be connected to smart metering equipment enabling remotely controlled charging and operation. The Norwegian authorities require that such equipment is installed in all homes by 2019.

If the frequency is above the upper limit of normal grid operations, extra charging of cars and operation of heat pumps could be activated until the frequency drops. If the frequency is too low, cars and heat pumps can be decoupled. According to Graabak, customers would not really notice: "It would only be for a few seconds or minutes."

At present, the minimum requirement of reserves in the joint Nordic power system is 600 megawatts (MWs). The NORSTRAT estimation of aggregated frequency reserve capacity from cars and pumps is from 6951 MW to as much as 15 609 MW if the EV penetration level is 100 percent and all the heating from the fossil fuels and electric heating in the residential heating sector are replaced by heat pumps. "This would be a resource for short-term balancing that largely exceeds the requirement," Graabak says.

"The Nordic countries are lucky to be in a good position to develop a power system without greenhouse gas emissions," says Ingeborg Graabak. (Photo: SINTEF)

PROJECT FACTS:

PROJECT NAME: Nordic power road map 2050: Strategic choices towards carbon neutrality

PROJECT LEADER: Research Scientist Ingeborg Graabak, SINTEF Energi

PERIOD: 2011–2015

FUNDING: NOK 12.2 million from NER, NOK 14.4 million total budget

OUTPUT: 15 peer-reviewed papers, 20 non peer-reviewed publications, 11 events and presentations, 1 PhD

PARTNERS: SINTEF, Technical University of Denmark, Stockholm Environment Institute

WEBSITE: http://www.sintef.no/projectweb/norstrat/

The Nordic power balance in 2010 [TWh/y]

	Denmark	Finland	Norway	Sweden	Sum
Wind power	8	0	1	4	13
Hydro power	0	13	117	66	196
Other RES	3	10	0	12	25
Nuclear	0	22	0	56	78
Fossil fuels	26	31	5	8	70
Non identifiable	0	1	0	0	1
Production	37	77	123	145	382
Consumption	36	88	130	147	401

To completely remove the greenhouse gas emissions from the Nordic power system would mean substituting 70–100 TWh/y of fossil fuel based production, based on 2010 figures. (Table: NIFU)

TOP-NEST

Nordic cooperation paves the way

PROJECT FACTS:

PROJECT NAME: Technology Opportunities in Nordic Energy System Transitions (TOP-NEST)

PROJECT LEADER: Research Professor Antje Klitkou, Nordic Institute for Studies in Innovation, Research and Education (NIFU)

PERIOD: 2011-2015

FUNDING: NOK 8 million from NER, NOK 9.4 million total budget

OUTPUT: 15 peer-reviewed publications, 24 conference papers, 2 book chapters, 1 PhD

PARTNERS: Nordic Institute for Studies in Innovation, Research and Education, CIRCLE Centre for Innovation, Lund University, Technical University of Denmark, VTT Technical Research Centre of Finland, Riga Technical University

WEBSITE: www.topnest.no

Electricity from renewable sources should be balanced against hydrogen and advanced biofuels on Nordic roads.

THERE IS MORE THAN one path to carbon neutral road transport. Diversification and flexibility is an important recommendation from the TOP-NEST project – a project in which researchers want to guide industrial strategies and governments in making the transition.

Nonetheless, project leader Antje Klitkou does not hesitate in naming the energy pathway for which she has the highest hopes: "Electricity – if it comes from renewable sources."

ELECTRICITY, HYDROGEN AND BIOFUELS

With more renewable sources and battery developments, electricity as an option is growing increasingly strong. The TOP-NEST project shows that across the Nordic region, more battery electric vehicles can reduce the total system cost slightly, compared to a baseline of mixed technologies.

More hydrogen fuel cell electric vehicles might increase the total system cost. This is currently the least distributed option. Both electric and hydrogen cars can contribute to grid integration of variable renewable energy.

Biofuels rely on a scarce resource but are very compatible with existing infrastructures. The only sustainable kind is advanced or second generation, made from various types of non-food biomass or organic waste – as opposed to first generation from sugars and vegetable oils in arable crops. Klitkou explains that a lock-in into first generation biofuels has become a barrier for the commercialization of advanced biofuel technology.

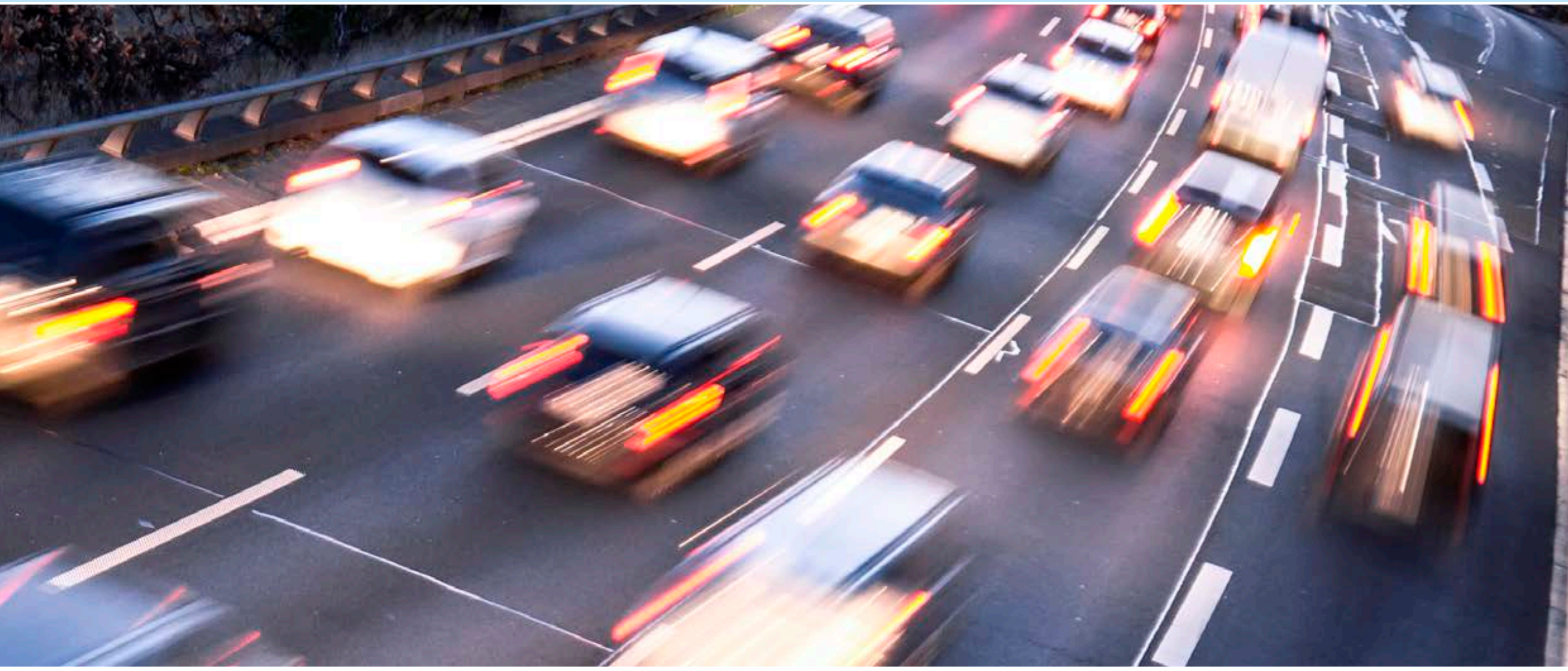
"We also need those resources for other production processes, transitioning into a bioeconomy. Biofuels for private cars is not very useful. For heavy goods vehicle transport, aviation or shipping it might be necessary."

RENEWABLE VS. FOSSIL

In the scientific literature and public debate, renewable energy is usually pitted against fossil-dependent energy systems. At the same time, the different types of renewable energy compete for public support and funds, political incentives and support measures.

Path dependency is a key concept in the TOP-NEST project and refers to the specialization and concentration of resources tied to any given economic development. The most striking example is fossil fuels – an important and severely entrenched path dependency from which we are finding it difficult to break free in spite of changing conditions.

"Path dependency can be a positive mechanism in the beginning, ensuring investment return. Such dependencies take time to emerge, with a multitude of factors working together to make it happen - from political measures to establishment of robust companies," Klitkou says.



PROJECT AT A GLANCE:

Identifying the most promising pathways for decarbonizing Nordic road transport.

The identification of technical solutions to cut fossil usage is not enough. The TOP-NEST project leader says countries need to find strategies that strengthen, rather than hinder the competitiveness of the desired paths.

Klitkou says path creation processes are key for transitioning to more sustainable fuels and vehicles for road transport.

DIFFERENT EMPHASIS

The Nordic countries all have ambitious goals, but somewhat different preconditions and strategies for developing cleaner road transport. There is a relative focus on electricity in Denmark, electricity and hydrogen in Norway and biofuels in Sweden and Finland. The energy sectors also differ between the countries. In analytical frameworks, sustainability transition approaches have largely disregarded geographical aspects so far.

"We need to consider connections between the energy sector and road transport. Traditionally, we have looked at them separately. Transition efforts should consider specific local, regional and national resources, infrastructure and institutional conditions, and not just copy policy," Klitkou says.

INFRASTRUCTURE ALIGNMENT

Nordic countries also need to prevent the development of technology islands which makes driving from one country to the other in the same car impossible. The TOP-NEST project prescription is diversity and flexibility, as well as an alignment of infrastructure.

Klitkou points out that the Nordic countries are far from such an alignment today. "Sweden and Denmark both produce biogas, but if you drive a biogas car from Sweden to Denmark, you will find very few filling stations in Denmark."

Policy coordination between different domains and instruments must improve. The Nordic countries need to establish better coordination between them. To enable a concerted development, decision makers must commit to some broad innovation policies. "Political incentives and support measures cannot change every second year," Klitkou says.

PARALYSIS

Transition and creative destruction is the only road to sustainable transport systems. Such extensive change might intimidate policy makers as well as major industry actors – and lead to paralysis. Long-term planning, coordination and cooperation are the antidotes to such states, according to the TOP-NEST project leader: "To manage the required structural transition, the cooperation must be extensive."

Speaking with one voice is also a great advantage for the Nordic countries. The development of sustainable transport technology platforms is conditioned by EU policy – while the EU emphasis on this objective might not be at the Nordic level.

"The advancement of sustainable road transport in the region would benefit if the Nordic countries aligned their positions on this topic at the European level, despite their differences in technological emphasis and choices," Klitkou says.

As a more sizeable partner and a larger market, with substantial research and innovation resources, the Nordic countries can become an important test bed for the implementation of sustainable energy systems for road transport. ■■

The Nordic countries have somewhat different preconditions and strategies for developing cleaner road transport. (Photo: Shutterstock)

"Transition will not happen spontaneously in the market," says Antje Klitkou. (Photo: NIFU)

ENERWOODS

Doubling Nordic forest productivity

Bioenergy is the dominating renewable energy in the region. It is mainly derived from wood and woody biomass, the production of which can be doubled at the stand scale.

NORDIC ENERGY DEMAND for biofuels and waste is expected to increase from an 18 per cent share of total primary energy demand in 2013 to 35 per cent in 2050, according to the carbon neutral scenario presented in the recently published Nordic Energy Technology Perspectives (NETP) 2016.

Wood and woody biomass is already the most important source of bioenergy in the Nordic and Baltic region. According to the ENERWOODS project leader Palle Madsen, forests can contribute much more towards carbon neutrality. “Forests can become much more productive by using well-known measures. In a transition period, we can also harvest more low-grade wood material to foster an increased biofuel supply in the coming decades,” he says.

NO NEED FOR IMPORTS

Net imports will be needed to meet approximately 16 per cent of the total biomass demand from all sectors in the Nordic region in 2050, according to the NETP 2016 scenario.

The ENERWOODS project researchers, on the other hand, consider it a realistic scenario to intensify management in parts of the forest area to fulfil the needs for domestically produced biomass in the Nordic and Baltic regions, even as global demand for bioenergy increases. “Societies need to act soon. There is only 35 years left, which roughly corresponds to half a forest stand rotation length in the region,” Madsen says.

The project researchers assess that it is possible to increase Nordic forest productivity at the stand scale by at least 50–100 per cent of the current level.

WIDESPREAD LACK OF UNDERSTANDING

According to Madsen, areas with productive forest species can compete with energy crops. The main challenge is to increase the awareness that in spite of being long-term affairs – a typical rotation length in the region is 70 years. Forests are dynamic and potentially very productive systems. “There is a widespread lack of understanding of the dynamics and functions of forests,” Madsen says.

It is also the experience of the project researchers that stakeholders representing nature and biodiversity interests tend to see more intensive forestry as counterproductive to their interests. Madsen reminds us that what the ENERWOODS project researchers have been working on is not relevant for all of the forest area. “Highly productive stands can neighbour areas that are managed for biodiversity without negative impact. It is up to society how to prioritize the different functions of forests,” he says.

HARVESTING MORE

More intensive forestry must be founded on an increased use of timber, since this is the most profitable and sustainable use of the harvest. Replacing energy-intensive materials like concrete, steel or aluminium will give an important substitution effect. Subsequent recycling or burning of the wood after use, to replace fossil fuels, will be the most energy- and climate-effective use. However, large proportions of wood waste and low-grade materials are only suitable for direct use as energy, pulpwood or fibre boards, etc.

On average, 65 per cent of the annual forest growth is harvested in the Nordic and Baltic regions. In the short run, forest biomass can be increased by harvesting more. The historical need to ensure forest recovery explains why sustainable forest management so far has been equivalent to harvesting quite a lot less than the annual growth. Before ENERWOODS, other studies have indicated that a utilization of up to 89 per cent of the growth is currently within the limits of long-term sustainable use. That would also include an increased harvest of low-grade material such as small trees, branches and stumps.

INCREASING GROWTH

A stronger potential for boosting the biomass from Nordic forests can be found in increasing the growth of the forests. The measures suggested in the ENERWOODS

A Danish forest officer leans against a Norway spruce in the central part of Gotland. This is a not a native species in Denmark. While Danes are used to non-native species, this is a big issue in many other countries. (Photo: ENERWOODS) project can typically increase productivity by at least 50–100 per cent in combined efforts and at the stand scale.

Nurse crops of fast-growing pioneer species provide shelter that favour survival of desired and slower-growing species in the regeneration and young stand phases. This requires careful management and thinning. Mixing in productive, late successional species, for instance fast-growing conifer species, can make a big difference. This would challenge forest legislation and certification schemes in most of the Nordic and Baltic countries. "The number of native tree species in Europe, and particularly in the Nordic and Baltic regions, is low compared to other continents. Forestry is primarily resting on just two tree species – Norway spruce and Scots pine. That means a very low spread of risk in our forests management when facing climate change." Madsen says.

Genetically improved material, which can be produced, for instance, by the use of breeding programmes, can increase the genetic variability and support the forest adaptation capacity towards climate change, for example. Fertilization can speed up the growth in some regions, and afforestation of abandoned farmland can further increase the forest area to a limited extent.

PROJECT AT A GLANCE:

Strengthening Nordic forestry in the development of competitive, efficient and renewable energy systems.

WELL PREPARED

"We have used an open mindset to identify and evaluate possible solutions to develop the potentials of forests and forestry much further than today. There will always be advantages and disadvantages," Madsen says. The question is whether society and decision-makers are aware of the opportunities, or willing to exploit them. The large forest areas and the well-established forest management, forest industry and infrastructure in the Nordic and Baltic regions make these regions well prepared along all of the value chains to implement a more intensive management – if there is confidence in the long-term profitability of the investments. "Nordic countries should act and speak with one voice to the EU and the rest of world, to highlight the important role of forests and forest management towards a low-carbon society," Madsen says.

"Nordic and Baltic forests can become much more productive," says Palle Madsen. (Photo: Inger Ulrich)

PROJECT FACTS:

PROJECT NAME: Wood based energy systems from Nordic and Baltic forests (ENERWOODS)

PROJECT LEADER: Senior Researcher Palle Madsen, Forest & Landscape, IGN, University of Copenhagen

PERIOD: 2011–2015

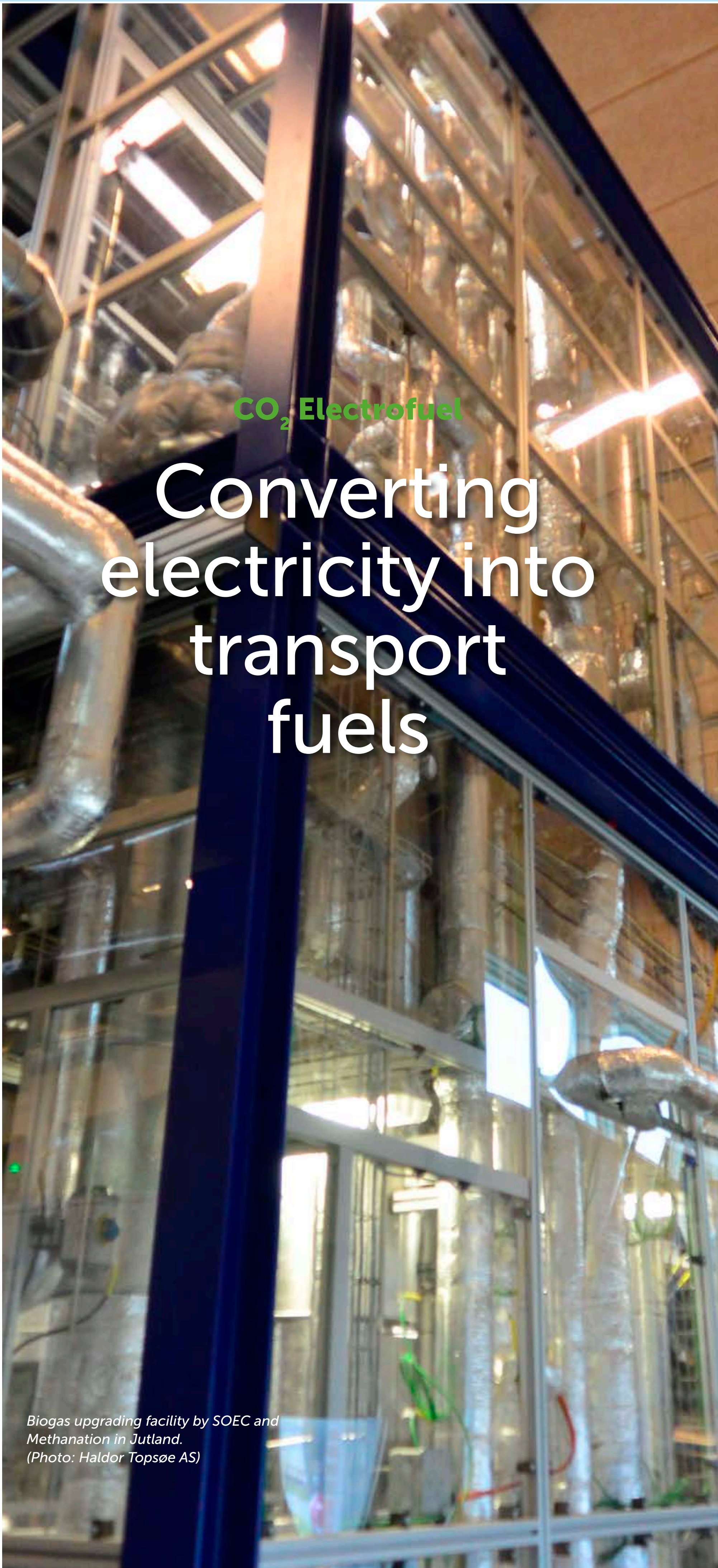
FUNDING: NOK 14 million from NER, NOK 18.6 million total budget

OUTPUT: 20 peer-reviewed publications, 75 non-peer-reviewed publications, 52 presentations, 19 workshops/seminars/conferences, 8 PhDs

PARTNERS: The University of Copenhagen, The Forestry Research Institute of Sweden, Finnish Forest Research Institute (currently Natural Resources Institute Finland), School of Engineering at Linnaeus University, Southern Swedish Forest Research Centre at Swedish University of Agricultural Sciences, School of Forest Sciences at University of Eastern Finland, Finnish Environment Institute, Norwegian Institute of Bioeconomy Research

WEBSITE: http://enerwoods.ku.dk

Advanced electrolysis can boost biomass conversion and transform electricity into transport fuels with an efficiency of up to 80 per cent.



Biogas upgrading facility by SOEC and Methanation in Jutland. (Photo: Haldor Topsøe AS)

CO_2 Electrofuel

Converting electricity into transport fuels

COUPLED WITH BIOMASS CONVERSION, advanced high-temperature electrolysing techniques can efficiently convert electricity into liquid or gaseous fuels that are suited for heavy-duty transport.

"The biomass potentials can be doubled or tripled without jeopardizing sustainability criteria," says CO_2 Electrofuel project leader John Bøgild Hansen.

NO BIOMASS IMPORTS

Projections for 2050 show that the Nordic region will need to import a significant amount of biomass in order to decarbonize the transport sector.

Currently, biomass is converted to heavy-transport biofuels (like methanol) with an energy efficiency of no more than 60 per cent. Project estimates show that the heavy transport sector will use around 300 PJ in 2050. This is final energy consumption, so the primary biomass use for biofuels would amount to around 500 PJ every year.

PROJECT FACTS:

PROJECT NAME: CO_2 Neutral Electrolysed Synthetic Fuels for Heavy Transportation and Electricity Load Balancing (CO_2 Electrofuel)

PROJECT LEADER: Senior Advisor John Bøgild Hansen, Haldor Topsøe AS

PERIOD: 2011–2015

FUNDING: NOK 7,1 million from NER, NOK 11.9 million total budget

OUTPUT: Invited talks at 8 different international conferences, a test station for pressurized SOEC at DTU Energy Conversion Lab

PARTNERS: Haldor Topsøe AS, Chemrec AB, EA Eergianalyse AS, EON Nordic AB, Innovation Center Iceland, SORPA, Oliudreifing ehf, Volvo Powertrain Corp, Wärtsilä Oy

WEBSITE: http://www.co2-electrofuels.org

"If the biofuel production was integrated with solid oxide electrolyser cell (SOEC) technology, this biomass consumption could be reduced with at least a factor of two, and eliminate the need for biomass import," Hansen says. The electricity consumption would increase by more or less the same amount as the predicted electricity export for 2050.

ELECTROLYSIS

In an electrolyser cell, electricity is used to drive chemical reactions – for instance to split water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2). In this way, electrical energy is transformed into chemically bound energy. In this sense, a SOEC is a fuel cell in reverse. "Starting with CO_2, water and electricity, it is possible to make a wide range of fuels," Hansen says. The challenge is to do it in an energy-efficient way.

While fuel cells have been under development during the last three decades, and are deployed in the market, no SOEC demonstration plants were deployed outside laboratory settings until recently. Demonstration projects are underway in Denmark and Germany and a biogas upgrading facility has been started in Jutland.

Because of the high operating temperature of SOECs of 700 to 800°C, the conversion efficiency is very high. The unavoidable losses in the cell stacks produce heat, but this helps drive the chemical reactions, so the electricity is not wasted.

There is also a strong synergy between the SOEC and biofuel synthesis. SOECs use steam, not liquid water, as feedstock. Steam is generated downstream in the catalytic fuel synthesis. By using this for the electrolysis, water does not need to be electrically heated to produce steam, so the heat from chemical fuel synthesis is not wasted.

BOOSTING BIOFUELS PRODUCTION

The hydrogen that comes out of the SOEC can boost the production of biofuels. "Biomass contains too much carbon compared to hydrogen. Consequently, a lot of CO_2 is wasted in the production of biofuels. Adding hydrogen produced from electrolysis increases the biomass potentials dramatically," Hansen explains.

The fundamental project idea is to couple the emerging SOEC technology with existing catalytic conversion methods that are integrated with biological and thermochemical methods.

In addition to splitting water, the SOECs can also electrolyse carbon dioxide (CO_2) to carbon monoxide (CO). If water is electrolyzed at the same time, the result is a mixture of hydrogen and CO. This is called synthesis gas (syngas), and is the starting point of a large number of syntheses of hydrocarbons, meaning fuel, in the chemical industry. Syngas can also be reacted with surplus, renewable carbon from biomass or other natural sources to produce the fuels.

PROJECT AT A GLANCE:

Investigating whether the production of transportation fuels via SOEC-assisted technology is a viable option for the Nordic region.

CHEAPER THAN BIOFUELS

The project included analysis of resource availability, conversion efficiencies and the projected price structures in 2020, 2035 and 2050. The findings show that electrofuels will be more expensive than fossil fuels, considering the low oil price of today. They will, however be somewhat cheaper than biofuels. Projecting prices can be difficult, and Hansen prefers to focus on how much electrofuel can be produced.

Using the same price assumptions, three cases have been analysed: Biogas upgrading of anaerobic digester gas by means of SOEC in Southern Sweden and Iceland, and coupling of an SOEC unit to a wood gasification plant. Iceland had the most profitable case.

In parallel, the use of the produced electrofuels in heavy-duty engines, and the logistics and economics of fuel distribution have been studied. "Existing or slightly modified engine technologies, fuel logistic chains and infrastructure can be used," Hansen explains.

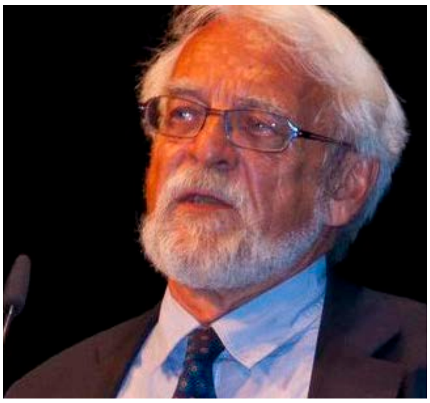
PLANNING DEMONSTRATION PLANTS

As well as having enough biomass and electric energy resources to become independent of fossil fuels, the Nordic region also has industries that are able to deliver the technology – for production as well as for refitting engines and so on. "As a whole, our region is unique with actors in the whole value chain, a lot of renewable electricity and good biomass potential. I don't think it would have been possible to execute this project in just one of the Nordic countries," Hansen says.

Another important advantage is the potential for balancing fluctuating power from sun and wind. Production of electrofuels can be designed for dynamic operation to contribute to such load-balancing. Electrofuels is also a way to store electric power.

According to Hansen, the strategy could defuse the controversy around biofuels. "All discussions on whether biofuels are sustainable or not would go away. SOECs make the production so much more effective, and the biomass that is already available in the Nordic region would be enough," Hansen says.

He does emphasise that the technology needs to be tested on large scale to confirm that it is able to fulfil the political goals. "Our next step is to build large demonstration plants. We also recommend that energy technology analysis for the region are redone, taking these possibilities into account," Hansen says.



Far left: SOECs operate at relatively high temperatures (700–800 °C), which makes the efficiency very high. (Photo: Haldor Topsøe AS)

Left: "Part of our work now is to explain this option to decision makers," John Bøgild Hansen says. (Photo: Haldor Topsøe AS)

AquaFEED

Hydrogen from aquatic microorganisms

Hydrogen from microalgae and cyanobacteria is a promising pathway for using photosynthesis to produce chemical energy.

TWO DIFFERENT PATHWAYS can be used to generate third-generation biofuels from microalgae or cyanobacteria. The tiny organisms can be harvested as biomass and used as feedstock for biofuel production. Alternatively, they can act as biological machines that produce hydrogen or other biofuels directly. Both pathways have been explored in the AquaFEED project.

FIRST AND SECOND GENERATION

First-generation biofuels are produced from food crops that are easy to ferment – like sugar cane or grain, or from vegetable oils. This is controversial and considered to be in conflict with food supply and biodiversity.

Second-generation biofuels, also known as advanced biofuels, are made from plant dry matter, woody crops or agricultural residues or waste. This dampens the land-use conflict, but the extraction of the required fuel is more energy intensive. In woody or fibrous biomass, the useful sugars are locked in complex carbohydrates that must be split enzymatically or chemically before fermentation. The conversion to biofuels is harder to do in an efficient and economical way.

60 PER CENT

Just like plants, algae and cyanobacteria (also called blue-green algae) are photosynthetic organisms. Unlike plants, they don't need to spend energy growing fibrous roots, stems and support structures. They only need the photosynthesizing cells, which may contain large amounts of sugar or starch. The AquaFEED project researchers have shown that the cyanobacterium *Synechococcus* can contain 60 per cent fermentable sugar in dry weight. Similarly, the green algae *Chlorella sorokiniana* can contain 60 per cent starch per dry biomass.

According to project leader Esa Tyystjärvi, the AquaFEED project started from the perspective that biomass production was the most obvious option for generating renewable fuels based on aquatic organisms. "But even before the project was a reality, we realized that just producing biomass might not be the most profitable pathway for energy production," he says.

FINNISH HYDROGEN-PRODUCING STRAIN

Consequently, most of the AquaFEED project researchers worked towards the goal of producing something more directly related to photosynthesis. "The biochemical reaction series required to produce usable biomass leads to a large energy loss. More efficient energy production using photosynthesis is possible," Tyystjärvi says.

Biohydrogen is the most studied alternative among the direct biofuels. In the AquaFEED project, a large number of nitrogen-fixing cyanobacteria native to Finnish lakes and the Baltic Sea were screened, and a good hydrogen-producing strain was revealed. "A research group in the AquaFEED projects sequenced the genome of this exceptionally interesting cyanobacterium," the project leader says.

In addition, project researchers examined hydrogen-producing genetically modified cyanobacterial strains.

IMPROVING THE YIELD

Another line of research was related to biotechnological, mechanical and process methods that improve the hydrogen yield. In addition, a large number of algal-growth facilities suitable for research on biohydrogen or other biofuels have been established in the project.

Approximately half of the energy in sunlight is of no use for natural photosynthesis, which only utilizes the wavelengths from 400 to 700 nanometres. In an effort to make use of near-infrared radiation with wavelengths higher than 700 nanometres, materials-chemists worked on conversion of near-infrared to visible light using special materials that up-convert two near-infrared photons to one visible photon.

The mechanism could be used by

PROJECT AT A GLANCE:

Looking for novel solutions for making renewable fuels through the photosynthetic systems in algae and cyanobacteria.

PROJECT FACTS:

PROJECT NAME: Conversion of solar energy to infrastructure-ready transport fuels using aquatic photobiological organisms as the hydrocarbon feedstock producer (AquaFEED)

PROJECT LEADERS: Dr. Patrik Jones, University of Turku (until 30.9.2013) and Adjunct Professor Esa Tyystjärvi, University of Turku (from 1.10.2013)

PERIOD: 2012–2015

FUNDING: NOK 13 million from NER, NOK 15.2 million total budget

OUTPUT: 20 peer-reviewed publications, more than 50 other publications, interviews and public lectures, 2 PhDs, 4 master's degrees

PARTNERS: University of Turku, University of Copenhagen, Uppsala University, Norwegian Institute of Bioeconomy Research, St1 Biofuels Oy

placing such an up-converter underneath an algal-growth facility. Radiation above 700 nanometres passes through the aquatic microorganisms. Converted to visible light at the bottom, it could be reflected back to the growth facility, improving illumination of the bottom layer. Tyystjärvi explains that the conversion efficiency is currently too low for practical applications, but the idea will be further explored.

"Researchers within the AquaFEED project conducted extensive research in biology, biochemistry and technology and established a Nordic network in the field of bioenergy research," says Esa Tyystjärvi. (Photo: Kuva-Paijula)

MEASURING SINGLET OXYGEN

AquaFEED also contributes with a method to measure a certain reactive oxygen species in plant material, a damaging by-product of photosynthesis. Because it is reactive, singlet oxygen is poisonous to the cells. Measuring it is an important part of understanding it better.

The new method is based on quantitative mass spectrometry, available in many laboratories, and allows rapid scans of singlet oxygen from a large number of samples. "If we want to fight the reactive oxygen species, we need to know if they are there, and how much of them there are," says Tyystjärvi.

PRODUCTION OF OTHER COMPOUNDS

A large part of the research in the field is currently moving towards making microalgae and cyanobacteria produce different compounds – for instance those needed in medicine or as raw materials for industry. According to Tyystjärvi, a popular idea is to combine this with energy production from the remaining biomass.

An 80-litre tubular photobioreactor built in one of the AquaFEED project's research groups. The algae growing inside are Nannochloropsis oculata. (Photo: Dimitar Valev)

Using algae to purify waste waters is another active field of research. In the AquaFEED project, cyanobacteria and algae of Scandinavian origin were screened for their ability to grow in waste waters and produce biodiesel oil.

A number of other basic research advances have been made in the project. Tyystjärvi highlights the findings related to biohydrogen, but there is still a long way to go. "We need big breakthroughs to get to anything that is usable on an industrial scale," he says.

The Nordic research group in the AquaFEED project is continuing the collaboration after the project. "Sustained collaboration through common applications or projects is developing the Nordic competence platform," the project leader says.

Offwind

Making offshore wind farms more competitive

Improved prediction of potential power output leads to optimized location and layout of offshore wind farms, as well as better wind turbine design.

THE NEW FRONTIER of the wind industry is large-scale offshore wind farms, according to the Offwind project leader Mohammad Mansouri. The Nordic countries have an advantage, with long coastlines and favourable wind conditions. Currently, there are significant plans for offshore wind energy farms, for instance in the North Sea region.

Development depends on economic profitability, the assessment of which depends on proper tools for planning and prediction of expected power output.

COMPETITIVE WIND ENERGY

The countries around the North Sea have a great potential for wind energy because of their very favourable wind conditions. The tool developed in the Offwind project improves the accuracy of power output forecasts, and provides better foundational knowledge for modelling the design, location and layout of offshore wind farms. Different models combined in one single tool enables more competitive wind energy through identification of optimal operational parameters.

These are some of the important questions: Where can we find the best conditions for wind farms? How should the farms be oriented, as well as positioned in relation to each other? How much space should there be between turbines and farms to make sure they do not affect each other negatively?

WIND INTERACTIONS

Turbines and wind farms are grouped together to reduce installation and operation costs. The closeness means they affect each other aerodynamically, reducing the amount of energy that can be harvested. For instance, the wind wake caused by the first row of turbines means less wind will reach the ones behind. In order to optimize production, it is critical to be able to predict the interaction between wind farms and individual wind turbines.

To accurately predict the wind profile in any given area, available wind resources must be assessed by taking historical data into account. In addition, the desirable strong wind over water often comes with higher waves, and the power production from wind turbines depends on the interaction between the two.

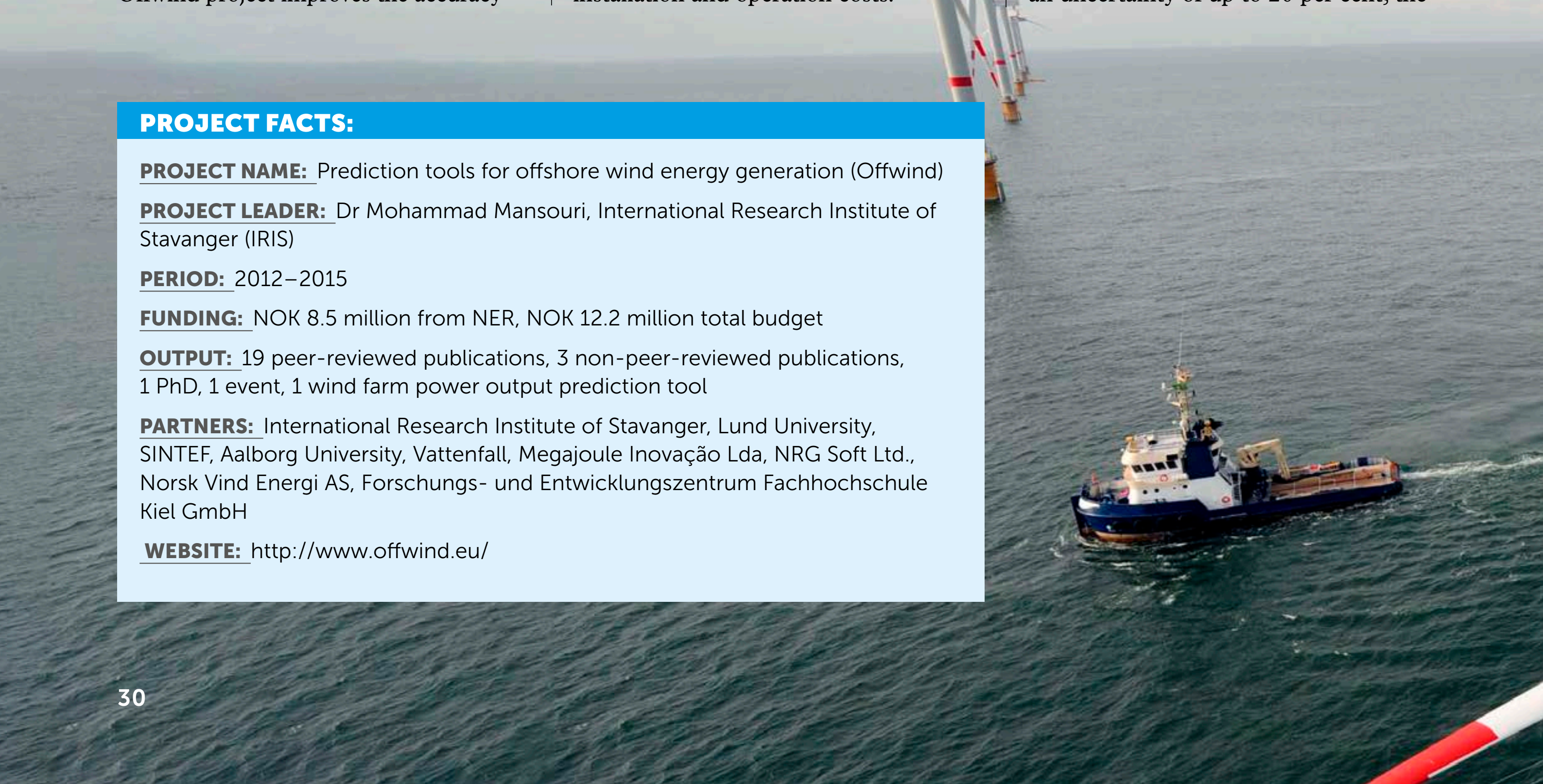
Turbine wake interactions, wind resources and wind–wave interactions have been modeled separately by different partners in the project. In the final prediction tool, all the models have been integrated. The Offwind tool also includes control and nowcasting models, meaning forecasting less than 60 minutes ahead based on measurements of wind speed and direction.

TWO MODULES

According to Mansouri, the main use of the tool will be in the planning phase of offshore wind farms, but it can also be used by existing wind farms to predict the power output and improve control.

The developed tool is available in a web-based environment, in two different modules. "The engineering module provides fast predictions with limited accuracy. These calculations are done in seconds or a few minutes. The advanced module is more accurate, but requires significantly larger computing resources," Mansouri explains.

While the engineering module has an uncertainty of up to 20 per cent, the



PROJECT FACTS:

PROJECT NAME: Prediction tools for offshore wind energy generation (Offwind)

PROJECT LEADER: Dr Mohammad Mansouri, International Research Institute of Stavanger (IRIS)

PERIOD: 2012–2015

FUNDING: NOK 8.5 million from NER, NOK 12.2 million total budget

OUTPUT: 19 peer-reviewed publications, 3 non-peer-reviewed publications, 1 PhD, 1 event, 1 wind farm power output prediction tool

PARTNERS: International Research Institute of Stavanger, Lund University, SINTEF, Aalborg University, Vattenfall, Megajoule Inovação Lda, NRG Soft Ltd., Norsk Vind Energi AS, Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH

WEBSITE: http://www.offwind.eu/

PROJECT AT A GLANCE:

Developing an open access prediction tool for offshore wind farms that more accurately provides forecasting of electricity production.

advanced approach can estimate power production with an uncertainty of around 5 per cent.

Before making any decisions about wind farm projects, rough estimates of efficiency and economics are needed. The engineering module is useful in this regard, according to Mansouri. When going deeper into design and execution, however, more precise estimates are needed.

OPEN ACCESS

Industrial actors already use similar tools, but these are kept within companies. According to professor and project participant Johan Revstedt at Lund University, an open access version is a significant contribution.

"Users can cooperate and contribute to the development. The open access licensing is contagious, so any application that makes use of this work in the future will have to be open access too," he says. Mansouri adds that there is a current trend in the offshore industry towards more open access tools.

"The project has led to the establishment of a strong technical and scientific network, and extensive information exchange between Norway, Denmark and Sweden," says Mohammad Mansouri. (Photo: IRIS/Elisabeth Tønnessen)

"Increasing foundational knowledge has been the most important part of the Offwind project," says Johan Revstedt. (Photo: Kennet Ruona)

Revstedt thinks a continuation of the work would be valuable, particularly with an emphasis on user needs and interface. "For such a tool to be user friendly, there are many considerations that are not directly related to scientific modelling, but more related to application design," he says.

IMPROVING MODELS

As well as providing the open access tool, an equally important project objective was to contribute with a solid increase in knowledge by studying the phenomena and improving existing models. For instance, partners at Lund University investigated wind–wave interaction. "We were able to make improvements," Revstedt says.

In this regard, the project has been successful within the research community, Mansouri says. In terms of industrial use, there have been some challenges.

"Tools like this need a post-implementation and marketing plan," the project leader says.

The Nordic scientists used advanced methods and time-consuming simulations to generate background data, on which the faster models were built. The coupling of models from different research institutions also connected the scientists in a new research network.

"This has been incredibly valuable to us, and we are hoping to make use of this network in future projects," Revstedt says.

To maintain the leading position of the Nordic countries in this field, maintaining competence is crucial. That means ensuring that researchers and industry actors are working on furthering knowledge and techniques. "A follow-up project will be possible in the future," says the Swedish professor.

The Offwind project has provided a tool that can boost widespread deployment of offshore wind energy. (Photo: Shutterstock)

NorthSol

Effective solar panels in a cold climate

Solar panels in Piteå perform better than other systems in Sweden, and can be compared to installations in southern Europe.

PITEÅ IS A SMALL TOWN by the Bay of Bothnia at 65ºN. Near its parking lot, the local energy company PiteEnergi has a grid-connected photovoltaic (PV) system. Two arrays of solar modules with different solar trackers and PV technologies deliver energy to the company offices, as well as results to researchers. This has been the best-performing system in Sweden since it became operative in early 2012, with an annual output of around 1500 kWh/kWp.

"This is a record, even in a European context," says NorthSol project leader Øystein Kleven.

MISCONCEPTION

Nordic countries have a limited power output from PV systems. In Germany, PV covered almost 7 per cent of the electricity demand in 2014. Off-grid and grid-connected installations combined amounted to about 0.06 per cent of Sweden's total energy consumption in 2014. For the other Nordic countries the figure is even lower.

The idea that northern regions are not so suitable for grid-connected PV systems is an important underlying reason. "This is quite a common misconception," says Kleven. Already in 2010 the Northern Research Institute (Norut) presented simulations that showed how the available amount of solar radiation in Northern Scandinavia is comparable to that of Central Europe.

SOLAR TRACKERS

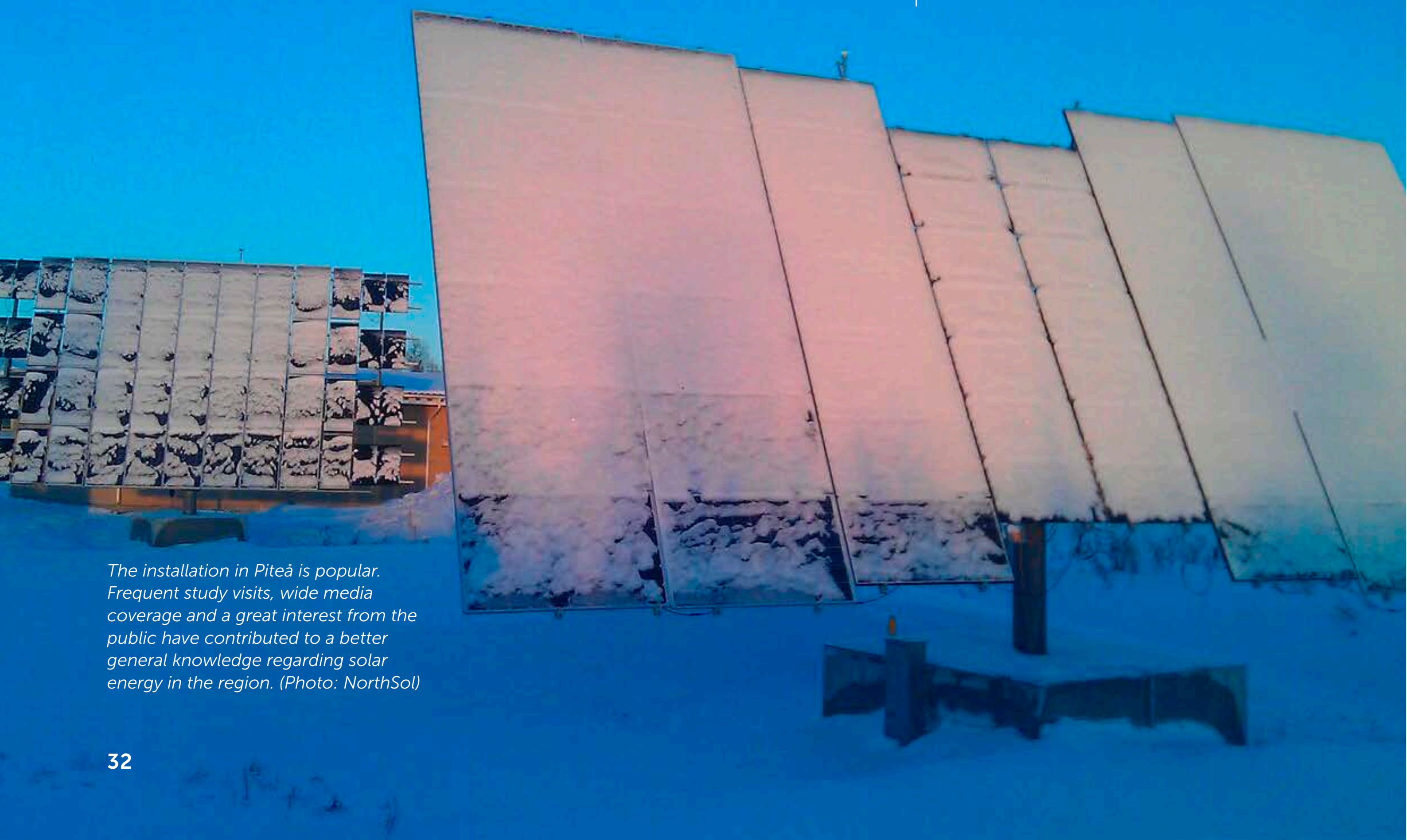
Snow and ice might pose challenges in some ways, but a cold climate is actually the biggest advantage for northern PV cells. The general rule is that when the temperature drops by 20°C, energy production rises by about 10 per cent. Also, new snow reflects up to 90 per cent of the sunlight.

According to Kleven, the main limitations in northern latitudes are the large annual variations, with a solar path of almost 360º on long summer days. "Consequently, it is impossible to utilize all the incoming sunlight on a fixed plane," he says.

The simulations from 2010 showed that the area around Piteå in northern Sweden was the perfect place to show the full solar energy potential of the region and debunk common myths.

The results attracted the attention of PiteEnergi, and the collaboration with Norut was initiated. Like certain flowers, solar tracking PV arrays turn with the sun. One of the arrays near the company offices turns towards the brightest point in the sky, and the other one calculates the sun's position. The first option gives a slightly higher efficiency.

Some potential improvements can easily be implemented in the systems, such as reducing the effects of shadows and choosing the right modules. According to Kleven, the total yield from the Piteå



The installation in Piteå is popular. Frequent study visits, wide media coverage and a great interest from the public have contributed to a better general knowledge regarding solar energy in the region. (Photo: NorthSol)

PROJECT AT A GLANCE:

Testing whether photovoltaic power plants can be technically and economically feasible in high latitudes.

For solar panels, a cold climate means both advantages and disadvantages. (Photo: NorthSol)

system can be improved by 7 per cent using fairly simple measures, and probably by over 10 per cent. Technically, he has no doubt that PV in a cold climate is feasible.

MEASURING SUNLIGHT

Economically it can be feasible as well, but that is a more complicated question. "It depends on so many factors," the project leader says. A specific answer can be calculated for each project, and NorthSol presents a way of doing so. "An increasing number of systems are becoming economically feasible," Kleven says.

A lack of information on actual solar conditions is clouding the economic estimates and hampering the development of PV systems in the Nordic region. Take Norway, for instance. Only one weather station certified by the World Meteorological Organization is actually measuring solar radiation. There are, however, some new local initiatives to map solar resources – for example on the rooftops of Oslo.

HEALTHY MARKET

The knowledge from the NorthSol project indirectly contributes to clarifying the cost of running a solar power plant in the north, because the project has showed what is required. According to Kleven, it is a mistake to forget that the conditions are different from those in countries like Germany. "How should a PV system for northern conditions be designed and installed? How should it be maintained? In that sense one might say that we have been working to make things more difficult."

He does not want a market with a bad reputation. Finding out how to plan, install and maintain solar power panels in northern conditions is in fact laying the foundations for a healthy market – even if it means that the initial installation costs are a bit higher. "Like in Germany, a well-established market means reduced costs," Kleven says.

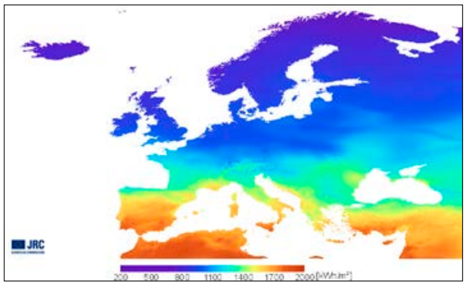
GRID CONNECTED

In one part of the NorthSol project, research partners at Luleå University of Technology (LTU) investigated what kind of challenges large installations of PV can pose for the grid in Scandinavia. One passing cloud can cause a big drop in production, resulting in rapid voltage variations.

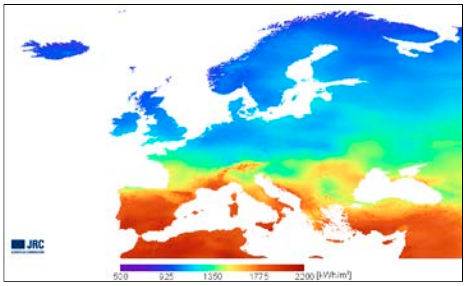
The power quality analysis revealed some new challenges for large PV-installations on low-voltage grids. The risk of overvoltage is one of the most obvious problems. Project findings show that this could be a limiting factor for PV-systems on low voltage grids. Normally, overvoltage would be handled directly by disconnecting the inverter, lowering production. To avoid such cut-offs, new solutions need to be developed.

NEW PROJECTS

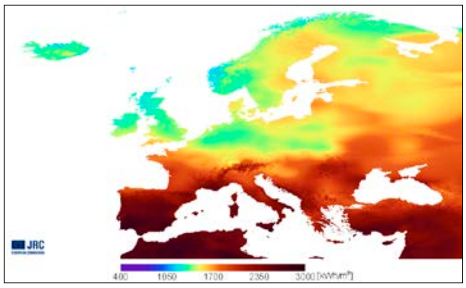
The experience gained in the NorthSol project is a stepping stone for further solar activities in the northern region, and the work is being continued through several other projects. The Aucusticum project involves a solar cell plant of close to 1000 panels on a rooftop in Piteå. For the park behind the Acusticum building, more artistic plans are in place in the SolStol project. An architect has contributed to drawing up a 200-metre-long loop of 165 solar panels facing in different directions. ■■



Insolation per year on a horizontal surface. (Graphics: JRC)



Insolation per year on an optimally angled surface. (Graphics: JRC)



Insolation per year with an ideal solar tracking system. (Graphics: JRC)

"From the economical perspective, the future is looking brighter and brighter, and solar panels are becoming increasingly relevant," says Øystein Kleven. (Photo: Solbes AS)

PROJECT FACTS:

PROJECT NAME: Solar Power Plants in the North

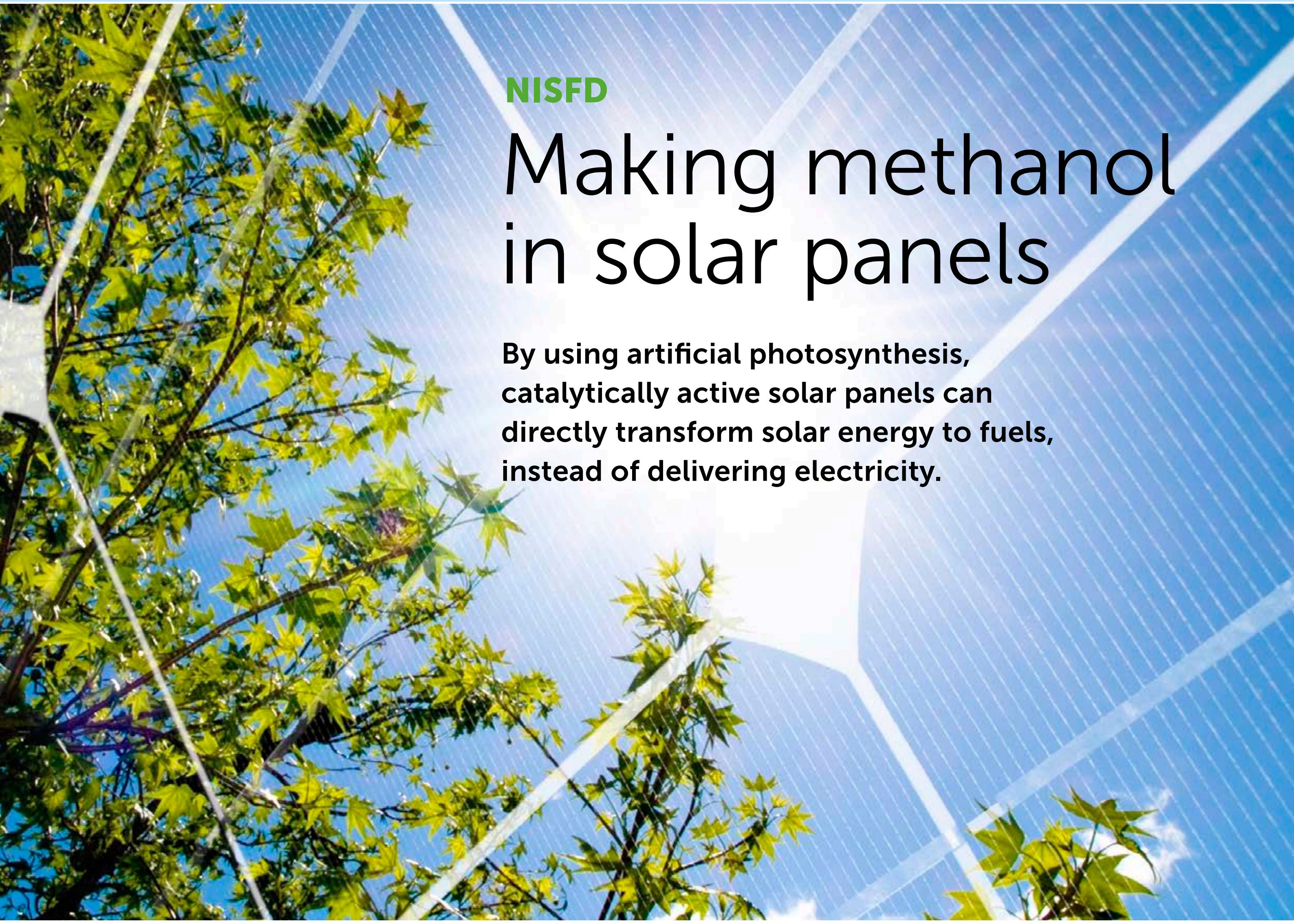
PROJECT LEADER: Senior Research Scientist Øystein Kleven, Norut Northern Research Institute AS

PERIOD: 2011–2013

FUNDING: NOK 2.2 million from NER, NOK 3.7 million total budget

OUTPUT: 6 non-peer-reviewed publications, 10 events and presentations

PARTNERS: PiteEnergi AB, Norut Narvik, Kemi-Tornionlaakso Municipal Education and Training Consortium Lappia, Luleå University of Technology



NISFD

Making methanol in solar panels

By using artificial photosynthesis, catalytically active solar panels can directly transform solar energy to fuels, instead of delivering electricity.

Artificial photosynthesis in solar panels could produce the fuel of the future. (Illustration: Shutterstock)

PROJECT AT A GLANCE:

Designing and developing a photo-electrochemical system that captures solar light and generates renewable chemical fuels from CO_2 and water on one photoelectrode.

CONVERSION OF CARBON DIOXIDE and water into renewable chemical fuels is possible using only solar energy. This can be done with high efficiency and in a direct way, according to the NISFD project leader Dinko Chakarov. Specifically, the project has made some important contributions towards methanol-producing solar photoelectrodes. "Methanol is the fuel of the future," Chakarov says.

PHOTOSYNTHESIS

In photosynthesis, plants use solar energy to split water into free oxygen, which is released, and hydrogen. The plants do not utilize the hydrogen directly but combine it with carbon dioxide captured from the air to produce hydrocarbons in the form of sugars, starches or plant oils.

Current photovoltaic solar cells have a higher energy conversion efficiency than plants do, but the produced electricity has important limitations in terms of storage. Heavy transport cannot realistically be electric with presently known battery technologies.

Hydrogen is considered as an alternative fuel but is difficult to store and transport. It is volatile and requires huge volume in its gas phase. Hydrogen must be stored in some other way, requiring high-pressure or cryogenic systems. "To avoid the difficulties with manipulation and storage of hydrogen, our project is based on the idea that hydrogen can be bound into methanol," Chakarov says.

METHANOL ECONOMY

In the 1990s, Nobel prize winner and chemist George A. Olah was already advocating using hydrogen and CO_2 for methanol production. "The advantages are enormous. Methanol is liquid and enables the use of existing infrastructure. The production means that carbon dioxide, which is one of the required ingredients, becomes a resource – instead of just a waste product that is released into the atmosphere as a greenhouse gas," Chakarov says.

The NISFD project researchers propose a scheme, based on solid, inorganic materials, that operates in a similar way and has similar efficiency to photovoltaics. The difference is that the energy of the sun is stored in chemical bonds (fuels) instead of in electrical current – making the process more like an artificial photosynthesis, but with an efficiency at least 10 times higher than its natural counterpart.

"THE MOST ENERGY EFFICIENT PATH"

In the future, Chakarov hopes it will be possible to condense carbon dioxide from the air. That would result in a completely CO_2 neutral cycle. Until then, the carbon dioxide could be provided in concentrated form by the industry, or from other sources, the project leader says. He thinks the inherent efficiency and durability of the scheme is superior to any of the known alternatives for transformation and storage of solar energy as fuels. Chakarov admits that this is not the simplest and cheapest path so far. "It is, however, the most energy efficient path, with the lowest environmental and social impacts," the project leader says.

ALL ON A SINGLE DEVICE

The project revolves around utilizing solar energy for the promotion of endothermic chemical reactions. The primary findings are related to specific solutions for the production of methanol, including the discovery and design of active light absorbers and photo-catalytically active materials. According to Chakarov, it will be difficult to distinguish photovoltaic solar panels from panels with photo-electrochemical cells. "They will be made of different materials, of course, and maybe have a different colour," he jokes.

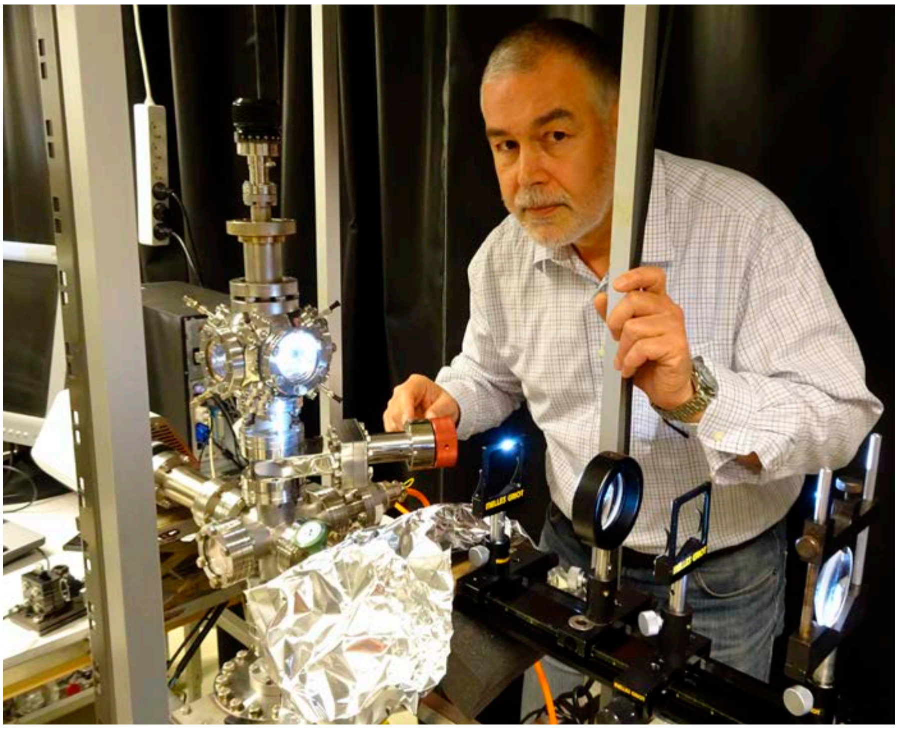
Combining all the processes into a single device is an important part of the approach. "The electrons or charge carriers that are created under solar irradiation can be conducted to drive the chemical transformations locally," Chakarov says.

NANOSTRUCTURE

Materials need to be nanostructured in order to accomplish this. "The distance which charge carriers can travel in the materials is very short – in the order of nanometres. If the materials have larger dimensions, they will simply recombine, making the whole excitation useless, producing only heat. If the material is nanostructured, the charge carriers can reach the interface between particle and environment – say, the water. That makes them able to induce chemical reactions," Chakarov explains.

SEVERAL ADVANCES

He points out that the project contribution is incremental, as the concept has been proposed by a number of people over the last 30 or more years. Advances in different related disciplines, within the fields of physics, chemistry and materials science, have created conditions that make such schemes more possible and reliable. "We have demonstrated the importance of nanostructured materials for such applications, and contributed by proposing different material combinations for the photoelectrodes, and different materials for the water-splitting and CO_2-hydrogenization reactions," Chakarov says.



Dinko Chakarov looking at graphene-composite photo electrodes decorated with optically active plasmonic nanoparticles, studied in an ultra-high vacuum, optical scattering chamber constructed at Chalmers. (Photo: Dinko Chakarov)

STILL A WAY TO GO

Future panels could be connected to the electrical grid and keep generating fuel even when there is no sunlight to provide the required energy. In that way, installations with photo-electrochemical panels could also contribute to equalizing the load of the electrical system.

Efficiency, cost-effectiveness, stability and durability still need to be improved. According to the project leader, project findings and developments are of generic character, and could be applied broadly: "For instance to transform excess electricity into fuels, and to optimize the processing of oil and gas."

Chakarov also says the conversion to synthetic fuels is inevitable in a longer perspective. Limitation of the natural (fossil) resources, as well as sociopolitical and environmental demands will force the transition, he thinks. "The countries with know-how and trained personnel will have a clear advantage. One of our important aims is to explain to the potential users the benefits of an early conversion," the project leader says.

PROJECT FACTS:

PROJECT NAME: Nordic Initiative for Solar Fuel Development (NISFD)

PROJECT LEADER: Professor Dinko Chakarov, Chalmers University of Technology

PERIOD: 2011–2015

FUNDING: NOK 10 million from NER, NOK 16.2 million total budget

OUTPUT: More than 30 peer reviewed publications, more than 15 other publications and invited talks, 9 PhDs.

PARTNERS: Chalmers University of Technology, University of Oslo, University of Iceland, Aalto University, Technical University of Denmark, Carbon Recycling International, Norwegian Electro Ceramics AS

HEISEC

Combining the collection of light and heat

If a solar thermal power plant could focus the sunlight on a photovoltaic device operating at high temperatures, the efficiency potential would be very high.

SUNLIGHT CAN BE USED for the generation of electricity or heat – or both. Existing high-temperature solar thermal collectors concentrate sunlight by using mirrors or lenses, and employ the solar energy as a heat source in a conventional thermal power plant. Typically, a parabolic mirror or large field of mirrors direct the sunlight into a collector. Only the heat is harnessed and converted to electricity.

The more commonly deployed photovoltaic (PV) solar cells convert the solar energy quanta, or photons, directly into electric current. The efficiency of commercial PV cells is getting close to 20 per cent. As opposed to thermal solar energy systems that depend on high temperatures, heat is a problem for conventional solar cells. "As the temperature rises above room temperature, the efficiency for PV solar cells diminishes rapidly," explains HEISEC project leader Jyrki Tervo.

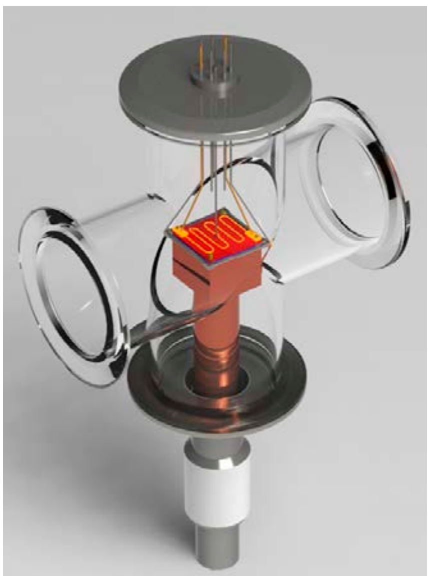


Illustration of an experimental set-up for demonstration of the operation of a PETE device. (Image: VTT)

PETE

The large difference in the operating temperatures of the thermal approach and the quantum approach prevent a tandem use of technologies, where the thermal power system could utilize the waste heat of the photovoltaic system.

In 2010, a new type of solar cell operating at high temperatures was proposed, namely the photon-enhanced thermionic emission (PETE) device. It combines quantum and thermal mechanisms into a single physical process, potentially overcoming the losses inherent to PV cells while bypassing some of the challenges faced by traditional thermal methods.

The device is based on thermionic emission of photoexcited electrons from a semiconductor cathode at high temperatures. In other words, it makes electricity by using the entire spectrum of sunlight, including wavelengths that generate heat. In fact, the device needs heat to function, and the efficiency improves dramatically at high temperatures.

POTENTIALLY HIGH EFFICIENCY

In theory, such a technology could be applied in existing thermal solar energy systems, potentially reaching over 50 per cent total conversion efficiencies. An integrated solar energy converter of such high efficiency has the potential to achieve large economic and environmental returns. "The 2010 publication generated some interest in the energy field. It was a nice idea that we felt the need to study more deeply, and our team focused on modelling as well as materials testing," Tervo says.

So far the PETE cell is theoretical, because the characteristics of it present some engineering challenges. "The questions are how to operate such a device reliably at high temperatures, how to handle large currents efficiently and how to reduce the intrinsic losses within materials so that high efficiency can be realized," the project leader explains.

NEW MATERIALS REQUIRED

In the HEISEC project, researchers focused on modelling and designing PETE solar cells, testing and evaluating materials for such cells and evaluating the overall feasibility of a functioning PETE solar cell demonstrator. "The team carried out extensive theoretical analysis," Tervo says.

The modelling work also showed that efficient PETE solar cells are difficult to realize in practice with the currently available materials. According to Tervo, high efficiency would require materials that do not exist at the moment.

Specifically, the work function of the cathode material needs to be decreased, and the energy barrier between the materials needs to be low enough so that electrons can travel across the vacuum. The high temperature of operation is also problematic in relation to structural integrity and long-term stability of the cathode, the anode, the surface coatings and the contacts. The need for a high-temperature cathode in close proximity to a low-temperature anode is another challenge due to the required small dimensions.

"At the moment this is a dream. Before new materials have emerged, an efficient PETE cell cannot be realized," Tervo says.

FOLLOWING THE DEVELOPMENT

Hypothetical super materials would be able to reach efficiencies approaching 60 per cent.

The project researchers have been able to specify the properties of such materials, and have delivered some new ideas about structure and research devices. Silicon (Si), gallium arsenide (GaAs) and indium phosphide (InP) were investigated as cathode materials, and found to be promising.

Tervo says the materials development cycle has been estimated to take at least 10 years. However, he does not think it will be possible to reach the envisioned 50 per cent conversion efficiency in that period: "That will require more time, I am afraid."

According to Tervo, the researchers are now following the materials development closely. "If there is any hint of materials improvement, we will check our models to see if there is something that can be done." ■■

PROJECT FACTS:

PROJECT NAME: High Efficiency Integrated Solar Energy Converter (HEISEC)

PROJECT LEADER: Senior Scientist Jyrki Tervo, VTT Technical Research Centre of Finland

PERIOD: 2011–2014

FUNDING: NOK 7.2 million from NER, NOK 8.8 million total budget

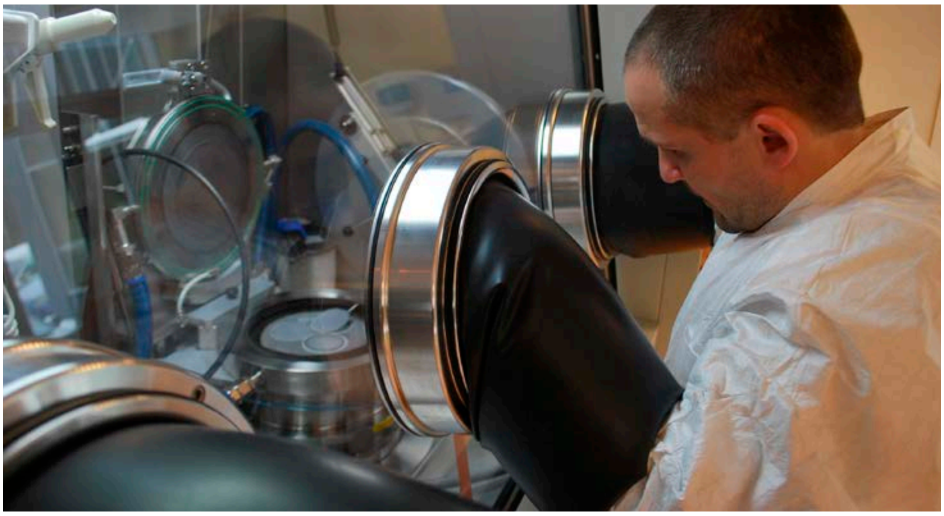
OUTPUT: 7 peer-reviewed publications, 1 non-peer-reviewed publication

PARTNERS: VTT Technical Research Centre of Finland, Technical University of Denmark, KTH Royal Institute of Technology, Vilnius University, Fortum Ltd, Picosun Ltd

Existing solar thermal power plants could theoretically become much more efficient with a PETE cell. This is the Ivanpah Solar Electric Generating System in the Mojave Desert, south-west of Las Vegas. It deploys 173,500 heliostat mirrors spread over approximately 3500 acres and focuses solar energy on boilers located on top of three solar power towers, generating steam to turn a conventional steam turbine. The project – owned by NRG Solar, Google and BrightSource Energy – is currently the largest solar thermal plant in operation in the world. The project was constructed by Bechtel. (Photo: Gilles Mingasson/Getty Images for Bechtel)

PROJECT AT A GLANCE:

Exploring how to combine photovoltaic and thermal conversion – the two most important methods of generating electricity from the sun.



Materials research was a central part of the project. This is a metalorganic vapour phase epitaxy (MOVPE) device at Vilnius University. A chemical vapour deposition method is used to produce thin films. (Photo: Vilnius University)

"Materials improvements are necessary to fabricate an efficient PETE solar cell,", Jyrki Tervo says. (Photo: Private)

STRONGrid

Controlling the grid of the future

The grid is getting smarter, enabling improved and automated solutions for monitoring and controlling power systems.

Top: Smartgrid applications can improve or take over some of the work that is done by operators today, like here in the national control centre of Statnett in Norway. (Photo: Statnett)

PROJECT FACTS:

PROJECT NAME: Smart Transmission Grid Operation and Control (STRONGrid)

PROJECT LEADER: Professor Kjetil Uhlen, Norwegian University of Science and Technology (NTNU)

PERIOD: 2011–2015

FUNDING: NOK 17.5 million from NER, NOK 24.4 million total budget

OUTPUT: 17 peer-reviewed publications, 72 non-peer-reviewed publications, 3 PhDs, Nordic Wide Area Platform, software interfaces, 13 applications for monitoring and control in different stages of development

PARTNERS: Norwegian University of Science and Technology, Aalto University, KTH Royal Institute of Technology, Technical University of Denmark, Institute of Physical Energetics, Tallin University of Technology, University of Iceland, Statnett, Fingrid, Svenska kraftnät, Landsnet, Elering

SMARTGRIDS ARE A VISION for future electric power systems. They involve digital processing and communications in the power grid. Data flow, data management and digital applications will become central to grid reliability, security and efficiency.

PHASOR MEASUREMENT

Two important enablers for the smartgrid vision are phasor measurement units (PMUs) and wide area monitoring and control systems. In the STRONGrid project, the wide area is the common Nordic synchronous power system, partly also the Baltic system. In most aspects, the Nordic power grid and electricity market is operated as an integrated system, and the interconnections to the Baltic countries are increasing.

PMUs, also called synchrophasors, are devices that measure the electrical waves on the grid using a common time source for synchronization. GPS time stamping can provide better than one microsecond accuracy of synchronization for widely dispersed locations. This extremely high resolution for wide area grid diagnostics makes PMUs one of the most important measuring devices in the future grid, recording conditions with great accuracy and offering insight into grid stability or stress.

WORLD LEADING

An increased amount of diagnostic data will not, however, make the grid smarter unless tools and applications are developed to make use of the information.

"It has been our ambition to make the Nordic countries world leading in applying synchrophasor technology," says STRONGrid project leader Kjetil Uhlen. The project has developed solutions and knowledge that put the Nordic transmission and distribution system operators in a better position to control the next-generation power system. Nordic and Baltic transmission operators have participated actively in the project.

According to Uhlen, a key message to policymakers is that new and emerging tools provide totally new system information and control possibilities. "This can radically enhance power system operation and the possibility to cope with a changing and less predictable system based on renewable energy sources," Uhlen says.

The results can also benefit the industry, especially ICT companies developing smartgrid solutions for power system monitoring and control.

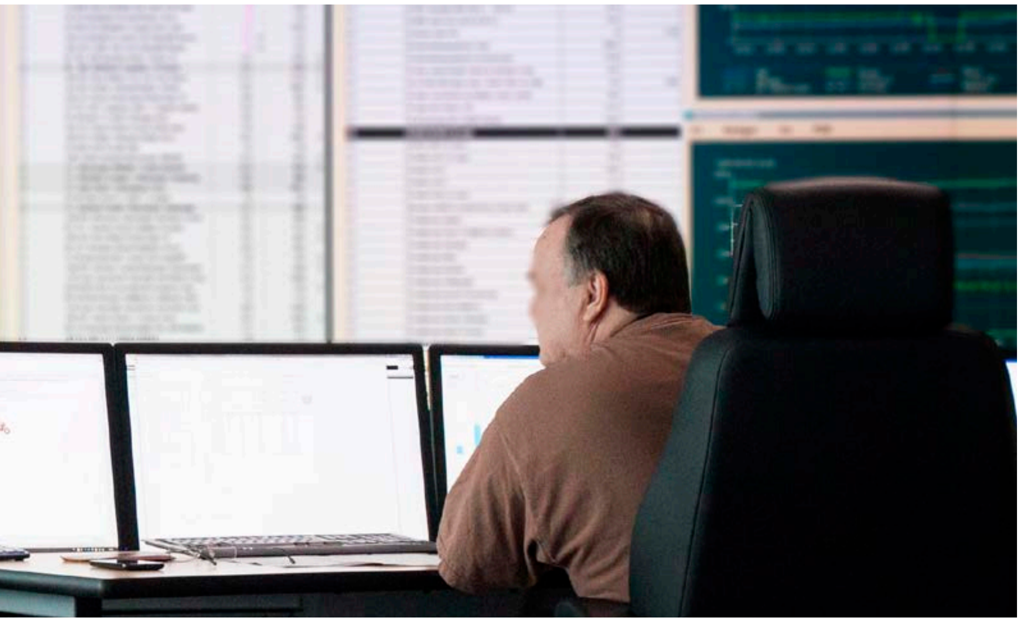
AUTOPILOT

The PMUs enable applications that could more or less autopilot the grid, as well as identify essential information for human operators. Today, operators are looking at information that is updated once every second. “One second can be a very long time in the power system. Power and voltage in our wall sockets vary 50 times a second, and the new monitoring systems update at the same frequency,” explains Uhlen.

This kind of detailed grid diagnostics will be required to operate and control a future power system characterized by more uncertainty and variability, because it enables better and faster grid control.

However, there is no way for human operators to follow all the details in such a huge information flow. That is the reason why STRONGrid project researchers have been developing applications that can identify or even handle problems. “We need the applications to help us make use of all the information from the grid,” Uhlen says.

All the universities in the project have set up PMUs in their laboratories. The PMUs stream out synchronized measurements to the other project participants, creating a Nordic university cluster with an integrated wide area research platform.



PROJECT AT A GLANCE:

Developing knowledge and solutions to improve security and efficiency in operation and control of the next-generation electric power systems.

STREAMING MEASUREMENTS

A set of software interfaces has also been developed to allow application development and implementation. This includes easy access to online measurements. “We are like the YouTube of power system research,” Uhlen says. The different laboratories are streaming measurements to each other. Applications show what is happening with the power and voltage in the different locations, and in common experiments the researchers can explore how the Nordic system is interconnected.

“We need to develop applications to make use of the digital information that can be extracted from the grid,” says Kjetil Uhlen (left). Together with the project’s PhD-candidate Dinh Tuc Duong he is holding a PMU, which can provide real-time measurements across the power system. (Photo: NTNU)

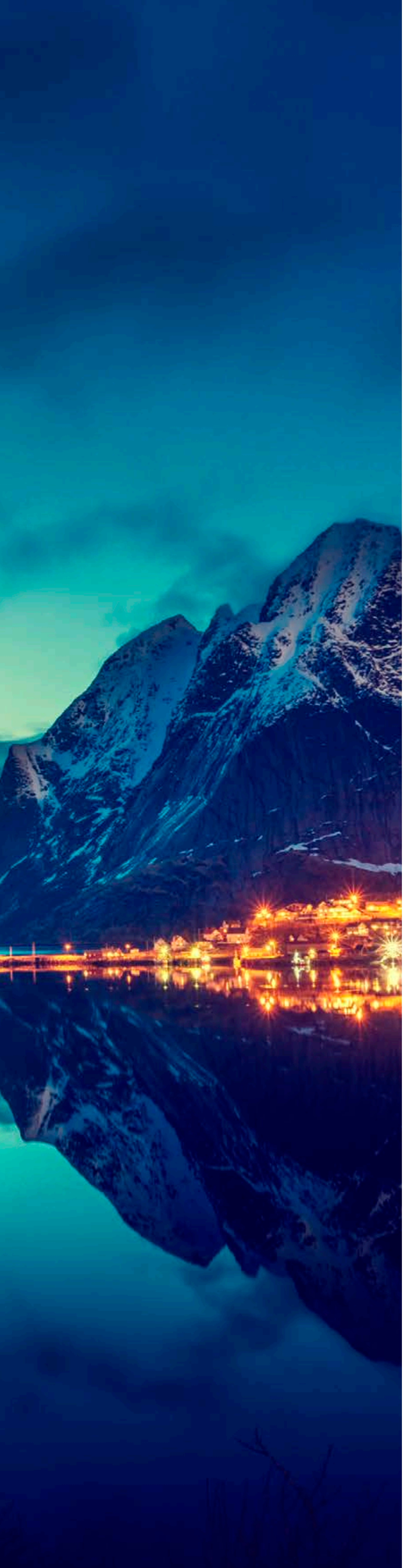
The project applications are at varying readiness levels, ranging from prototypes of indicators for power system stability monitoring to more basic research on advanced control systems.

STRONGrid project researchers have also been running models for blackout episodes, for instance a large blackout in 2003 in South Sweden and Sjælland. The purpose is to work out what could have been done to prevent collapses. “Since we can’t exactly run such tests in the real grid, we have to base much of the research on running computer models. We can’t just wait for things to happen,” Uhlen says.

LAYING THE FOUNDATION

Different strategies to provide new and fast balancing-tools by selectively cutting off electricity consumption are under discussion. Disconnecting power-intensive industry, remotely cutting off the charging of electric vehicles or disconnecting household water heaters through smart meters exemplify such possibilities, commonly referred to as demand side participation (DSP). In Norway, smart meters will be installed in all households by 2019. Monitoring and control tools, like the ones from the STRONGrid project, are laying the foundation for the deployment of DSP, and for ensuring that consumption is not cut off unless it is really necessary.

The Nordic countries have been a pioneering region when it comes to coordinating and integrating the electricity markets, and the STRONGrid project leads the way for continued frontrunner positioning in this respect. “In follow-up projects, we are already working with transmission operators to implement and test selected applications in operation centrals,” says Uhlen. ■■



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June 2016
ISBN 978-82-92874-28-8

Text: Inger Strand Karni, Karina Barnholt Klepper, Peder Söderlund and Torill Meistad at Nordic Energy Research, and freelance journalist Kristin S. Grønli
Layout and print: Framnes Tekst & Bilde AS

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