Faculty of Engineering

Research strategy 2018 – 2022

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NTNU/IV REPORT

NTNU

Faculty of Engineering

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ABSTRACT:

This report is the Research Strategy for the Faculty of Engineering (IV) at NTNU. The period covered by the plan is 2018 – 2022.

Work on the strategy has been carried out by five working groups with representatives from all the research groups at IV, other NTNU faculties, SINTEF and Norwegian business and the public sector. The work was performed during the period August 2016 to August 2017. The working groups' reports are compiled in the sub-reports B2 – B6.

The selection of strategic research areas is based on frameworks and policies for NTNU, IV's social mission and strategy, the needs of Norwegian business and the public sector as well as expected access to funding. The strategic research areas describe the initiatives given priority in IV's research. Research at IV is to form the basis for education in the bachelor's and master's degree programmes. A faculty of IV's size will therefore also have some research in areas other than those given priority in the research strategy. These are not described in this report.

Vision for the work: *Research at the Faculty of Engineering shall be internationally outstanding and one of the major competitive advantages of Norwegian business and industry*

When IV has achieved this vision in 2022, the following must be fulfilled: *Business leaders, politicians and media use the interaction between NTNU/IV and Norwegian business and government as an example of how a high-cost country can maintain its competitiveness and quality of life while helping to find answers to global challenges by investing in expertise, technology, innovation and advanced business clusters.*

In this way, IV's research will be in line with NTNU's vision Knowledge for a Better World.

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1 Introduction

The Faculty of Engineering (IV) at NTNU consists of eight departments distributed across three campuses (Trondheim, Ålesund, Gjøvik). The Faculty's field of expertise covers classical engineering disciplines such as civil, mechanical, marine, energy, geoscience and petroleum engineering. The Faculty educates bachelor's, master's and PhD graduates for business and the public sector. The Faculty has a wide-ranging research portfolio for business and the public sector.

The research strategy describes the Faculty's priority research areas during the period 2018 to 2022. The Strategy Report consists of two parts:

- Sub-report A Research strategy (this report) defines strategic research areas and research challenges, goals and strategies
- Sub-report B1 describes the project execution
- Sub-reports B2 – B6 document the basis for the working groups' contribution and their priority research areas and research challenges, as well as references to overarching political guidelines, trends, strategy documents, visions and goals that IV has taken into account in the choice of research areas.

The strategic plan is to function as decision support for the Faculty's leadership to achieve the following:

> *During the plan period, IV will concentrate its resources on fewer and larger research projects aimed at the specific needs of Norway and Europe, as well as global challenges. The research will be conducted in cooperation with the public sector and leading universities and companies, both nationally and internationally. The Faculty aims to host major national and international programmes within these areas. The research will have a greater degree of basic research; publishing and citations must be increased.*

The research is to be at an internationally outstanding level and generate new knowledge and technology.

Sustainability, innovation and green transformation will be guiding principles. Digitization is an especially important enabling technology.

After NTNU's merger with three university colleges, the IV Faculty has conducted a major reorganization, with fewer and larger departments. It is a goal to develop an excellent research culture throughout the new organization within the framework conditions that apply, in that there are two career paths for academic staff.

Important initiatives will be to:

- Create a new strategic staffing plan for top academic positions
- Establish formalized cooperation with other outstanding national and international research communities, business and the public sector
- Facilitate concrete cooperation with business and the public sector through university/business networks, professorships and strategic collaborative agreements
- Ensure funding of basic research through large programmes at the EU and the Research Council of Norway
- Give priority to internal research resources
- Invest in laboratories and infrastructure
- Draw up annual action plans for research at the IV Faculty

The starting point for the strategy is a vision that in 2025 Norway will be sustainable, competitive, and an attractive place to live, and that Norway will contribute knowledge for a better world. To fulfil this vision, five societal goals have been formulated within the Faculty's area of responsibility. The societal goals will be achieved through research in 27 strategic research areas. For each area, a set of priority research challenges has been defined, which will form the basis for the Faculty's action plans during the period.

With research as its point of departure, IV will achieve results that provide a basis for fulfilling its vision for 2025. A variety of issues are subject to political debate and extensive discussion in the media. IV must help to ensure that the public debate is based on facts from internationally recognized research.

2 Background and framework conditions

In 2011, the Faculty of Engineering Science and Technology at NTNU developed its research strategy for 2012-2020. This strategy was named Science Plan 2012-2020, and has provided policy guidelines for the Faculty's initiatives and priorities since it was adopted. In the context of NTNU's reorganization in 2016/2017, which involves the integration of new academic environments at NTNU in Gjøvik and Ålesund as well as new colleagues from the former Sør-Trøndelag University College (HiST) in a completely new Faculty of Engineering, a revision of the research strategy is an important tool for consolidating our strengths and finding a common way forward. We must acknowledge different research cultures and traditions in the different units. At the same time, our goal is to achieve harmonization and to strive for outstanding research in all parts of the organization. The research plan is a common plan to cover research needs for both bachelor's and master's degree programmes

Many of the assumptions in the previous strategy process remain relevant. We still see the same global challenges related to climate and energy, clean water and sustainable food production, and there is little change in the university's social responsibility. However, we see that developments in general and individual events during the past five years have created a need to adjust the direction in a revised strategy. Some examples of such trends and policies are available in White Papers to the Storting (Norwegian Parliament) in recent years, but other global events have also prompted policies:

- In 2013 a new White Paper on research was published, Meld. St. 18 (2012-2013) Lange linjer – kunnskap gir muligheter [Long perspectives – knowledge creates opportunities]). The main messages in this long-term plan for research concern the need for improving quality through collaboration, concentration, and distribution of work, increased internationalization, increased recognition of basic research, while simultaneously strengthening business competitiveness through innovation and research-based education. The long-term plan is to be revised during 2017, but the indications so far are that the main messages of the White Paper have been maintained over the first 4-year period and will still apply in the time ahead.

- In 2015, the Research Council of Norway conducted an evaluation of the academic communities in Norway that carry out research in technology and engineering – "Basic and long-term research within engineering science in Norway" (Teknologievalueringen 2015). The results of the evaluation show that the relevance of the research to industry is good, and must be maintained. At the same time, Norway has too little basic research. The engineering science groups were advised to concentrate their research and establish good relationships with compatible environments internationally.

- The plunge in oil prices that the world experienced in 2015 had a major impact on Norwegian industry and has prompted an increased focus on improving efficiency in the oil industry, while sharpening the focus on other sources of energy. The project BRU21[1] was launched to identify potential for improving efficiency, with the aim of reducing costs to a level where the break-even price is USD 30 per barrel. Research in areas that play a pivotal role in the Faculty's fields of expertise is necessary for achieving this ambition.

- In March 2017, the Industry White Paper was published, Meld. St. 27 (2016–2017) Industrien – grønnere, smartere og mer nyskapende (A greener, smarter and more innovative industry). It highlights the need for transformation within sustainable limits, the importance of the availability of capital and skills, and the importance of research, innovation and technological development to the survival of Norwegian industry in the future. The White Paper expresses clear guidelines for interaction between Norwegian business and the R&D sector.

- At the climate summit in Paris in 2016, the countries of the world adopted a historic climate agreement. The agreement specifies that global warming must not exceed 2° C, and that all countries are obliged to contribute.

[1] www.ntnu.edu/igp/bru21

Keywords from these White Papers are the Green Shift, Digitization and Industry 4.0. The IV Faculty must continue to focus on sustainability in its research, while focusing on renewal through industry's needs for development, and must serve as an ambassador for the development of new ways to realize the potential inherent in digitization technology.

In the autumn of 2015, the UN General Assembly adopted 17 new Sustainable Development Goals. The aim is to achieve the goals at the latest by 2030. The Sustainable Development Goals represent an integrated and coherent set of goals, and NTNU IV's research is vital to many of them. Keywords where IV has central contributions are shown in bold text:

1 End poverty
2 End hunger **and achieve food security**
3 Ensure **health** and well-being
4 Ensure equal access to education
5 Ensure gender equality
6 Ensure access **to clean water**
7 Ensure access to **sustainable energy**
8 Ensure **sustainable economic growth** and work for all
9 Resilient **infrastructure and sustainable industrialization**
10 Reduce inequalities within and among countries
11 Sustainable cities and communities
12 Sustainable consumption and production
13 Combat climate change
14 Sustainable use of the world's marine resources
15 Sustainable use of ecosystems on land
16 Promote peaceful and inclusive societies
17 Revitalize the global partnership for action

3 Trends

In February 2017, the Government presented its strategy for the ocean economy – "Ny vekst, Stolt historie" (New Growth, Proud History), and in March 2017 it presented its Industry White Paper to the Storting. The Government's Energy White Paper, Meld.St. 25 (2015-2016) Kraft til endring – Energipolitikken mot 2030 (Power for change – an energy policy towards 2030), was presented to the Storting in April 2016. These documents highlight both national and international trends and what will become important in the years ahead. The trends and developments listed below are largely from these sources, and they will provide a guidance for research at NTNU IV in the years ahead.

3.1 The Green Shift

Global warming, rising sea levels and more extreme weather conditions are factors of great importance to the food supply, critical infrastructure, accidents, etc., both here in Norway and internationally. There is widespread scientific consensus that a large proportion of the changes that we are seeing can be attributed to human activity. Limiting the increase in temperature is perhaps the most important thing we can do to counteract the negative consequences we see. The Paris Agreement[2] from the climate summit COP21 (December 2015) lays the foundation for a worldwide cooperation to limit the temperature rise to 1.5-2 degrees. This means it is important to understand the environmental footprint of the activity in a society. The development of a *circular economy* becomes important in this respect. A circular economy involves reusing resources, but also reducing the volume of waste, making better and more effective use of resources, increasing product lifetime and using more recycled materials in new products. To attract Norwegian and international players to invest in Norway, in the future it will be necessary to demonstrate that the activity is sustainable, and to use the knowledge we have from the circular economy to choose the best solutions. Both research and further development of the methodological basis are needed, but we also need to apply these methods in the development of business and the public sector.

The green shift and the mindset of the circular economy are important to achieve sustainability as it is defined by the Brundtland Commission. But the concept of sustainability goes further: it includes societal challenges, such as financial security for the individual. Research that contributes to the green shift involves many of IV's disciplines, and will need to be given high priority in the years ahead. Effective logistics is a key factor in work towards the green shift. IV's research includes many aspects of the logistics concept and works with improvement of cost and energy efficiency in both land and sea transport, including vehicles, vessels and infrastructure. Production logistics with modern manufacturing methods and control systems, choice of materials and design are another aspect of IV's activities. These elements are explored in greater depth in this strategy.

The transport sector has particular challenges under the climate agreement, because it accounts for almost a third of emissions that are not subject to emission allowances in Norway. From 2025, only zero-emission passenger cars will be sold in Norway, and from 2030 the remaining road traffic will also be zero-emission or low-emission vehicles. New climate-friendly construction materials are needed, and life cycle analyses must be performed to ensure a correct understanding of climate impacts.

3.2 Digitization and automation

For a long time, information and communications technology (ICT) has been regarded as an enabling technology. In recent years, we have seen a change from looking at ICT only as an enabling technology to the change processes in the work methods that the technology enables, that is, digitization. In the area of production, we are now seeing a development in which digitization provides better potential for real-time production control and value chains using sensor technology, the Internet of Things (IoT), cyber-physical systems and calculation algorithms for big data. In Germany, such opportunities are being launched under the concept of "Industry 4.0". In Norway, we also need similar initiatives to realize the potential that digitization offers.

[2] http://unfccc.int/paris_agreement/items/9485.php

Automation where manual work tasks are replaced by work tasks carried out by industrial robots is not new, but now appears to be increasing exponentially. The level of automation in Sweden is twice as high as in Norway. This may partly be due to a different type of industrial production, but it is clear that increased automation will become important in Norway in the future. Experience shows that companies that have succeeded in bringing production back to Norway from low-cost countries achieved this because they were successful in digitization and automation. Increasing activity in mainland industry will become important at a time when activity in the oil and gas industry has been reduced. Success in digitization and automation is therefore vital.

Today, Norway has a well-developed digital infrastructure and a population with relatively high ICT skills, which gives us promising opportunities in this area. On the other hand, we see that the education system has not given us engineers with sufficient programming skills, which will be critical for developing digital solutions. We therefore see that many companies outsource ICT tasks to countries such as India where good skills are available at a low cost. Recently, several events have shown that this strategy is highly vulnerable, and it will become important to strengthen ICT skills in Norway and to use Norwegian resources in digitization processes.

Experience from many countries shows that large numbers of ICT students specialize in areas such as artificial intelligence and machine learning because companies such as Google and Facebook offer extremely attractive conditions for students with this background. This is a challenge because other areas within digitization are experiencing shortages of skills. On the other hand, it is important to increase skills in artificial intelligence and machine learning, because these skills are important in many areas such as production management, maintenance, and autonomous vessels.

Digitization and automation are important for virtually all physical processes, autonomous vessels, transport solutions, etc. where NTNU IV participates in research. In addition to the more physical processes, digitization is essential for efficient work processes. For example, we are seeing dramatic developments in the construction process[3] where it is easier to coordinate digital building information and exploit it in all phases of construction – the data models follow the project from cradle to grave. Correspondingly, digitization of coordination processes with government agencies will become important.

3.3 Energy

The need for energy is increasing worldwide due to the growing population and improved standards of living. We also know that the current global energy mix with 80% fossil energy leads to large emissions of CO_2 and other greenhouse gases that are not consistent with the goal to limit global warming. Therefore, it is necessary to change the energy sources we use, how we distribute energy, and how we use energy services. Important questions are therefore how and how quickly we can change our energy system, that is, realize the green shift at an acceptable cost and in a way that ensures adequate security of the energy supply. We need a coherent and step-by-step development of the energy system, preferably choosing solutions with low or no greenhouse gas emissions. Reducing energy consumption through improved efficiency will be extremely important. This development demands long-term and interdisciplinary research with skills development and technological development. Today's consumption of oil and natural gas and the increase ahead that has been forecast are not consistent with the Paris Agreement, and a limitation of climate change to 1.5-2 °C. Until we have "zero-emission technology" in place, oil and gas will be important energy carriers in an energy mix in which the top global priority is to reduce coal use. Research-based technological development for reducing greenhouse gas emissions will become more important than ever.

Norwegian energy production and consumption are unusual compared with most other countries. In 2015, electricity production in mainland Norway was 144[4] TWh (95.8% hydropower, 2.5% gas power and 1.7% wind power); that is, 97.5% from renewable energy sources. The renewable share of Norwegian energy consumption is in a class of its own, the highest in Europe. This has given and continues to give mainland Norway abundant access to "environmentally sound" power, which is used in energy-intensive industry where the environmental accounts for production in Norway give us very promising opportunities. Increased

[3] BIM = Building Information Modelling
[4] https://www.ssb.no/energi-og-industri/statistikker/elektrisitet/aar

production of renewable energy is important, while reducing environmental problems linked to necessary interventions in the natural landscape to a minimum.

The reduction in oil prices has led to great challenges in the supply industry in the maritime sector. This has forced the supplier industry to adapt both in terms of competition and with the aim of using its expertise to reach other markets, such as renewable energy. Research at NTNU IV must contribute to this adaptation.

3.4 The oceans

The OECD estimates that ocean-based industries can double their contribution to the global economy by 2030. At the same time, the oceans are under pressure due to climate change, overfishing and pollution. A prerequisite for future growth in the ocean economy is that we are able to harvest the resources and exploit the oceans in a sustainable way. Today, Norway is a world leader in the oceans, and this offers us promising opportunities. We have good fishery resources and a strong aquaculture industry, a long coastline that represents an effective transport route, a supplier industry based on maritime, oil and gas activities that we see are adaptable to entering other maritime areas and we have a strong shipbuilding industry that delivers solutions to the ocean economy.

In the area of energy, oil and gas will still be important energy carriers in a sustainable energy mix, but the oceans will also be a source of renewable energy in tacking climate challenges. In particular, offshore wind power (fixed and floating installations) is promising.

Sustainable exploitation of minerals represents a major challenge, in terms of both the scarcity of resources and the way we can extract them. Expectations for extracting minerals from the seabed are high and so-called "Blue Mining" is regarded as having great potential.

3.5 Globalization

As a maritime nation, Norway has benefited from international collaboration and trade. Globalization means that more and more players interact across national boundaries. This provides attractive opportunities for increased exports of products and services as well as opportunities for importing products and services that we need ourselves. The result is an interweaving of the value chains across national boundaries that also gives Norway potential to interact with many players to optimize the value chains for the products we want to sell. Effective organization of value chains is becoming an important business area and field of knowledge in itself.

Participating in a global network also demands a conscious attitude to fundamental values that cannot be "priced" in economic models. These may be related to child labour, health, safety and environmental (HSE) challenges in other countries, environmental standards, unnecessary transport, etc. Internationally agreed regulations, environmental requirements etc. are essential for sustainable global operations.

Often, globalization means larger units and multinational companies as well. We see that Norwegian companies are acquired by foreign companies or merge. This may be both positive and negative for research. On the one hand, it may be difficult to convince large multinational companies to fund research in Norway. On the other hand, we end up with larger units that have more muscle to contribute with research funds here at home.

3.6 Societal challenges

Economic, environmental and social sustainability represents global challenges that NTNU must address. "Societal challenges have a prominent role in EU H2020 and in the discussions for the next Framework Programme. Social sustainability is also an important part of the UN's 17 Sustainable Development Goals. Engineers from NTNU will be an important resource for building the society of the future. In areas such as infrastructure and industry, IV should be a leading partner in research to help to solve the societal challenges in Norway and Europe.

In Norway, changes in demographics with the grey wave and the employment situation will bring challenges for the Norwegian welfare state. There is a clear desire for better integration of people with disabilities in working life, and for elderly people to continue working for more years and to live independently in their own homes for a longer period. New technological solutions and universal design of tomorrow's buildings, infrastructure and workspaces will enable increased participation of all in working life and in society.

Digitization and automation will cause manual work tasks to disappear at an increasing rate, and will lead to changed work content in sectors such as health, transport, construction and industrial companies. At the same time, new ICT solutions and modern equipment provide extended possibilities for learning and human-oriented industrial processes. This requires research on how industry develops its knowledge base, where concepts such as "learning factories" should be developed further together with ICT-based solutions for lifelong learning.

3.7 Changes in the Norwegian supply industry

Norway has a strong industrial structure with global competitiveness in several areas. We are world-leading in production related to maritime operations such as vessels, ship equipment, oil rigs, subsea equipment, equipment for the aquaculture industry, etc. This industry is characterized by one-of-a-kind manufacturing. Increasing pressure on prices and lower margins in this sector due to lower oil prices have recently forced parts of the industry to change and to think in new ways. In addition, parts of Norwegian industry such as the wood-based construction industry have mainly focused on the Norwegian market without international competition. These businesses, too, will need to think in new ways in the future.

Norway has world-leading industrial environments that deliver products to globally demanding markets with an export ratio of almost 100%, such as the defence industry, the automotive industry, aviation and aerospace. These industries are characterized to a greater extent by mass production with extremely high demands for productivity. This sector is also undergoing a transition. New demands for more customized products demand changes in production methods and processes in the direction of mass-produced customization. Enabling technology and advanced production methods such as additive manufacturing, flexible automation using sensor technology, computer vision and artificial intelligence for adaptive control contribute to this. IV must be a leading partner to ensure sustainability and continued competitiveness for Norwegian industry.

4 Overarching objectives for research at IV

NTNU's vision is

> "*Knowledge for a better world. NTNU – internationally outstanding*".

The IV Faculty must help NTNU to fulfil its visions and plans through implementation of a targeted strategy for research within the Faculty's areas of expertise.

IV's mission is, through education, research and dissemination, to foster graduates and technological solutions that benefit the community. The IV Faculty must contribute to tackling global challenges, such as adequate and clean energy, climate/environment, food, water and mineral resources, based on national prerequisites and research infrastructure. Through this, it must establish a basis for competitive operations in Norway. Our role is to develop technology for sustainability and innovation. By focusing on solutions that respond to global challenges, we contribute to positive social development while creating new commercial opportunities for our partners nationally and internationally.

The IV Faculty must be an outstanding faculty by international standards. To achieve this, several main objectives and accompanying choices of direction have been established.

- Create an attractive and competitive offering of study programmes for a national and international market. This will be achieved through a focus on high quality and relevance in our study programmes, by establishing alliances with universities with internationally high rankings and users in business and the public sector. We will give priority to research-based education using laboratories as key elements and will at the same time commit resources to innovative new forms of education.

- Recruit the best students and staff. Students and doctoral students will be recruited through study programmes and research of high quality as well as through a job market that demands engineers with master's competence and graduates with PhD skills. There is a need to increase awareness of PhD skills in business and the public sector. Employees will be recruited through an attractive research community and infrastructure as well as competitive working conditions – increasingly from internationally leading academic environments. An attractive student environment is regarded as essential for recruitment of the best students.

- Develop research groups at a high international level, where several achieve top international ranking. This will be achieved through research strategy, strategic staffing plans, forward-looking programmes of study, setting priorities for resources, continued commitment to publishing, as well as international collaboration with universities and business. It is vital that NTNU's main profile in science and technology is used in extended and strengthened cooperation with business and the public sector. NTNU's distinctive interdisciplinary character must be developed further as a competitive advantage. Research in engineering disciplines requires first-class research infrastructure and access to outstanding doctoral students.

- Establish a resilient and productive organization characterized by participation, co-determination and a good work environment. This will be achieved through good human resources policy, motivation and leadership as well as communication of our fundamental values.

- Build and maintain an appropriate and good infrastructure for education and research at NTNU's new campus. IV's academic activities, including laboratory use, are well taken care of in NTNUs campus project. IV will work towards realization of the laboratory committee's recommendations through the campus project.

- Within the marine and maritime area, we will help to realize the development of the Ocean Space Centre. As part of this, NTNU will continue to commit resources to development of the sea as a laboratory, where NTNU AMOS (the Centre for Autonomous Marine Operations and Systems) has been a driving force. This includes the Applied Underwater Robotics Laboratory (AUR Lab), the Gunnerus research vessel, the Unmanned Aerial Vehicles Laboratory (UAV Lab), the underwater centre at Trondhjem Biological Station (TBS), small-scale satellites, the Trondheimsfjord as a laboratory of unmanned systems and autonomous vessels. Collaboration with be launched with

NTNU Ålesund in the development of the southern Sunnmøre district in western Norway as a laboratory for digital ocean space.

- Have a good innovation culture**.** This will be achieved through continued commitment to development of new ideas for commercialization and close cooperation with Norwegian business and the public sector. The extent of innovation activity must be showcased better. An innovation mindset must also be in focus with regard to students, and must be integrated to a greater extent in selected technology courses in the programme for the Master of Science in Engineering (*sivilingeniør*).
- Strengthen and help to realize NTNU's strategic research areas. IV must contribute to realizing NTNU's four strategic research areas, the TSOs (Oceans, Energy, Sustainability and Health) and ensure that they contribute to new national and international interdisciplinary activity at IV.
- Proactive countercyclical measures. Norway faces a significant transition in business and the public sector in that the activity level in the oil and gas sector has fallen. This will have ripple effects for a variety of industries and is likely to affect student recruitment and access to research funds. IV must respond to this with countermeasures that stimulate restructuring so that we can continue to recruit good students and maintain close cooperation with business and the public sector. The merger with the university colleges creates new potential for this, but IV must also take advantage of its strong finances to fund countercyclical measures. The commitment to PhDs as well as to continuing and further education (EVU) is an example of measures for this. In addition, communication directed at young people and the working world is important to showcase the positive aspects of technological research and education.

5 Overarching strategies for research at IV

IV's research builds on fundamental disciplinary knowledge (mechanics, thermodynamics, materials science, etc.) used in multidisciplinary constellations. Disciplinary knowledge provides resilience to changes in research areas that result from framework conditions and development of enabling technologies. The interdisciplinary constellations will vary according to the changes in the research areas. An important part of the strategy is that research, education and innovation must be closely linked.

In its areas of expertise, IV will conduct research at a high international level. The research will partly be of a basic nature, and partly applied and industry-oriented.

5.1 Basic and applied research

IV is characterized by a high volume of research with a clear focus on applied research. The Faculty has a tradition and a culture of working in close partnership with business and industry, with research questions of a typical applied nature. There is a prevailing view that IV fulfils its social mission in a good way by working in close collaboration with business and industry and government administration.

The funding system for research in Norway is largely based on applied and/or thematic programmes. Most of the Research Council of Norway's programmes also require co-financing from business and industry. This results in a preference for applied research. For IV it is important to participate in such projects to ensure that our research has sufficient industrial relevance.

At the same time, IV has a great need for free research funding to build long-term and general expertise. The most important resource for this is the research time of the academic staff, but there are also opportunities through the Research Council of Norway's scheme for free projects (FRIPRO). The EU also has research programmes of a similar nature. Examples are FET (Future and Emerging Technologies) and ERC (European Research Council). All these programmes have stringent requirements for quality and boldness in their research (groundbreaking research). The grant rate is low, and IV currently has only one ERC project and only a few FRIPRO projects. In this respect, it is far behind environments such as the science environment at the University of Oslo.

An important source of funding of more basic research is the Research Council of Norway's scheme with centres such as Centres of Excellence (SFF), Centres for Research-based Innovation (SFI) and Centres for Environment-friendly Energy Research (FME). IV has experienced success with SFI and FME, but less so with SFF. The Faculty will continue to give priority to such centres and will give talented researchers opportunities to develop their CV so that they can position themselves for future calls for proposals.

The evaluation of technology disciplines that the Research Council of Norway conducted in 2015 concluded that a sharper focus was needed on publishing, strategic planning of research, mobility, innovation and basic research. For IV, there must be a stronger commitment to basic research of high quality. The Faculty's strategy is to achieve a higher proportion of basic research with funding primarily from the Research Council of Norway (free projects and centres) and the EU (ERC) as well as with support from the Faculty's own strategy and restructuring funds. This implies cultivating potential applicants, and development of skill in writing applications at this level. Applicants should be given increased research time and other support for their development.

5.2 Enabling technologies

We are seeing constant development of technologies that can enable major leaps and transformations within all areas – "enabling technologies". IV does not primarily work with research and development of enabling technologies, but must be outstanding in applications.

The need for change in Norwegian business and the public sector requires the technology disciplines to base innovations on applications of the enabling technologies to a greater extent. This is also consistent with the Government's view expressed in Report to the Storting (Stortingsmelding) 27 for 2016 – 2017 (the Industry White Paper), which emphasizes:

- Advanced materials
- Micro- and nanoelectronics
- Nanotechnology
- Phototonics
- Industrial biotechnology
- Information and communications technology

It is especially important for IV to follow up technology trends such as digitization, automation and advanced materials technology.

The IV Faculty must seek cooperation with other faculties within disciplines where this is natural. IV will typically focus on application and issues in engineering and challenges where there is an overlap with other faculties

5.3 Interdisciplinary research

Interdisciplinary organization of research is becoming increasingly important. Many of the major challenges require interdisciplinary research teams. The organization of Norwegian and European research is increasingly in the direction of larger initiatives (such as FME, SFI) and/or interdisciplinary programmes. Professors and researchers are expected to participate in and contribute to multidisciplinary initiatives outside their own research group. Development of a culture of arenas and forms of work in which multidisciplinary cooperation can be developed is also expected.

In implementation and application of new technology, humans are always the most important factor. There is unrealized potential here for stronger involvement of the behavioural and social sciences.

A prerequisite for interdisciplinary research is that leading-edge expertise within the various subject areas be included. The IV Faculty has a strong focus on outstanding research (leading-edge expertise). This must be reconciled with the ability to see issues from a broader perspective and to launch cooperation with complementary environments both within and outside the IV Faculty. The Faculty will use suitable incentive schemes to promote interdisciplinarity.

NTNU's strategic areas of focus (TSOs) are an important instrument for stimulating interdisciplinary research. The aim is that the TSOs will contribute to coordination between different NTNU environments and encourage initiatives to increase the scope of research activities and to achieve more interdisciplinary research. IV will develop effective cooperation with the four TSOs and will allocate resources to interdisciplinary initiatives.

5.4 Research infrastructure

Much of IV's research is experimentally based and therefore requires access to laboratories and other advanced research infrastructure. First-class laboratories that enable laboratory-based research and teaching have been and will continue to be an important goal of the research strategy. The laboratories are vital for understanding physics in a variety of processes and for quality assurance of the results from ever more advanced models and simulation programmes. The laboratories are a strong competitive advantage for IV, both for recruiting students and academic staff, and for establishment of new research activity.

The laboratories must have:

- Skilled lab technicians
- Modern instruments and measuring equipment
- Good infrastructure (gas supply, compressed air, cooling systems, suction, clean air, etc.)
- Effective operations
- Customized capacity and good use of resources
- High HSE standards

IV will organize its laboratories in five large units in Trondheim as well as one unit in both Ålesund and Gjøvik:

1. Laboratory in energy and process engineering
2. Laboratory in geology, engineering geology and petroleum
3. Laboratory in marine technology
4. Laboratory in infrastructure, construction, water and the environment
5. Laboratory in structures, materials and production
6. Laboratory in manufacturing and civil engineering in Gjøvik
7. Laboratory in maritime technology and civil engineering and infrastructure in Ålesund

It is important to coordinate and achieve effective exploitation of laboratory and workshop resources at NTNU. Organization in large units will improve the use of resources and make it easier to achieve development based on strategy.

One goal is to take part in national and international collaboration on the development and use of research infrastructures, in line with the intention behind ESFRI.

Computing resources are another form of infrastructure important for research. More and more disciplines see numerical methods as both cost-effective and innovative tools for their research. Results from experimental activity are often combined in laboratories with numeric analyses. IV's strategy is to contribute to access to the use of the supercomputing centre at NTNU and other national resources. In addition, IV will coordinate interested departments for procurement and involve NTNU IT in the operation of local computing resources to the extent needed by the academic environments and the departments.

IV wants to be an active partner in industrial research and innovation, and wants to participate in future catapult centres[5] and other industrial technology centres for pilot production and testing of new innovations.

5.5 Innovation

A goal for research at IV is that it leads to new innovations, in the form of new products, processes or new services. Research-based innovations must be patented to protect the innovations before they are published. It is very important to handle intellectual property rights at NTNU professionally. Later, research results can be published in the usual way. Innovations must be reported to the NTNU Technology Transfer Office (TTO), which will provide professional help to protect the ideas and innovations. These can in turn be developed into licences and technology sales to existing companies or may lead to a new start-up; NTNU TTO makes such decisions in cooperation with the academic environments (department management and specialists).

We are the world's happiest, we live in the most developed country and have the highest national income per capita. This is the positive way in which international statisticians depict Norway. One of the reasons for this is that we have considerable natural resources and we have managed them well. In 1970, our national per capita income was almost 40% lower than for the United States. Now it is 10% higher, and we have passed Switzerland, mainly due to the oil and gas industry. Roughly estimated, oil and gas accounts for 15% of real income, but gradually this sector will need to make up a smaller part of our economy. Markets and the environment are both drivers for such a development.

Perspektivmeldingen (Report. St. 29 (2016–2017) indicates these issues. If, as our point of departure, we consider that the oil and gas component of real income will initially decrease by 5-10%, we must fill this gap with other activities. This is not a gap to be filled with money, but a space to be filled with activities, either in the form of new enterprises or restructuring of existing ones. Most of this must take place within industries in which there is no resource rent based on natural resources. As an open economy, we must therefore compete in an international market on the same terms as others.

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[5] https://siva.no/wp-content/uploads/2015/03/norsk-katapult-forslag-til-program.pdf

If Norwegian business and industry are to be restructured in line with this, we must invest heavily in renewed growth in productivity. The most important driver for such growth is new knowledge and technology. Here, NTNU, and the IV Faculty in particular, must play a key role both through research and through education. In this respect, one contribution is to allow parts of the teaching to have an integrated innovation approach. Based on research-based teaching and special courses, this is even easier because it can be linked directly to the development within the course/discipline.

Innovation and entrepreneurial thinking should be developed and integrated in all bachelor's, master's and PhD programmes.

5.6 The professor who conducts research

NTNU has decided that there should be two career paths for academic positions – the "docent track" and the "professor track".

For the professor track, the policy in effect is that tenured staff (professor, associate professor) must as a norm spend 40% of their time on education, 40% on research and 20% on activities related to change, development and administration. For the docent track, the proportion of research is lower.

For new positions, the Faculty must make a strategic assessment of whether the position is to follow the professor track or the docent track. This must be specified in the Faculty's strategic staffing plan.

Expectations related to the scope and quality of research for a professor/associate professor should be described. At the same time, it is important for a university environment to look at institutional expectations for results as guidelines, and that significant differences between different professors are acceptable – for a number of good reasons, such as the potential for funding. There is not necessarily a correlation between the scope of research, academic quality, academic advancement, and contribution to society in general. However, it must be a goal that everyone in an academic post strives to become internationally outstanding. Leading researchers must have a profile as actors in society in their discipline.

There are differences in talent and motivation for achieving an international top level, and this cannot be expected of everyone. It is natural that only a few professors reach this level, and there is a cultural acceptance that some have better opportunities to make a commitment to research than most others.

A professor/associate professor should aim to have a group of bachelor's, master's and PhD candidates, postdocs and researchers. Such a group might also include cooperation with people from other units at NTNU and SINTEF.

A good professor is expected to emphasize interaction with others for multidisciplinary initiatives that can solve important problems and attract increased funding and increased activity (research positions and infrastructure) that lead to action and dynamism in relation to the challenges we face.

5.7 Gender equality

IV aims to achieve a general gender balance in its research activities. A general challenge is that the proportion of women decreases at higher levels in the hierarchy. The proportion of women in the study programmes of at IV has developed in a positive direction, and is now just under 30%. The proportion of women among PhD candidates is about 26%, while it is 24% for associate professors and 7% for professors. This requires special measures and adaptation to encourage more women to apply for PhD candidate positions as well as for professorships.

5.8 Research-based teaching

Research-based teaching takes place when academic staff teach within their field of research or associated disciplines, and when their skills, experience and insight as researchers have an impact on their teaching. Research-based teaching may involve communicating established knowledge, recognized new knowledge, or research results that have just become known. The concepts also include supervision within the employee's area of expertise. Students have the opportunity to develop attitudes and abilities related to scientific dialogue, critical thinking, the ability to formulate problems, and the ability to solve problems.

IV's strategy is that the study programmes must be research-based, and that students' learning outcomes include both an understanding of research and experience from research activities. The research strategy must lay a future foundation so that the courses that IV teaches are based on state-of-the-art research, and that most of the teaching is provided by active researchers. As part of their studies, students must be more actively involved in research.

5.9 Internationalization

NTNU has some 350 agreements with international universities. Most of these have the aim of facilitating student exchange. NTNU works together with four Nordic technical universities through a number of master's degree programmes; one of them is in energy, which is led by NTNU.

International collaboration takes place in many different ways – pure student exchange, often with contact between professors in the same disciplines; co-supervision of master's or PhD candidates for one or more students and many other ways, governed by the individual employee. When there is an opportunity to enter into collaboration with greater commitments that include finance, a suitable solution will often be sandwich agreements, in which each university finances its own students, with joint supervision and joint publication in journals and at conferences.

IV must participate actively in the international research arena through the following:

- Active participation in international research collaboration, such as in the EU's framework programmes
- Research results must be published in international journals with peer review")
- Research results must be presented at conferences and other professional meetings
- Exchange of researchers (sabbaticals, PhD exchange)
- Effective utilization and coordination of research infrastructure
- Participation in networking bodies, such as EERA

The research results must be published openly and to some extent communicated to the public, through participation in debates, features or op-ed articles and other contributions, blogs, active dialogue with journalists and use of social media.

IV focuses on the ability to be internationally outstanding. This requires the academic staff to become involved in the international arena through publishing, research collaboration, student exchange, etc. Mobility for the individual researcher is important and IV will actively use the sabbatical scheme to achieve this.

6 IV's research map

Work on developing the Faculty's research strategy is based on the Faculty's vision for its research:

> *Research at the Faculty of Engineering shall be internationally outstanding and one of the major competitive advantages of Norwegian business and industry*

This vision imposes requirements both for the content of the research and how the research is organized and funded. The content is strongly influenced by the guiding principles expressed in key national and international policy documents and priorities, and the vision for the strategy has thus been developed in line with the societal challenges we face where the IV Faculty's academic environments can help to make a difference.

During the time frame of the plan, 2018 – 2022, the overarching research goal for IV is:

> ***Ensuring Norway's sustainability as a well-developed, competitive society with good living conditions. Through this, IV will contribute knowledge for a better world.***

This main goal will be reached through research linked with five specific societal goals adapted to the potential and needs of Norway and the IV Faculty,

- Sustainable and reliable energy
- Green shift in the built environment
- Competitive and sustainable manufacturing
- Sustainable exploitation of mineral resources
- World-leading in the oceans and the High North.

For each of the five societal goals, strategic research areas and research challenges are described where the Faculty's researchers must set priorities for their efforts. The research groups develop their strategies and build their project portfolio with issues related to the research challenges. Figure 1 illustrates the hierarchy of societal goals with designated research areas and research challenges

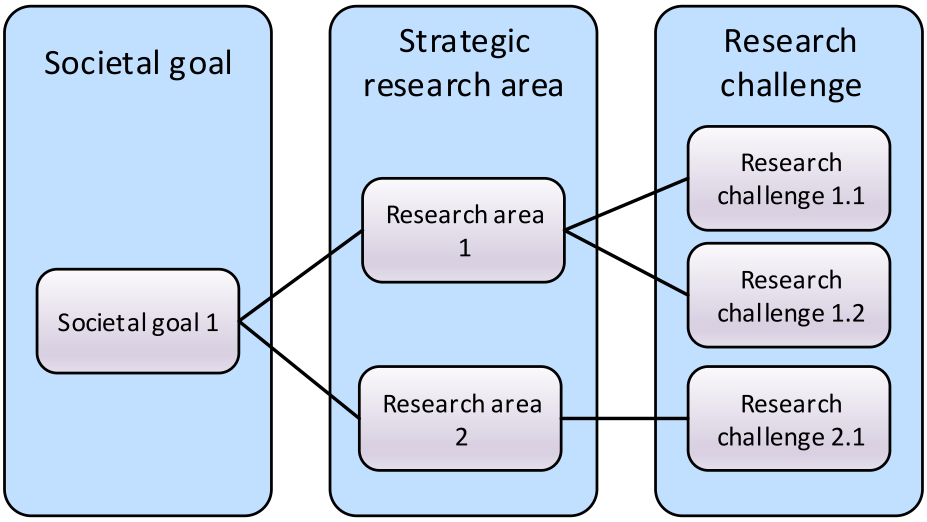

Figure 1 The relationship between societal goals, strategic research areas and research challenges.

Figure 2 shows the research map. It illustrates the IV Faculty research strategy from an overall perspective. The starting point for the map is the Vision for Norway that Norway will be sustainable, competitive, and an attractive place to live, and that Norway will contribute knowledge for a better world.

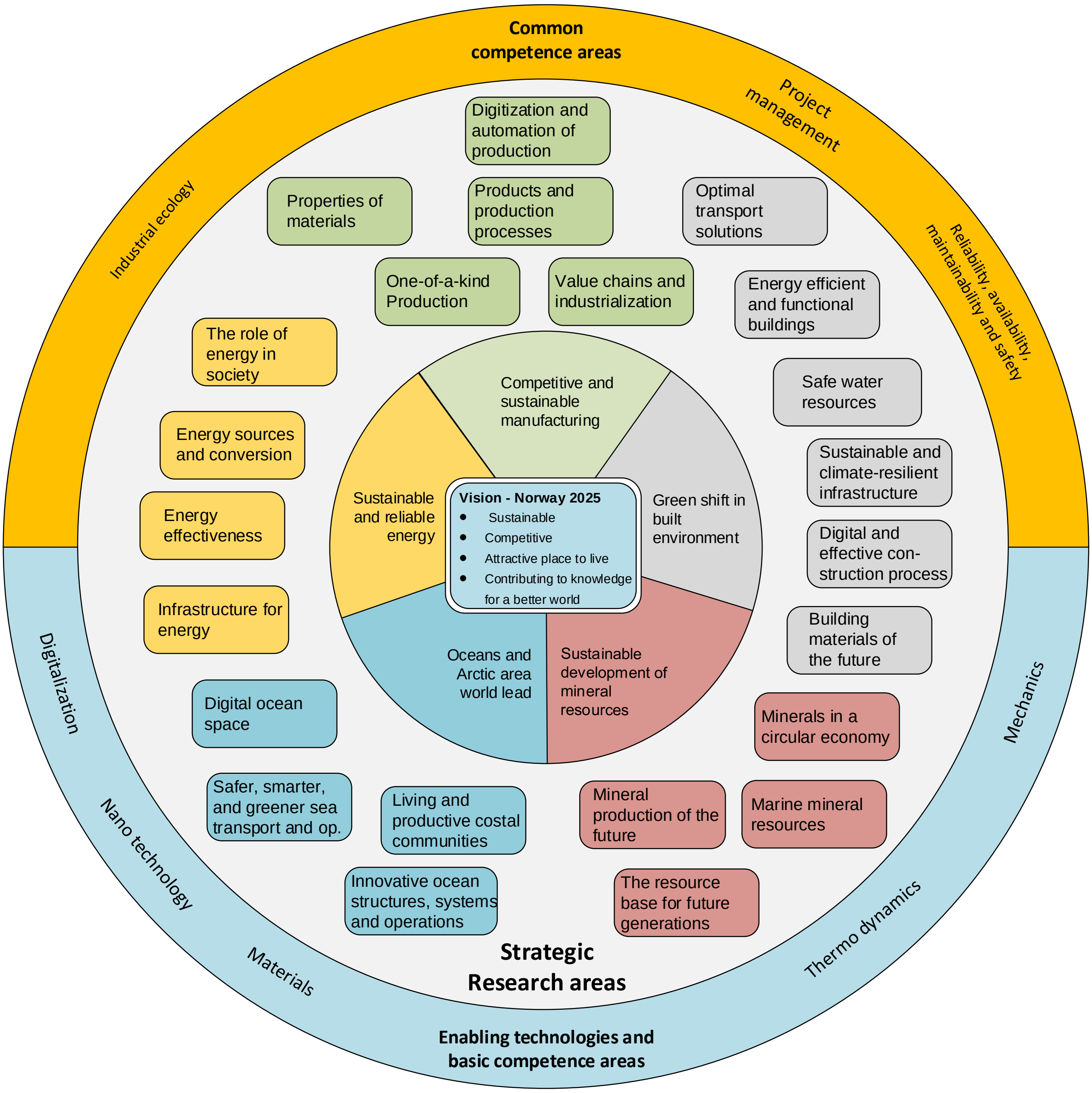

Figure 2 Research map for the IV Faculty.

Based on this vision, five societal goals have been defined with associated strategic research areas on which research activities must be focused to achieve the goals. Each strategic research area is described in more detail in the supporting reports B2 – B6 for each societal goal.

The research map also shows relevant enabling technologies, underlying subjects and common areas of competence that are relevant in solving the priority research challenges within the various strategic research areas. These are subject areas that are important for the IV Faculty, but where the underlying research lies within another faculty's area of responsibility. Figure 3 shows how the research takes place in research groups and is directed at the research challenges that have been identified and given priority.

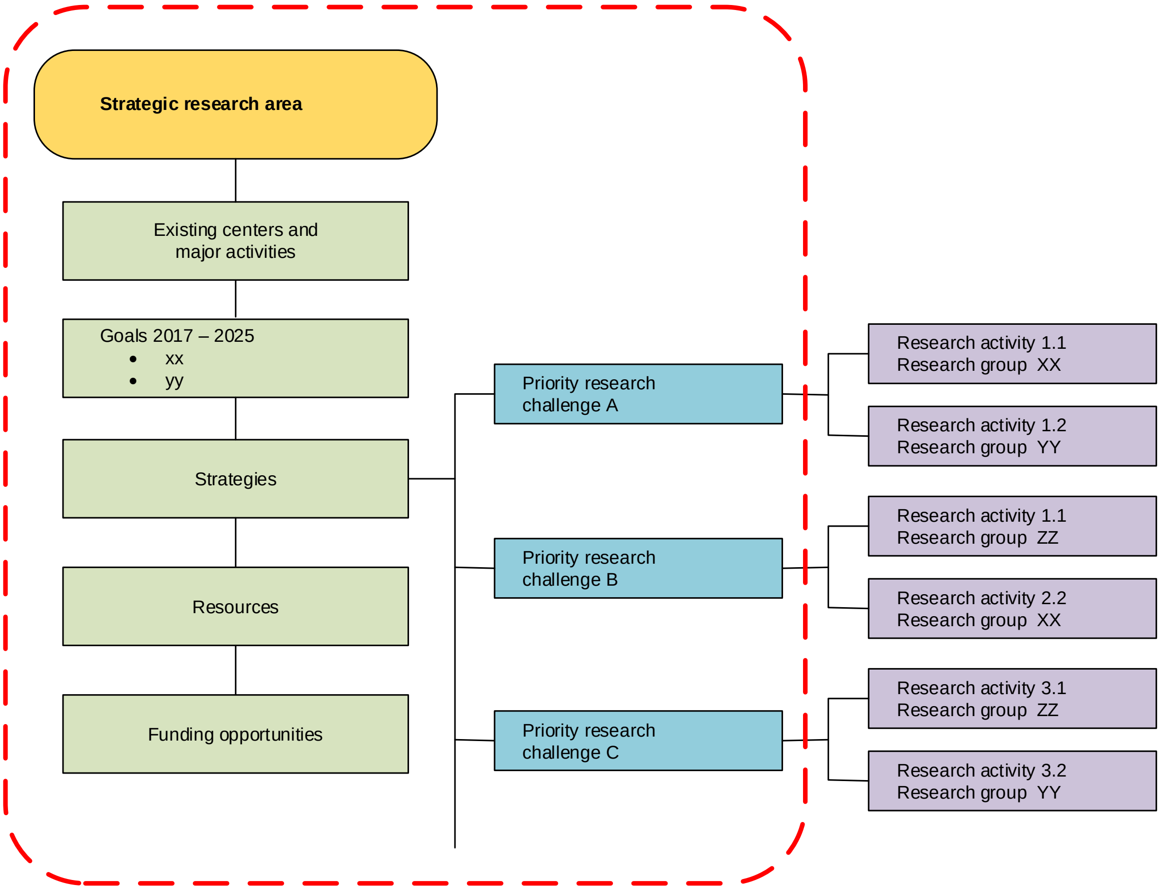

Figure 3 Strategic research areas and the interface with research groups.

7 IV's strategic research areas

The five societal goals and strategic research areas are briefly described below, focusing on the societal and environmental challenges they address and the typical issues seen in efforts to tackle these challenges. The same societal goals are described in more detail in the supporting reports in part B2-B6, which describe the status, goals, strategies, research challenges and professional ambitions related to each goal. Table 1 lists the research areas for each societal goal.

Table 1 Societal goals and associated selected research areas.

Societal goals	Strategic research areas
Sustainable and reliable energy	The role of energy in society Energy sources and conversion Infrastructure for energy Energy efficiency
Green shift in the built environment	Sustainable and climate-resilient infrastructure Optimal transport solutions Digital and effective construction processes Energy-efficient and functional buildings Safe water resources Building materials of the future
Sustainable exploitation of mineral resources	The resource base for future generations Mineral production of the future Minerals in a circular economy Marine mineral resources
Competitive and sustainable manufacturing	Products and production processes Properties of materials Digitization and automation of production Value chains and industrialization One-of-a-kind production
Oceans and Artic area world lead	Digital ocean space Safer, smarter and greener maritime transport and operations Living and productive coastal communities Innovative ocean structures, systems and operations

7.1 Sustainable and reliable energy (Energy)

Sustainable implies that environmental and climate impacts are understood and handled along the entire energy chain.

Sustainable also implies that energy use contributes to sustainable development of society, that is, contributes to fundamental human needs such as food, health, housing, clothes, security, work, recreation and communication. This must be seen from the perspective of a world population of 7.5 billion at present, which is likely to increase to 9 billion in 2040 and 10 billion in 2060.

Reliable energy involves delivery reliability: energy must reach the end user at the right time and in the right quantity. Reliable also involves the balance between consumption, production and capacity of storage of energy. At the same time, the risk of accidents must be reduced and the extent of any accidents must be limited.

NTNU has a national responsibility for research and education in the energy sector, by virtue of its size, good laboratories, good students, close cooperation with and trust in business and the public sector, strong cooperation with SINTEF, and a staff of experts who are outstanding in their fields.

NTNU IV's contribution to the societal goals, based on Section 1-3 of the Act relating to Universities and University Colleges, is research that results in new knowledge, which in turn provides a foundation for:

- Relevant and top-level international education of bachelor's, master's and PhD candidates
- New technological solutions and a transformation of the way energy is used, to deal with the great challenges related to anthropogenic climate change
- Increased value creation in the business sector based on national energy resources
- Development of internationally competitive business and industry
- Dissemination and outreach in various forums, both nationally and internationally
- Interdisciplinary cooperation with partners, both nationally and internationally

7.1.1 The role of energy in society

Energy is used for many purposes such as heating and cooling, production of products and services, transport of products and people, electronics, and light. The challenges include understanding the consequences of different ways of using energy and minimizing the environmental footprint. This requires insight into large and complex systems, where research must contribute with methods and tools. Through such insight, we build a knowledge base to influence and control behaviour related to energy use; in residential environments, transportation, and consumption of goods and services. We also gain a knowledge base for managing a growing population, increased urbanization, development of transport systems and mobility in general, organization of product chains and service delivery, and further development of industry. Technological development, including developing and applying enabling technologies and digitization in the field of energy, will be very important in the development of a sustainable society – the *low-emission society*. We must also understand our role and significance in an international context – where our knowledge, technology and natural resources will be contributions.

7.1.2 Energy sources and energy conversion

As a nation, Norway is in a unique situation with regard to energy sources, and these have been vital for the development of our society. Hydropower enabled an industrialization of the country with renewable energy, and today substantial industrial activity depends on Norwegian hydropower. Hydropower represents a large and lasting capacity to produce electricity with unique flexibility. Petroleum resources were discovered and exploited from 1970, and have been of critical importance for the development of Norwegian society. The economic contribution from the petroleum industry has had and still has major national economic significance. The remaining resource base for petroleum is still large, estimated to be as large as the production has been up to now. It is a dilemma that today's consumption of oil and natural gas and the forecast increase ahead are not consistent with the Paris Agreement, with a limitation of climate change to 1.5-2 °C. *Biomass*, primarily wood, is another significant national energy resource. The potential for bioenergy is large in Norway, but we have realized this potential to a very limited extent. Wind as an energy resource for wind power production is considerable in Norway – on land and even more in our ocean areas. *Wind* as a resource has been exploited to a very limited extent. Ocean waves and tidal currents are also potentially a major resource for electricity production, but are hardly exploited at all.

Further exploitation of our energy resources will be a very important part of NTNU's strategy. The development of technologies and costs will control this exploitation to a great extent. In addition, environmental considerations will become increasingly important for the utilization of energy resources. Greenhouse gas emissions from petroleum activities and from the subsequent use of petroleum products are one of the major global challenges we face. There are also other and different environmental challenges related to all types of energy sources, which will be vital to address in the research. NTNU can contribute through knowledge and technological development related to decarbonization, both through production of hydrogen and through CO_2 capture and storage.

NTNU will research many different technologies and components for conversion between energy forms or technologies for storage of energy. These may include components such as turbines, pumps, heat exchangers, heat pumps, and boilers. Research on development and further development of components will be focused on energy efficiency, availability and cost. This research will be based on fundamental knowledge primarily in fluid mechanics, solid mechanics, thermodynamics, materials and control systems.

7.1.3 Infrastructure for energy

The national infrastructure for energy systems is extensive and represents very high economic values. The infrastructure is: electricity grids, “smart grids” that enable many small production units, control consumption patterns and with storage capacity, dams and water reservoirs, wateways and water tunnels, production facilities for oil and natural gas, oil and gas terminals, pipelines for the transport of natural gas and oil, multiphase well flow, systems for the transportation of natural gas such as LNG, distribution of fuels such as LPG, LNG, petrol, diesel, biofuel and hydrogen, and bioenergy chains. Research on infrastructure will cover security and availability, cost efficiency, environmental considerations, and roles and business models in an increasingly integrated infrastructure.

7.1.4 Energy efficiency

Energy efficiency is partly related to energy technologies in themselves, but is also highly dependent on the systems in which different energy carriers and energy technologies are applied. Here, research will focus on how energy technology is used, and how energy technologies can be integrated to achieve a low consumption of energy with the smallest possible environmental footprint. Examples of such systems are buildings and built areas, manufacturing facilities including process industry, food production and distribution, water supply, vehicles and vessels. Such systems use energy in one or more forms as an input factor. By its nature, research on such systems will be interdisciplinary, where energy efficiency is one of several goals of the systems. Integration and optimization at various levels will be important.

7.2 Green shift in the built environment (Construction)

The importance of the built environment for living standards and quality of life is indisputable. Based on societal needs, political policies, the potential for funding and the IV Faculty’s expertise in the sector, IV will meet the challenges of the built environment nationally and globally, such as efficiency, use of energy and resources, the environment, the climate, durability and resilience, with research aimed at a sustainable built environment. This includes operations, maintenance, modernization and development of the existing building stock. It is estimated that 80% of the buildings that will be used in 2050 have already been built. The research is directed at a *Green Shift* and a *Digital Future*.

A prerequisite for the research strategy is development and basic research within structural engineering, hydrological disciplines, transport studies, building materials and building physics (including acoustics and fire), construction engineering, geotechnical engineering and geology, with targeted use of information technology and laboratories as research tools. The strategy must be considered as a combined, coordinated commitment, where contributions from all relevant academic environments at NTNU and collaborating institutions in the field of construction are necessary.

7.2.1 Sustainable and climate-resilient infrastructure

In the research strategy, we have chosen to define infrastructure as follows: Physical infrastructure such as buildings, structures and facilities for transport, underground openings and caverns, water and wastewater treatment, solid waste management and production and supply of energy. The physical land-based infra-structure in Norway represents a large proportion of the country’s real capital and the replacement cost is estimated at more than NOK 4000 billion, excluding the value of land (Norges tilstand – State of the Nation 2015, RIF (Association of Consulting Engineers, Norway)). The value of Norwegian water and wastewater facilities is estimated at NOK 1200 billion (Norsk Vann 2013). In Norway, the construction sector has revenues of about NOK 350 billion, and employs some 350 000 people (The Federation of Norwegian Construction Industries (BNL)/Statistics Norway (SSB)/Reve).

The Norwegian National Transport plan (NTP) 2018-2029 has a cost framework of more than NOK 900 billion and highlights the need for extensive research projects for a technological transformation in the areas of roads, railways, aviation and the coast. With a substantial backlog in maintenance and new construction, Norwegian municipalities face major challenges in water and wastewater infrastructure in order to fulfil the EU Water Framework Directive. This is the EU's most comprehensive environmental directive for a green transformation in water and wastewater, with a corresponding research commitment. The research focuses on sustainable planning, building and maintenance to ensure optimal infrastructure for safe, secure and effective transport of people, goods, water and energy with a reduction in noise/dust and greenhouse gas emissions as well as a long-term approach to land use.

The transport plan specifies that all travel chains must be accessible without barriers so that Norway's transport system is as accessible as possible to the greatest possible number of travellers. IV will conduct research on methods and solutions for universal design of infrastructure that support this objective.

Snow, frozen ground, ice, low temperatures and darkness are factors that influence almost all our activities in one way or another. Infrastructure such as housing, roads, railways, bridges, harbour facilities, boats, pipelines, platforms, dams, etc. must be designed and built to withstand frost and snow. All machinery that functions outdoors (vehicles, pumps, cranes, etc.) must be constructed of materials that can withstand winter conditions.

7.2.2 Optimal transport solutions

Road traffic deaths and injuries have been declining steadily in Norway for many years, but the number is still unacceptably high. A particular challenge in future road safety is accidents with pedestrians and cyclists, because the NTP assumes that most of the transport growth in urban environments will be in the form of environmentally friendly means of transport. Much of the transport sector can thus be divided into urban areas and low-traffic areas.

Much of the transition to a low-emission society will involve developing systems for smart, seamless low-energy/zero-emission transport. Autonomous vehicles will impose new demands for roads and positioning, but will also affect traffic and the way we travel. New knowledge about traffic and transport models will therefore be needed. In traffic and transport models, access to detailed real-time data is changing quickly and in line with the number of vehicles that are connected. Effective and secure handling and analysis of large volumes of data (big data) is one of the fastest-growing fields in the information society. Research on transport solutions is based on digital representation of the built environment for effective information management, planning, design, numerical simulations, visualization, project management, effective construction, operation, maintenance and property management. In this connection, the opportunities offered by geomatics, intelligent transport systems (ITS) and Building Information Modelling (BIM) will be developed further; also see the strategic research area *Digital and Effective Construction Processes*. The strategic research area must contribute to the development of environmentally friendly, safe, and optimal transport solutions based on efficient utilization of existing infrastructure.

7.2.3 Digital and effective construction processes

Buildings and physical infrastructure are realized through projects that require great skill in engineering, design, analysis, planning, implementation and operation of buildings and facilities. Digitization affects all aspects of the construction process, within information management, planning, engineering, visualization, project management, design, computational mechanics analysis and numerical simulations, effective construction, operations, maintenance and management. The research must contribute to more effective construction processes from the cradle to the grave by taking advantage of digitization in combination with improving the efficiency of all phases and aspects of the projects. BIM and geographical information systems (GIS) have created the potential for a new virtual reality from the existing built environment and the opportunity space in the construction process, in terms of both infrastructure and buildings.

3D data acquisition and digital representation have already become practice, but virtual reality offers great potential for development in combination with sensor technology. For example, for all forms of monitoring and condition monitoring, in connection with operation and maintenance, structural behaviour, and as a basis for operations. Networking and improved interoperability between different types of data and models create great potential for development of customized systems (the Internet of Systems – IoS) in all parts of the construction sector. The research must contribute to more effective construction processes from the cradle to the grave by taking advantage of digitization in combination with improving the efficiency of all phases and aspects of the projects. The development of industrialized multi-storey wooden constructions that is sustainable presents special interdisciplinary challenges.

7.2.4 Energy-efficient and functional buildings

The building and construction sector accounts for 40% of total land-based energy use in Norway. Zero-emission buildings, passive houses and energy-plus houses enable substantial reduction in energy consumption. Research on reduced use of primary energy and on energy efficiency should be prioritized to achieve goals for reduced carbon emissions. In new construction and modernization, the choice of materials, measures and solutions must provide high reliability and safety in terms of indoor air quality, health, and energy supply from renewable sources. Greater demands on the building envelope impose greater demands for reliable heating, ventilation and air-conditioning systems that combine recovery of waste heat, renewable energy, storage and smart control systems.

Inclusion of buildings and neighbourhoods in energy production is a goal (with reference to ZEB and ZEN in progress). In densely built-up areas with homes, offices, schools, shopping centres, health institutions and indoor swimming pools, surplus energy can be exchanged between the buildings or exported to the grid or district heating grid. The interaction between the building and the grid becomes important. For energy-efficient buildings to be accepted, it is important that new solutions provide both financial and social returns. Solutions must also handle the new economic models of the future, "Energy Performance Contracts" (EPC) and climate changes, Official Norwegian Report (NOU) 2010:10 "Tilpassing til eit klima i endring (Adaptation to a changing climate)". The challenges relate to:

- Calculation of expected lifetime for sustainable construction solutions
- Technology for near-zero energy buildings
- Efficient energy use in new and existing buildings using sensor technology
- Participatory processes and integrated assessment systems

The research must contribute to a sharp reduction in energy demand in the construction and operation of new and existing buildings, focusing on functional and profitable solutions.

Based on demographic challenges, IV must conduct research on methods and solutions for universal design of buildings.

7.2.5 Safe water resources

The World Economic Forum's "Global Risks Report 2017" clearly illustrates the role of water in the greatest challenges facing the world in the time ahead. Water as a nutrient essential to life will become scarce; water in extreme amounts will cause disasters and major economic challenges. At the same time, water as a clean energy source and as a resource for reuse is an important part of the solutions. Population growth, urbanization, climate change, new types of pollution and generally more stringent demands for environmental standards create great challenges for water and wastewater systems in cities showing signs of age and wear; internationally, but also to a high degree in Norway (see "State of the Nation", 2010, 2012, 2015). The frequency of interruptions in water supply and wastewater systems because of damage or lack of capacity is increasing. A wetter and wilder future will be especially noticeable in the form of more intense and local precipitation events followed by local flooding which the existing infrastructure is not designed to withstand.

New national and international water directives impose stricter environmental requirements for watercourse management and measures, and increased design floods, caused by climate change, involve large-scale and extremely costly measures in dams and structures in the hydropower sector. Extreme weather events create challenges for the production of water, food and energy. Emerging pollutants are creating challenges for drinking water safety and environmental standards, which must be solved using advanced water treatment technologies. The transition to a circular economy entails a need for exploitation of resources in wastewater for energy and fertilizer production and for reuse of water in aquaculture facilities. Very large investments in water-related infrastructure are needed and planned in the coming decades. Leading economists predict that the global water and wastewater industry will experience dramatic economic growth in the 21st century. This creates great challenges and opportunities that must be met with increased research efforts.

7.2.6 Building materials of the future

Production and consumption of building materials account for a high proportion of harmful greenhouse gases. A dwindling supply of natural resources and increasingly stringent requirements for reduction of emissions during production and during the life cycle of the materials present great challenges for the construction industry, but also opportunities. Reinforced concrete is the world's most widely used building material, but production of cement is energy-intensive. However, the properties of concrete are necessary in many load-bearing structures, infrastructure and buildings. Research must therefore be conducted on compositions and design criteria for more rational use. The same applies to other traditional materials such as steel and light metals. Wood is a renewable and CO_2-binding material resource, which is produced with low energy input, and its energy can be recycled. Wood is an environmentally friendly alternative in more construction contexts than it has been customary to consider it, and has great untapped potential. Today's structures in solid wood are an example; similarly, the combination of wood and, for example, glass in hybrid solutions.

Future building materials and associated solutions will have new and environmentally friendly properties in a number of areas, such as insulation, durability and reuse. A wider variety of intelligent building materials – materials that adapt by changing their properties according to different conditions – will be introduced. Self-cleaning glass facades are already in use, while glass with transparency that changes according to the outdoor temperature is under development. Transparent and scientific environmental assessments of innovative materials and products also require new knowledge that supports such assessments. This applies in particular to new advanced materials such as nanomaterials, bio-based materials, hybrid structures and composites. The research will help to develop tomorrow's building materials for sustainable and eco-friendly structures.

7.3 Sustainable exploitation of mineral resources (minerals)

Our society depends on large amounts of mineral resources – far more than most people realize. Global population growth, improvements in living standards and increasing industrialization are causing a dramatic increase in the need for mineral resources. The transition to a society where growth and development take place within the critical load limits of environmental systems and where products and services have fewer negative effects on the climate and environment than today (*the green shift*) intensifies this need. Norway has the resources and expertise to become a significant supplier of important mineral raw materials to a green global economy. The Faculty's strategy therefore has the following goals:

> *NTNU's research in mineral resources must be internationally recognized, must represent the great advantages of the Norwegian mining industry, and must contribute to sustainable value creation and social development both nationally and globally.*

The commitment to mineral resources can be organized in four strategic research areas:

1. Geological raw materials for the next generation (mineral deposit geology, geophysics, resource modelling, advanced mineral characterization)
2. Mineral production of the future (mining, mineral processing, downstream processing, geometallurgy)
3. Minerals in the circular economy (system knowledge, urban mining, use of mining waste, mineral-based waste treatment solutions)
4. Marine mineral resources (mineral deposit geology, resource assessment, prospecting, extraction technology).

Focus on environment and sustainability is an integral part of all the areas.

7.3.1 The resource base for future generations

Future technologies will stand and fall with the supply of economical ore and mineral deposits with essential metals and minerals. The research area focuses on the formation and the physiochemical characteristics of solid geological resources. Based on this knowledge, methods can be developed downstream in the production chain to find new deposits and to design strategies for mining, mineral processing and environmental restoration after mining has ended.

The Scandinavian Peninsula, including the continental shelf, represents Europe's largest and richest area for the formation of economic ore and mineral deposits. Geology in Norway has greater geological diversity than any other area in this region, but paradoxically it is also the least explored area. One can therefore expect to find more world-class metal and mineral deposits in the Norwegian continental area, both on land and at sea. Future deposits will be found on land for many decades, but in parallel with technological developments, we will also see increased prospecting on the continental shelf, as new methods as well as technologies previously used in the oil and gas sector are adapted to ore prospecting. Key research challenges include developing better models for the formation of traditional ore deposits, as well as models for the formation of classical ore deposits in unconventional settings. In addition, new methods must be developed for the chemical and physical determination of mineral properties and more precise geophysical / geochemical exploration methods.

7.3.2 Mineral production of the future

Increased mineral production is a prerequisite for the green shift and a sustainable society. At the same time, the production of mineral resources requires substantial energy and land, and can cause significant environmental impact. In addition, the extraction of non-renewable resources entails a particular responsibility. A number of research challenges need to be tackled to help ensure that future mineral production is as safe, eco-friendly and socio-economically beneficial as possible.

The research area includes all production processes along the value chain from operational planning and extraction to ore dressing and downstream processing through technical processing of mineral concentrates. New concepts for ore mining should be developed aimed at high productivity, a safe working environment and minimal environmental disturbance. This includes stability analysis tools, advanced field mapping technology and intelligent monitoring. Future production of aggregate must have a sharper focus on alternative sources, local stone and crushing technology that reduces energy consumption and fine particles. Within ore dressing, there is a need for more energy-efficient fragmentation technology, better solutions for processing fine-grained and complex ore, more efficient and environmentally friendly flotation chemicals, as well as alternative concepts for downstream processing of mineral concentrates.

In addition to the fundamental focus on technology and unit processes, this includes expertise and systems for optimization across the value chain (geometallurgy), as well as maintenance, risk management, automation and digitization. At the same time, environmental aspects are central. The choice of specific technical solutions in mining and ore dressing has a direct and decisive impact on the burden on the environment. Expertise in mineral production, especially ore dressing, is also a prerequisite for solving more of the research challenges in the strategic research areas “Minerals in a Circular Economy” and “Marine Mineral Resources”

7.3.3 Minerals in a circular economy

Global population growth and increased industrialization trigger an ever-increasing demand for mineral resources. Increased mining of metals with unique properties is also a prerequisite for carrying out the green shift. Production of mineral resources demands substantial energy and land, and can cause significant environmental impact. Industrial countries in the West often have lower growth in population and infrastructure, but this is offset by old structures and products that need renewal or replacement. This increases the potential for recycling waste to reduce the need for primary raw materials and the negative environmental impacts related to primary extraction. Sustainable societal development therefore assumes that industrialized countries contribute to reducing global resource needs through recycling and environmentally friendly production.

To develop strategies for sustainable use of mineral resources, it is necessary to understand the cycles for each resource. These include extraction (mining), processing (ore dressing), downstream processing (concentrate processing), production and fabrication of products, use of products, waste management and recycling ("urban mining"). This requires quantitative system analysis to understand flows and layers of materials and energy, as well as model and scenario development to analyse important development drivers, anticipate changes in resource use and the supply of resources from secondary sources, and for evaluation of different strategies. The technology aspect is the second major part of the strategic research area. Here, material characterization and particle technology play a key role. The research area includes the development of technical solutions for recycling and tailings improvement, challenges related to the use, handling and disposal of mine waste, as well as the development of mineral-based treatment solutions. Research in these areas is strongly dependent on expertise in ore dressing and process mineralogy, and on the unique facilities of the Mineral Processing Laboratory.

7.3.4 Marine mineral resources

Marine mineral resources have received much attention internationally and nationally, with major stakeholders, especially in the EU, committed to marine mining. Marine mineral resources have great potential for value creation and represent a significant source of strategically important metals. Much of the international focus is directed at the large resources of polymetallic manganese nodules found in the oceans at water depths between 4000 and 6000 metres, but there is also a growing focus on seafloor massive sulphide (SMS) deposits associated with subsea hydrothermal chimneys. The latter category is particularly interesting from the Norwegian perspective.

The research area includes the value chain linked with the mining of marine mineral deposits. This includes exploration for the characterization of marine mineral deposits and all production processes along the value chain from operational planning and extraction to ore dressing and downstream processing through technical processing of mineral concentrates. Here, many of the issues will be closely linked to the research areas "the resource base for future generations" and "mineral production of the future", but there will be particular challenges because of the context of challenging or extreme environments (deposits far out at sea, in an Arctic climate or at great sea depths). This will require the development of new technology, for example with regard to preliminary separation and transport of ore to the surface. Expertise in maintenance, risk management, automation and digitization will also play a key role. In addition, it must focus on environmental aspects of mining marine mineral resources. There is very limited knowledge about the expected impact on ecosystems and the physical environment.

7.4 Competitive and sustainable manufacturing (Production)

Norwegian society is dependent on sustainable value creation, and the industrial sector is the backbone of this value creation. Development and utilization of technology to develop, manufacture and deliver products and services based on the natural factors of our environment and our expertise must be given priority.

Although the research focuses on conditions here at home, it must also be aware of the globalization aspects with the opportunities and challenges this presents for production in Norway.

The Government's Industry White Paper, which was presented in March 2017, highlights the need for applying new materials as well as for changing, automating and digitizing processes. A reindustrialization process is needed, in which Norwegian industry is able to bring back manufacturing previously outsourced to low-cost countries. Organizations that have succeeded in bringing production home highlight strategic initiatives in skills development, digitization and automation. Similarly, these factors are important to keep existing production in Norway.

The Industry White Paper highlights the need for restructuring within sustainable limits, the significance of access to capital and access to skills, and the importance of research, innovation and technological development.

In the area of sustainability, NTNU contributes with development of methodology, especially within the circular economy. A circular economy involves reusing resources, reducing levels of waste and energy in all manufacturing processes, making better and more effective use of resources, increasing product lifetime and using more recycled materials in new products. To attract Norwegian and international players to invest in Norway, in the future it will be necessary to demonstrate that the activity is sustainable, and to use the knowledge we have from the circular economy to choose the best solutions.

NTNU's research in production must be internationally recognized, must represent the great advantages of Norwegian industry, and must contribute to sustainable value creation and social development nationally and globally. The five strategic research areas for production include most of the Faculty's existing research to support competitive and sustainable manufacturing.

A success factor for the Faculty's research is effective collaboration with research groups at other faculties at NTNU. This applies especially to the disciplines in economics, science and information technology. Similarly, it is important to develop further collaboration with SINTEF.

NTNU IV will conduct research on product and process development throughout the Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) scales. We will contribute to basic research within TRL/MRL 1-4 and applied research in TRL/MRL 4-7, and research the best possible ways for industrial companies to introduce new technology and realize innovations in TRL/MRL 8-9/10.

7.4.1 Products and production processes

Products and systems to be developed and produced in Norway will be characterized by a relatively high price that justifies production in a high-cost country. To an increasing extent, products and systems are expected to have built-in sensor technology and computing power for self-diagnosis, integration with other products, etc. In the light of the green shift, sustainability and a circular economy will become essential at all levels for the products and systems of the future. Key research challenges related to product development are (i) new paradigms and tools for intelligent product design and product development, (ii) further development of lean[6] product development, (iii) development of intelligent IoT products with built-in sensor technology[7] and computing power that, through updates throughout the product life cycle, can increase functionality and maintenance-friendliness, and (iv) further development of methods that ensure good geometrical and material properties, longevity and high reliability.

Technological development of different production processes provides new opportunities for producing smart products of this nature in Norway. It is also important to consider product development and product characteristics in relation to production. Key research challenges related to production processes are (v) to understand how we can optimize process parameters in production processes to achieve optimal product characteristics, (vi) additive manufacturing, (vii) joining technology and thermal spraying, (ix) metal fabrication and forming, (x) hot forming (forging) and cold forming, (xi) injection moulding of thermoplastics, as well as (xii) machining and measurement methods.

7.4.2 Properties of materials

To develop products with adequate functionality over time, it is crucial to choose geometries and materials in the products that eliminate failure mechanisms as far as possible and ensure a long product lifetime. The research on materials ranges from material use in the smallest bolts to large-scale material use in a ship or load-bearing structures in an oil platform. Key research challenges are explored below.

Establish understanding of *material properties on the multi-scale* level (nano to macro) through: (i) fundamental theoretical understanding, (ii) experimental work, and (iii) modelling/simulation.

[6] Lean production focuses on eliminating waste and looks at the customer's experience of product value rather than at cost elements. An important element is to create added value with less input of resources.

[7] Built-in sensor technology becomes important in an expanded production scenario as well, for example, infrastructure production where built-in sensors are important for future operation and maintenance methods.

By applying *nanotechnology*: (i) develop new materials and innovative solutions, (ii) design nanostructured surfaces, and (iii) establish methodology and perform "multi-physical" characterization of material properties.

Design and manufacture of structures, components and equipment: (i) modelling/simulation/virtual representation of the design, characteristics and behaviour, (ii) verification of design through the combination of multi-physical and multi-scale models and testing, (iii) innovative, sustainable and robust solutions that include interaction between material and structure/component/equipment, and (iv) the optimization of the production methods and processes.

7.4.3 Digitization and automation of production

A strategic commitment to digitized production based on Industry 4.0 is proposed. This will focus on cyber-physical systems with a high degree of functional integration based on local intelligence and interconnection with open protocols such as IoT. Functional integration implies that the cyber-physical systems have the capability of automatic configuration, calibration and interconnection in advanced cyber-physical production systems. Cyber-physical systems include intelligent IoT products, industrial robots, mobile robots, camera systems, sensors and machine tools, and functional integration means that work tasks could be described at a higher level of abstraction than is possible today. This will be crucial for enabling effective development of cyber-physical production systems as well as programming and change-over of automated production processes. Capability is also planned for automatic generation of simulators and digital twins based on mathematical models. Industry 4.0 also entails new roles for process operators, and creates new opportunities for communication, learning, knowledge development and innovation through simulation, visualization and data analysis. New technology allows production systems to be adapted to human needs, and not the opposite, with better human-machine interfaces and new technical aids such as augmented and virtual reality. Although Industry 4.0 has its origins in the manufacturing industry, the concepts are also applicable to an extended concept of production, for example production, operation and maintenance of critical infrastructure where automation and digitization become key.

A vital point will be robotized production under Industry 4.0 adapted to Norwegian industry with small batches and specialized products with high added value. A special focus will be on rapid change-over for advanced products in small batches, which may be specialized for each delivery. Such product categories can typically be described with a common CAD (Computer Assisted Design) model with a number of parameters, and it will be possible to include production data such as weld paths and welding parameters in the CAD model. This can be used for automatic set-up and change-over of the production process. This is a first step in developing a full digital integration of the various phases in the product life cycle such as design, simulation, production, validation, documentation, accumulation of knowledge, and maintenance. Use of open communication protocols such as IoT raises potential security issues, and it is important to develop solutions that provide satisfactory security. This will include specialized protocols for connecting cyber-physical systems to networks based on IoT. In this context, analysis tools for data security and risk management are also important.

Key research challenges to achieving the goal of digitization and automation of production are summarized by: (i) Robotized production in a digitized framework based on Industry 4.0 adapted to Norwegian industry with small batches and specialized products with high added value, (ii) Industry 4.0 focusing on cyber-physical systems with a high degree of functional integration based on local intelligence and interconnection with open protocols like IoT. This includes automatic configuration and interconnection of cyber-physical devices in advanced cyber-physical production systems and automatic generation of simulators and digital twins based on mathematical models, (iii) digital integration of the various phases in the product life cycle such as design, simulation, production, validation, documentation, accumulation of knowledge, and maintenance, (iv) analysis tools for data security and risk management, (v) human-oriented automation, effective and intuitive programming, visualization, management and control, (vi) wireless sensor networks, signal processing and machine learning for condition-based maintenance, and process monitoring and control.

It is vital to develop digitization and automation of production in cooperation with Norwegian industry. Special emphasis is given to cooperation with industrial clusters for production at Raufoss and Kongsberg and the shipbuilding industry in north-western Norway. But we also see great potential for digitization and automation in "new" areas, for example, in multi-storey wooden construction and the fishing industry along the entire coast.

7.4.4 Value chains and industrialization

The background for the emergence of supply chain management is that it is no longer sufficient to improve and manage the logistics of your own business, as the potential for improvement may be significantly greater in the value chain than in your own business. It is equally necessary to involve all actors that contribute to the value creation of the product / service, directly or indirectly, all the way from the raw material source to the end user, including recycling and reuse. To achieve the greatest possible benefits and competitive advantages from logistics, there is a need to expand the internal logistics upstream to suppliers, suppliers' suppliers, etc. and downstream to customers, customers' customers, etc. In many ways, this is the core of the thinking that underlies supply chain management. Technological advances made possible by the fourth Industrial Revolution, Industry 4.0, can contribute to increased competitiveness in the ever tougher global market. These technological advances combined with refining existing theories, as well as the development of new theories, can lead to innovative solutions in logistics, new products and business models focusing on providing new services. This will ensure increased production capacity for Norwegian manufacturing companies in a global market with ever-increasing customer demands.

Supply chain management also provides a perspective to look beyond the specific manufacturing processes – which processes are most appropriate to automate, and how can companies develop skills to succeed in digitization and automation.

All of this must be seen in the light of the need for sustainability in the value chains of the future. With an ever-increasing population and economic growth, pressure on the environment is high. The market wants sustainable products and services, and the supply of resources is decreasing steadily. For this reason, it is important to plan and manage resources throughout the value chain to ensure sustainable activities for future generations. This can be achieved both with new technologies and with new theories focusing on optimal exploitation of resources with the least possible impact on the environment.

The competitive edge of Norwegian industry depends on the ability to develop products and manufacturing systems with the right characteristics, quality, price and quantity for a market willing to pay for them. Managing the value chain through handling customers and suppliers, quality management, continuous improvement and breakout innovations in products and processes as well as automation of production is key. Increasing digitization using big data analysis, visualization, optimization, simulation and decision support tools will make it easier to make correct decisions.

Key research challenges are: (i) innovative business models based on Industry 4.0 concepts, (ii) horizontal integration of value chains – configuration of the supplier network to take full advantage of new technologies and solutions, (iii) smart factories with an integrated manufacturing system where smart machines and products communicate with each other, collect data and provide a basis for flexible, optimized and synchronized operation, maintenance and production. (iv) configuration of production networks defined in terms of how the entire network of actors, processes and activities, material and information flow is composed and organized (the design of production networks also includes relationships with suppliers), (iv) use of big data, machine learning, analytical methods for real-time control of logistics and supply chains.

7.4.5 One-of-a-kind production

Scandinavian and especially Norwegian production is characterized by offering goods and services with differentiated design and innovation. Norwegian companies in the maritime, oil and gas, offshore, subsea, construction, heavy equipment, fish, furniture and electronics sectors design and produce capital-intensive, advanced and customized products. The manufacturer also adapts to the customer's specific needs. Production is characterized by low production volumes (often volumes of one), labour intensity, long lead times, high levels of demand uncertainty and frequent changes in product specifications. Manufacturing companies are also characterized by temporary and unique supply chain structures, as it is often necessary to have suppliers who can offer highly specific products or services. Varying framework conditions and increasing global competition require flexible, dynamic and adaptable production and value chain structures.

The main objective of the research area is to develop solutions for sustainable and smart customized one-of-a-kind and low-volume production in Norwegian manufacturing companies through the development and use of smart products, procedures and processes in production and supply chains to increase the competitiveness of these businesses in global markets. An important goal for realizing this is to establish a Centre for Research-Based Innovation (SFI).

It is important to apply for research projects involving a variety of Norwegian companies specializing in one-of-a-kind production: shipbuilding and marine equipment, oil and gas industry, aviation industry, fish farming and fish processing, as well as subsea equipment and other heavy equipment. It is also important to involve Norwegian companies that are working for a higher level of product customization, such as furniture and electronics.

Key research challenges are: (i) digitized real-time concepts for design, planning and control of one-of-a-kind production, (ii) digitized real-time concepts for optimization of smart factories in terms of logistics and integration with data-based control tools, (iii) use of real-time information for improved logistics operations, planning and control and management of the supply chain in one-of-a-kind production, (iv) development of methods for data acquisition and analysis to strengthen the sustainability of one-of-a-kind production, (v) methods for reducing lead times in production (effective contract negotiations and verification, concurrent engineering, handling of change orders, etc.), and (vi) the supply chain in one-of-a-kind production (use of automation, offshoring, modularization, etc.).

7.5 Oceans and Artic area world lead (Oceans)

The oceans are one of four strategic areas of focus at NTNU with broad support, where IV contributes in a respected role. The research strategy will help Norway to maintain its position as *world leader in the oceans and the Arctic area.*

The Government's ocean strategy (02/2017) summarizes the importance of this social goal:

> *Norway is today one of the world's leading ocean economies. Our coastline is one of the longest in the world, and we control expanses of ocean more than six times larger than the area of our land. Every day hundreds of thousands of Norwegians go to work in the ocean industries, which together represent about 70 per cent of our export income.*

The oceans with the three major blue industries *maritime transport, offshore oil and gas activities, fisheries and aquaculture* contribute to a significant share of value creation in Norway and will continue to do so in the future. In addition, new blue industries are rapidly developing and growing: *offshore renewable energy, marine management and research including marine prospecting, marine minerals, and tourism*. As part of climate adaptation with expected rising sea levels, more extreme weather (precipitation, wind) and innovative solutions for fjord crossings, *coastal infrastructure* will become increasingly important.

7.5.1 Digital ocean space

Norway's ocean areas are 6-7 times larger than the areas of land. The ocean areas include the coastal zone around Norway and Svalbard and the North Sea waters in the south, the Norwegian Sea, the Barents Sea, the North Atlantic and the Arctic Ocean, which follow new continental shelf boundaries, the Yermak Plateau into the Arctic basin. Mapping and monitoring of the ocean areas including the High North is important for knowledge-based management of marine ecosystems, the environment, climate, transport, fisheries, aquaculture, oil and gas, and other value creation in the ocean. In addition, inspection and maintenance of marine structures and equipment for oil and gas, aquaculture, offshore wind installations and marine minerals, using robotic systems with advanced sensors, are important for safe and cost-effective operation.

For oil and gas activities, integrated marine mapping and monitoring using advanced sensors on various technology platforms are vital for safe and environmentally sound mapping, extraction and production of hydrocarbons. A holistic approach centred on sustainability is crucial for national and international interests. As a maritime nation, Norway has a special responsibility for leading this work. The research area of digital ocean space at IV includes development of methods and technologies for integrated marine mapping, monitoring and operation of marine structures and systems using autonomous and robotic systems with advanced sensor technology for:

- Integrated marine mapping and surveillance in coastal regions, deep waters and Arctic areas
- Acquisition of data and material for marine prospecting, which could provide new knowledge for obtaining new medicines, food and energy from the ocean, or information to improve our understanding of the marine environment
- Increased operational efficiency, safety and security in mapping, inspection, management and maintenance for oil and gas activities, marine minerals and aquaculture
- Inspection and cleaning of ships, harbors and marine structures
- Classification and modelling of marine geohazards.

7.5.2 Safer, smarter and greener maritime transport and operations

International shipping is the backbone of international trade, but also a significant source of pollution. Energy efficiency and introduction of energy sources with lower emissions are important in reducing shipping emissions and making international shipping less harmful to the environment. Norway also has a key international role in the development of specialized vessels for various operations for the development and extraction of marine resources. These operations place high demands on efficiency, safety and the environment.

Benefits and research opportunities in maritime transport and maritime operations are largely in interdisciplinarity and application of enabling technologies. Key concepts include digitization, autonomy, big data analyses, virtual prototyping, alternative fuels, hybrid machinery systems, seagoing capabilities, multimodal logistics, risk management and life cycle analyses.

Norway has a strong maritime cluster with a long history and great breadth. NTNU must take advantage of this cluster, and has potential in increased collaboration with shipowners engaged in deep sea shipping, while the existing close collaboration with the equipment industry and offshore ship cluster needs to be developed further. Further automation of shipping using advanced sensor, communication and control systems will pave the way for vessels with no or reduced onboard crews that are partially remote controlled and autonomous. This is likely to change logistics patterns and business models. Trondheimsfjorden has been designated as the national arena for testing autonomous systems, including autonomous ships. A commitment must be made to developing numerical simulations at several different levels for different applications, while experimental investigations both at model scale in laboratories and through measurements on ships in operation are important. Improved understanding of risk and IT security systems (cybersecurity) with adequate testing and verification of autonomous ship systems will become important. The same applies to interaction between humans and technology for monitoring and handling individual vessels, fleets of ships and marine operations. Environment must be more than a slogan; lifetime analyses and life cycle analysis are valuable tools in this context.

7.5.3 Living and productive coastal communities

Norway has a long and unique coastline, and it is important for us to have many productive and vivid communities along the coast. A key ingredient is a safe and reliable coastal infrastructure for business, transport and housing. Traditionally, there has been ship transport along the coast, and fishing has been the major challenge. However, new challenges have emerged with renewable energy in the coastal zones, aquaculture, development of roads and railways along the coast, increased demand for coastal homes and Arctic coastal technology. Like any other infrastructure, it must have sufficient reliability and adequate regularity. Climate change and costs will make maintenance planning and management as well as adaptive design key principles in the design and operation of various types of infrastructure. The expected rise in the sea level and more extreme weather will challenge coastal infrastructure in Norway and the rest of the world. A large part of the world’s population lives by the sea. Mapping of risk and setting priorities for interventions will become a national task. All infrastructure is built to improve human living conditions and the environment so that sustainability and a direct impact on human life and health must be included. The new Copernicus programme provides new opportunities for monitoring and instrumentation. We find it natural to categorize into the following applications:

1. Ports and shipping lanes. This also includes electrification of ports suitable for electric ferries and vessels with hybrid electrical installations (combination of battery, gas, diesel, etc.)
2. Aquaculture
3. Renewable energy
4. Roads, railways and fjord crossings along the coast
5. Homes and other buildings
6. Arctic coastal engineering

7.5.4 Innovative ocean structures, systems and operations

Greater use of the sea for harvesting food and renewable energy is a prerequisite for achieving a sustainable society. In the future, it must be possible to harvest the oceans as a farm and contribute more to the global food supply. Wind and solar energy must make a significant contribution to a future carbon-neutral energy chain. In addition, further extraction of oil and gas in the safest and most environmentally friendly way possible is very important for Norway as a nation and for stable energy supply internationally in the years to come. This requires expertise and knowledge about innovative ocean structures, systems and operations. At the same time, it requires insight into environmental impacts to ensure that mining and exploitation of the ocean takes place in a sustainable way. We need to develop new basic and applied knowledge that may be useful in all ocean-related industries in Norway. At the same time, we must take advantage of knowledge and experience built over many decades in the oil and gas industry and transfer this to new applications.

Key factors here are ocean structures, systems and operations associated with them.

IV will deliver knowledge for technology in the forefront of research within these areas. We must focus on using the points of tangency between applied research and basic research, and between different disciplines, such as hydrodynamics, structures, optimization, design, reliability, sustainability, biology, materials technology, autonomy, operational reliability and maintenance, to open new, unknown opportunities. It is important to think outside the box".

7.6 Common areas of expertise, enabling technology and basic subjects

All five of the societal goals demand attention from a wide range of areas of competence. The IV Faculty has leading-edge expertise within both basic and leading-edge engineering disciplines that are necessary to meet these challenges, but acknowledges that relationships to other areas of expertise are vital for good results. These areas of expertise are both within and outside the Faculty's area of activity. Some of the Faculty's research areas are shared in the sense that, in addition to being independent disciplines, they represent competence that is used by or is central to other research areas. This applies to areas such as industrial ecology, project management and safety, reliability and maintenance. The Faculty's research is also based largely on key basic disciplines in engineering such as mechanics and thermodynamics. In addition, development within the five societal challenges depends on the forward-thinking and appropriate use of enabling technologies such as ICT / digitization, materials technology and nanotechnology. The IV Faculty's academic environments have expertise in developing such technologies and a fundamental role in creating a context for application.

7.6.1 Industrial ecology

The field of industrial ecology works with climate, environment and various sustainability evaluations across many sectors and thus most of the Faculty's disciplines. Research activities centre on application and development of models and methods for analysing the environmental characteristics of different systems. These models are used to compare individual technologies through analyses and scenarios for entire segments and sectors from city, regional, national and up to global level. The methods used are variants of LCA (life cycle analysis) and multi-regional input-output analysis models. Industrial ecology is also the scientific discipline that supports the circular economy. Central to this is work with material flow analyses. Studies and mapping of the major anthropogenic material cycles and their dynamics are crucial to sustainability research.

Overall, industrial ecology combines evaluation of the impacts that human activities have on the environment with the modelling of networks of industrial processes that exploit and convert various resources to provide services and goods in society; as well as how these must be changed over time to move into sustainable development paths.

The most important overall objective of the research is to acquire knowledge to support decisions on sustainable choices of direction. This ranges from decisions related to both operational and strategic priorities in research and development all the way up to overall actions in climate and environmental policy nationally and internationally.

The role of industrial ecology role in IV's research strategy is to contribute environmental and sustainability evaluations within and across the Faculty's research areas to ensure that technology research takes an environmentally sustainable approach. This means analysing individual systems and technologies as well as looking at the sum of several systems and technology choices within the various segments of the IV Faculty's area of responsibility. Through this, industrial ecology will help to link up many different technological and environmental challenges across disciplines. This is important because many of our transition challenges must be solved in parallel across different sectors.

7.6.2 Project management

Projects account for a significant proportion of the gross national product in most national economies. According to sources such as Hadjikhani (1996) and Miller and Lessard (2000), production of industrial projects is one of the largest sectors worldwide and, according to Wikström et al. (2010) and Liinamaa (2012), it is still growing. The proportion of a country's economy that projects represent is difficult to quantify and varies from country to country and over time, but an interval between 25-35% has been estimated by different sources, for example McKeeman (2002) and EURAM SIG (2012). This means that vast amounts of money are channelled through projects each year, ranging from buildings, infrastructure, ships, offshore installations, ICT systems and organizational development to public-sector reforms. In many sectors, there is now talk of "projectification" of their approach to work.

Ten years after "Rethinking Project Management", technological development and changes in projects have reached a point where we now also see the contours of "project management 3.0". This phase of the discipline's development is driven by digital/technological development in a variety of areas that represent areas/processes in projects. The two most pronounced developments driving this change are: Digitization/ICT development (in areas such as digital 3D/4D/5D modelling of technical systems using BIM (Building Information Modelling), sensor technology/IoT capability in materials and equipment, visualization of BIM models and plans using tablet computers/smartphones accessible to everyone from the project manager to workers. Use of big data, GPS control of construction machinery, transport equipment, assembly equipment, etc.) and technological development in the direction of industrialized production in projects, in the form of modularization of project deliveries such as buildings, ships, bridges, platforms, etc., industrial prefabrication of such modules for assembly at the construction site rather than construction on site. Robots that handle ever more advanced operations in project production, such as welding robots, robots that drill holes in ceiling structures, etc. and automated transport solutions for construction sites, shipyards or other production sites.

Key research challenges are: (i) human and digitized interaction in the projects; (ii) new and innovative project execution models; (iii) Lean and value chain management in project contexts; and (iv) performance measurement and fact-based improvement processes.

7.6.3 Reliability, availability, maintainability and safety

Reliability, availability, maintainability and safety are important characteristics of technical and socio-technical[8] systems. These properties briefly sum up the extent to which one can trust functions to work when they are supposed to, and what is needed to preserve the functionality over time and in a way that does not harm people, the environment and other assets of great importance to society. For maintenance, costs are

[8] Technical systems where human and organizational factors are included as an important part of the functionality.

also key, to ensure optimal utilization of resources. Activities with the purpose of deciding, detecting and maintaining RAMS[9] characteristics are often referred to as RAMS activities.

For all five overarching societal goals in the research strategy, components, systems and services will be developed, produced and operated. Ensuring good RAMS features will be central to all five areas. Development will increasingly be characterized by growing digitization and more autonomy. This means that ICT, including advanced sensors, computational operations and algorithms, is becoming an increasingly important component. Although more and more manual operations are automated, humans are involved in both design and operation by making decisions that are not yet possible to automate. New ways to operate can provide new opportunities, but also new risk factors that need to be addressed. There is a need to deal with systems of ever-increasing complexity, dependencies between subsystems and systems, and system-human interaction that may take place over large geographic areas. Connection with the Internet of Things introduces new vulnerabilities that must also be taken care of. Failure and unintended and unpredicted actions can lead to major accidents and long-term damage to the environment.

Today's RAMS methods are largely developed to understand electronic and mechanical equipment. Digitization and automation introduce complexity that means that traditional methods must be further developed in terms of understanding data-driven systems, complex systems, and dynamic socio-technical systems.

Key research challenges are: (i) methods for analysing the safety and reliability of complex cyber-physical systems: (ii) development of methods for analysing systems with dynamic behaviour, (iii) analysis, modelling and monitoring to prevent major accidents, (iv) integration and planning of operation and maintenance where real-time coordination of operational and maintenance tasks in an Industry 4.0 perspective becomes important.

7.6.4 Mechanics

Mechanics is a vital foundation subject for much of the Faculty's research, which in turn is a prerequisite for many of the proposed research challenges. If this research is to be relevant, however, it is also necessary to set priorities for research within the different branches of mechanics. In materials mechanics, the aim is to increase our understanding of the mechanical behaviour of the materials under external stress and to establish validated mathematical and numerical models that can describe the observed behaviour. This includes well-established theories such as elasticity and plasticity theory, dislocation mechanics and micromechanics, and damage and fracture mechanics. Nanomechanics focuses on the smallest material elements and can help us to understand fundamental processes. Computational mechanics focuses on the way we solve the basic equations in mechanics and the methods we use. The rapid development of digital computing and visualization paves the way for major research challenges in areas such as the finite element method (FEM) and corresponding formulations, such as the discontinuous enrichment method (DEM). In fluid mechanics, corresponding research in computational fluid dynamics (CFD) is required, especially in connection with hydrodynamic turbulent flow fields. Research in biomechanics combines material mechanics for the representation of tissue and bone structures and fluid mechanics for calculating the behaviour of blood. Biomechanics is an example of how the different branches of mechanics are combined in a growing number of research questions. Another example is wind-induced vibration, perhaps especially on bridges. Phase mechanics deals with the ability to calculate the influence of changes in geometry and properties, such as by the development of cantilever bridges. Most of the research in mechanics requires validation of theoretical calculations. The Faculty's laboratory facilities must therefore be continuously updated in line with the development of experimental equipment, such as microscopy, tomography and digital image correlation, important methods alongside more traditional tests.

[9] RAMS = Reliability, Availability, Maintainability and Safety.

8 Strategic partners

It is important for IV to participate in forums where national and international strategies are developed, both because of NTNU's social responsibility and to contribute to the design and gain insight into the future research agenda. Not least, this is important in relation to the EU, where both business and research environments are expected to engage in the development of road maps for research.

Implementation of major national and international research projects requires cooperation with others through the establishment of consortia. For example, this is a requirement for applying for funding through Horizon 2020.

IV must therefore build alliances both nationally and internationally. These alliances must include research environments, business and public administration.

Alliances with research communities abroad (universities, research institutions and industry) are an important factor for the ability to develop outstanding research. The Faculty must therefore have a proactive strategy to establish and maintain alliances with the best international environments in its area.

At the national level, SINTEF is the most important partner for research. Existing ways of collaboration such as the Gemini Centres must be continued and the principles for cooperation developed during the "Bedre sammen (Better Together)" process must be implemented. IV must develop common strategies with SINTEF in relevant areas. The collaboration must be based on trust and equality. The preferred collaboration model is that both institutions are partners in projects in which they wish to work together, but NTNU can also enter into cooperation on SINTEF's projects through institutional agreements.

Much of IV's research is based on the application of enabling technologies. This requires close cooperation with academic communities at other faculties at NTNU. Many of the solutions affect people's work situation and some create ethical dilemmas. Therefore, interdisciplinary research to which the humanities and social sciences contribute is important to IV.

Experimental activities depend on good research infrastructure. The Research Council of Norway provides funding for the development of national research infrastructures. This and other factors often require extensive cooperation with other national research communities. IV must be open to such cooperation where it leads to increased quality.

IV has a long tradition of close cooperation with business and industry in both education and research. Within several areas, there are "næringslivsringer" (university/business networks) serving as contact agencies between NTNU and industry. Our experience with these is positive and the networks are considered an important tool. The strategy is to continue and further develop cooperation with the business community. The relevance of research and education at IV, as well as innovation, is ensured through systematic contact with relevant parties in working life – for research and student projects as well as continuing and further education.

After the merger, through its campuses in Gjøvik and Ålesund, the IV Faculty has gained closer contact with industrial clusters in these regions. The academic communities in Gjøvik and Ålesund have a special responsibility for contributing to research collaboration with these.

The transfer of knowledge from IV to the outside world takes place through research-based education, publishing and collaboration with public administration and business activities, but primarily because IV's students take new knowledge out into society after completing their studies at bachelor's, master's and doctoral level. This requires close ties between education and research and that research relevant to business and public administration is conducted. Figure 4 illustrates how IV cooperates with industry and business in educating master's and doctoral candidates. IV increases its quality and relevance in education and research, and through access to graduates and research results, industry will strengthen its competitiveness.

The need for transformation in Norwegian industry and public administration requires access to expertise, which must come through the graduates that NTNU educates. The challenges related to the green shift and to new solutions for products and manufacturing based on digitization set a clear agenda for research activity. The results of this will shape future programmes of study.

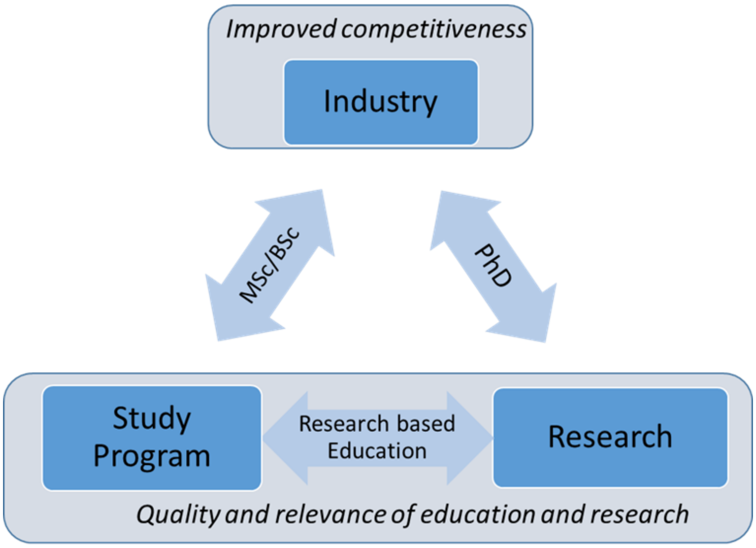

Figure 4 NTNU collaborates with industry and business to improve quality and relevance in research and education. Industry strengthens its competitiveness

Collaboration with business and other research environments can be achieved through centres where, for example, business enterprises can be members. Project Norway and the Norwegian Hydropower Centre are examples of such centres.

9 Funding of IV's research

A large part of the research at IV is conducted through funding from external partners, such as the Research Council of Norway, the EU's framework programmes, national and international industry, and other forms of funding. It is a goal to obtain funding for research equivalent to 2/3 of the Faculty's funding through the budget allocation model from the National Budget. A large part of the external resources is used to fund doctoral studies.

The external resources are either contributions or commissions from business or administration, both private and public sectors. The most important public funding sources are the Research Council of Norway and the EU's framework programmes for research.

IV has a number of collaborative agreements with private- or public-sector enterprises on research collaboration. External funding is crucial for maintaining doctoral education at the desired level.

In addition to the external resources, NTNU has significant internal resources in terms of research time for the academic staff, access to research infrastructures and strategic funds from the Rector or the Faculty.

Relevant funding sources are different for each area of research and are described more detailed in the basis reports B2 – B6.

10 Criteria for prioritization

Prioritizing resources for research must help to achieve the overall objectives of the Faculty. These goals are discussed in Chapter 4 and apply to all the activities at the Faculty. For research, the goals highlight:

- Quality in research
- Interdisciplinarity
- International collaboration
- Publication
- Good research infrastructure
- Industry-oriented

Quality in research is achieved by investing heavily on outstanding research. Such research is usually fundamental and long-term. The Research Council's evaluation of technology disciplines from 2014 also highlights this need. In addition, it is important for IV to commit resources to industry-oriented research to help to target the research with a view to future innovations in industry and public administration.

To set priorities for strategic research areas/research activities, it is important to use known criteria. The following criteria should be reviewed in such cases. There is no internal priority among the criteria.

- Relevance to vision, societal goals, strategic research areas
- Contribution to excellent research (long-term basic research)
- Quality of the researcher environment
- Interdisciplinarity
- International relevance or business relevance
- Responses to trends and challenges
- Opportunities for external funding

11 Implementation of research strategy

Sound implementation of the research strategy is a prerequisite for success. The implementation will primarily take place from the autumn of 2017. The owner of the research strategy is IV's line organization. The individual manager is responsible for involvement and planning in his or her own organization. Important activities will be:

- Goals and action plans for implementation of the revised research strategy, summer/autumn 2017
- Internal hearing
- External hearing
- Goals and action plans for research activities in the research groups (performed every year)
- Establishing new regular annual arenas, for example
    - Research day(s)
    - Thematic arenas
- Regular reporting in the management team

Abbreviations

AMOS	Autonomous Marine Operation Systems
AUR lab	Applied Underwater Robotics lab
BA (Norwegian)	Bygg og anleggsnæringen – the construction industry
BIM	Building Information Modelling
GDP	Gross Domestic Product
BRU21	Better Resource Utilization in the 21st Century – technologies of the future for the petroleum sector
BSc	Bachelor of Science, three-year engineering degree
CAD	Computer Assisted Design
CFD	Computational Fluid Dynamics
COP21	Paris Climate Change Conference 2015
DEM	Distinct Element Method
EERA	European Energy Research Area
EPC	Energy Performance Contract
ERC	European Research Council
ESFRI	European Strategy Forum on Research Infrastructures
ETO	Engineer To Order
EU	European Union
EURAM SIG	European Academy of Management Special Interest Group
EVU	Etter- og videreutdanning (Continuing and further education)
FEM	Finite Element Method
FET	Fundamental Emerging Technologies, programme in H2020
FME	Senter for forskning på miljøvennlig energi (Centre for Research on Environmentally Friendly Energy, programme in The Research Council of Norway)
FORNY 2020	Innovation programme in the Research Council of Norway
R&D	Research and Development
FRIPRO	Funding for independent projects, programme in The Research Council of Norway
GIS	Geographic Information System
H2020	Horizon2020, the EU's 8th Framework Programme for research
HiST	Sør-Trøndelag University College
HSE	Health, safety and environment
ICT	Information and communications technology
IoS	Internet of Systems
IoT	Internet of Things
ITS	Intelligent Transport Systems
IV	Faculty of Engineering
IVT	Faculty of Engineering Science and Technology
LCA	Life Cycle Analysis

LNG	Liquid Natural Gas
LPG	Liquid petroleum gas
MRL	Manufacturing readiness level
MSc	Master of Science, five-year engineering degree
NTNU	The Norwegian University of Science and Technology
NTNU IT	Central department for information technology at NTNU
NTNU TTO	NTNU's Technology Transfer Office
NTP	Norwegian National Transport plan
OECD	Organisation for Economic Co-operation and Development
PhD	Philosophiae Doctor, doctoral education
RAMS	Reliability, Availability, Maintainability and Safety
RIF	Rådgivende ingeniørers forening (Association of Consulting Engineers, Norway)
SFF	Norwegian Centre of Excellence, programme in the Research Council of Norway
SFI	Centres for Research-based Innovation, programme in The Research Council of Norway
SMS	Seafloor Massive Sulphide
TBS	Trondhjem Biological Station
TRL	Technology Readiness Level
TSO	Strategic Area of Research
UAV lab	Unmanned Aerial Vehicles laboratory
UN	United Nations
ZEB	Zero-Emission Building
ZEN	Zero-Emission Neighbourhoods