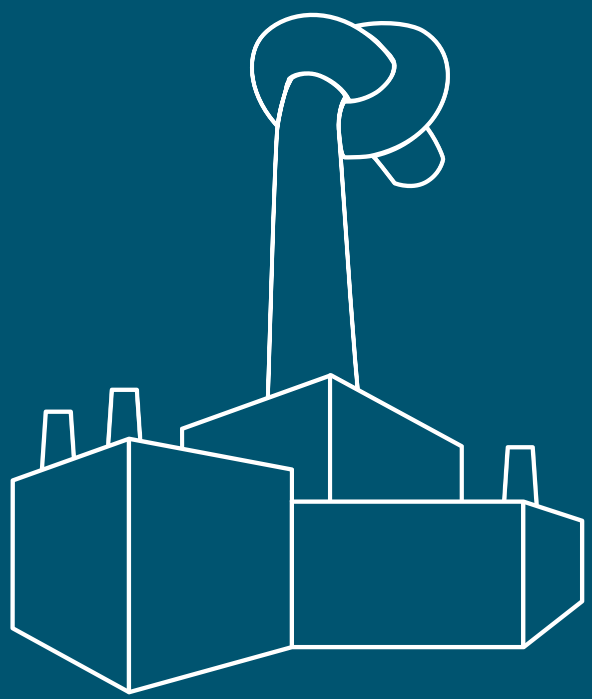
ccsp
Carbon Capture and Storage Program

CARBON CAPTURE AND STORAGE



CARBON CAPTURE AND STORAGE RESEARCH PROGRAMME

FINLAND IS WELL SET FOR DEVELOPING AND APPLYING METHODS FOR CARBON CAPTURE IN ENERGY PRODUCTION AND OTHER INDUSTRY. THIS VIEW WAS STRENGTHENED FURTHER IN FINNISH COMPANIES' AND RESEARCH INSTITUTIONS' JOINT CARBON CAPTURE AND STORAGE PROGRAMME (CCSP).

Carbon capture and storage aims to reduce carbon dioxide emissions, thereby mitigating climate change and ocean acidification. This will be inevitable in the world if we are to reach international climate mitigation objectives.

The ultimate objective of the research programme was to find out how carbon capture methods can be applied in different applications and what new methods will be available in the near future, as well as to strengthen Finnish technology expertise and companies' competitiveness in the international technology market. In this report, we present examples of the outcomes of the research programme and the foundation and operating environment of carbon capture and storage. Besides technological solutions, the scientists created an up-to-date overview of how carbon capture and storage will be taken into account in the climate policy of Finland and the EU, and what would contribute to the development of the industry.

There is expertise related to carbon capture and storage with an internationally significant position in Finland. Finnish scientists are among the global leaders in developing individual storage methods and following up their environmental impacts. The research programme further strengthened Finnish expertise and international cooperation, and some of the methods leaped to the threshold of commercialisation with modelling and test use. There is now an even more solid scientific foundation in Finland on which the developers of methods and plants can depend.

The five-year CCSP research programme ended in October 2016. A total of 18 companies and 9 research institutions took part in the programme. The total value of the programme was approximately EUR 15 million, with companies covering 30% of the costs, public research institutions 11% and Tekes 59%.

The research project was included in CLEEN Ltd's project portfolio. CLEEN was the Strategic Centre for Science, Technology and Innovation (SHOK) for companies and research institutions in the energy and environmental sector in 2008–2015. In September 2015, CLEEN and the Finnish Bioeconomy Cluster FIBIC merged to form CLIC Innovation Ltd.

CCSP PROGRAMME VOLUME: 15 M€ 2011-2016

CCSP consortium members

Industry partners 52 %

Fortum Oyj **19 %**, Ramboll Finland Oy **14 %**, Vibrometric Oy **12 %**, Helen Oy **8 %**, Gasum Oy **6 %**, Amec Foster Wheeler Energia Oy **6 %**, Neste Jacobs Oy **5 %**, Neste Oil Oyj **5 %**, ÅF-Consult Oy **5 %**, Fortum Power and Heat Oy **4 %**, SSAB Europe Oy **3 %**, Oil and Natural Gas Corporation (ONGC) Ltd **3 %**, Nordkalk Oy **3 %**, Oulun Energia **2 %**, Stora Enso Oyj **2 %**, Tapojärvi Oy **1 %**, Andritz Oy **1 %**, Outotec Oyj **1 %**

Research partners 48%

VTT Technical Research Centre of Finland **44 %**, Aalto University **14 %**, Lappeenranta University of Technology **13 %**, Geological Survey of Finland **7 %**, Åbo Akademi University **5 %**, Tampere University of Technology **5 %**, University of Oulu **5 %**, University of Tampere **4 %**, Finnish Environment Institute **2 %**

SEBASTIAN TEIR
Program Manager, CCSP research programme (2012–2016), VTT Technical Research Centre of Finland

ANTTI ARASTO
Program Manager, CCSP research programme 2011), VTT Technical Research Centre of Finland

RISTO SORMUNEN
Chairman of the CCSP program steering group, CCSP research programme, Fortum Power and Heat Ltd

JATTA JUSSILA-SUOKAS
CTO, CLEEN Oy/CLIC Innovation Ltd (2008–2015)

PIA SAARI
CTO, CLIC Innovation Ltd (2016–)

CARBON CAPTURE AND STORAGE

CARBON DIOXIDE RELEASED FROM ENERGY PRODUCTION AND OTHER INDUSTRY MUST BE CAPTURED IN THE FUTURE, IF THE EU WANTS TO ACHIEVE ITS CLIMATE OBJECTIVES. TECHNOLOGICALLY, IT IS ALREADY POSSIBLE, BUT AT A HIGH COST.

In 2015, governments agreed at the Paris climate conference that global warming must be limited to below 2°C by cutting carbon dioxide emissions. It is largely up to each country to decide how it will control its emissions, but the range of methods is the same for everyone – and limited. Carbon dioxide emissions can be mitigated by reducing energy consumption and choosing emissionless or low-emission methods in energy production.

"Moreover, we will have to capture part of the carbon dioxide emissions of energy production and industrial processes. Without capture it would be considerably more expensive, and perhaps even impossible, to reach the internationally agreed objectives", says **Sebastian Teir,** head of the CCSP research programme at VTT. He considers carbon capture and storage particularly important in areas that need fossil fuels and limestone as raw materials in production.

"In some areas of industry, carbon capture is even the only option", Teir says.

TECHNOLOGICALLY FEASIBLE – ECONOMICALLY INCOMPLETE

Carbon capture from energy production has been under development since the 1990s, and the methods have become increasingly diverse during the last decade.

"There are excellent methods that are technologically feasible, but they are not yet reasonably economical for application on a large scale", says Chairman of the CCSP programme management team **Risto Sormunen** at Fortum. With current methods, it is possible to capture up to 90% of the carbon dioxide emissions of a combined heat and power plant, for example. However, consuming a lot of energy, capture would reduce the efficiency of the plant by approximately 5–10%-units, in particular at the cost of power generation.

Some of the capture methods are already being used in oil refining and in a small scale in industrial processes that need carbon dioxide as a raw material. The most promising solutions relating to power plants are still maturing in development projects, at small pilot plants and a few dozen plants around the world.

CARBON DIOXIDE EMISSION CAN BE CUT

- by reducing energy consumption
  - by improving energy efficiency in energy production and energy-intensive devices, buildings and industrial processes
  - by giving up some energy-intensive activities
- with energy production using
  - emissionless methods, such as nuclear, solar, hydro and wind power
  - renewable fuels, such as biomass
  - lower-emission natural gas instead of coal
- by avoiding industrial processes that produce carbon dioxide emissions
- by capturing carbon dioxide and storing or utilising it

"The next significant step in the field is the comprehensive testing of the methods in full-scale pilot plants. Only then can investors and the general public be convinced of the feasibility and actual costs of carbon capture", Sormunen says.

CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
Bio-CCS	Carbon capture and storage from combustion of biomass or from refining biomass into biofuel

SECURE STORAGE UNDER THE SEABED

In order to be able to deploy carbon capture, a storage location is needed for the captured carbon dioxide to keep the carbon dioxide permanently away from the atmosphere.

Sufficiently large storage places can be found in porous rock formations in the soil or bedrock. According to international surveys, the most usable storage areas are located in the bedrock under the seabed at a depth of over 800 metres. The pressure caused by the depth keeps the liquefied carbon dioxide like a liquid, and it is not able to get to the surface or water and thereby atmosphere. Liquid carbon dioxide can be pumped to depleted oil and natural gas fields, unutilised coal deposits and saline aquifers in the bedrock, among other places. "Carbon dioxide has been pumped into oil deposits for decades, as it makes it easier to get the oil moving. At the same time, part of the carbon dioxide remains in the bedrock", Teir says. Finland's dense bedrock is not suitable for geological storage; storage requires transporting the carbon dioxide via pipelines to intermediate storages and to the final storage by ship.

LARGE GLOBAL MARKET

Currently, there are 45 projects underway around the world to test carbon capture in a large scale, primarily in power plants that only produce electricity. In all, these plants can capture 80 million tonnes of carbon dioxide per year, which is equivalent to 1.5 times the annual carbon dioxide emissions of the whole of Finland. Global CCS Institute, an international organisation focusing on carbon capture and storage, has estimated that the annual capture capacity needs to increase to 4,000 million tonnes, or 50 fold, by 2040 for the world to reach the climate objectives set in Paris.

"Alongside technological development, carbon capture and storage is largely influenced by the development of legislation and regulations on emissions trading", Teir says. Currently, carbon capture is accepted in the scope of EU's emissions trading system only when combusting fossil fuels, meaning that biofuels are not included in the scope of emissions trading for the time being. Only pipelines are accepted for transporting carbon dioxide and geological storages for storage.

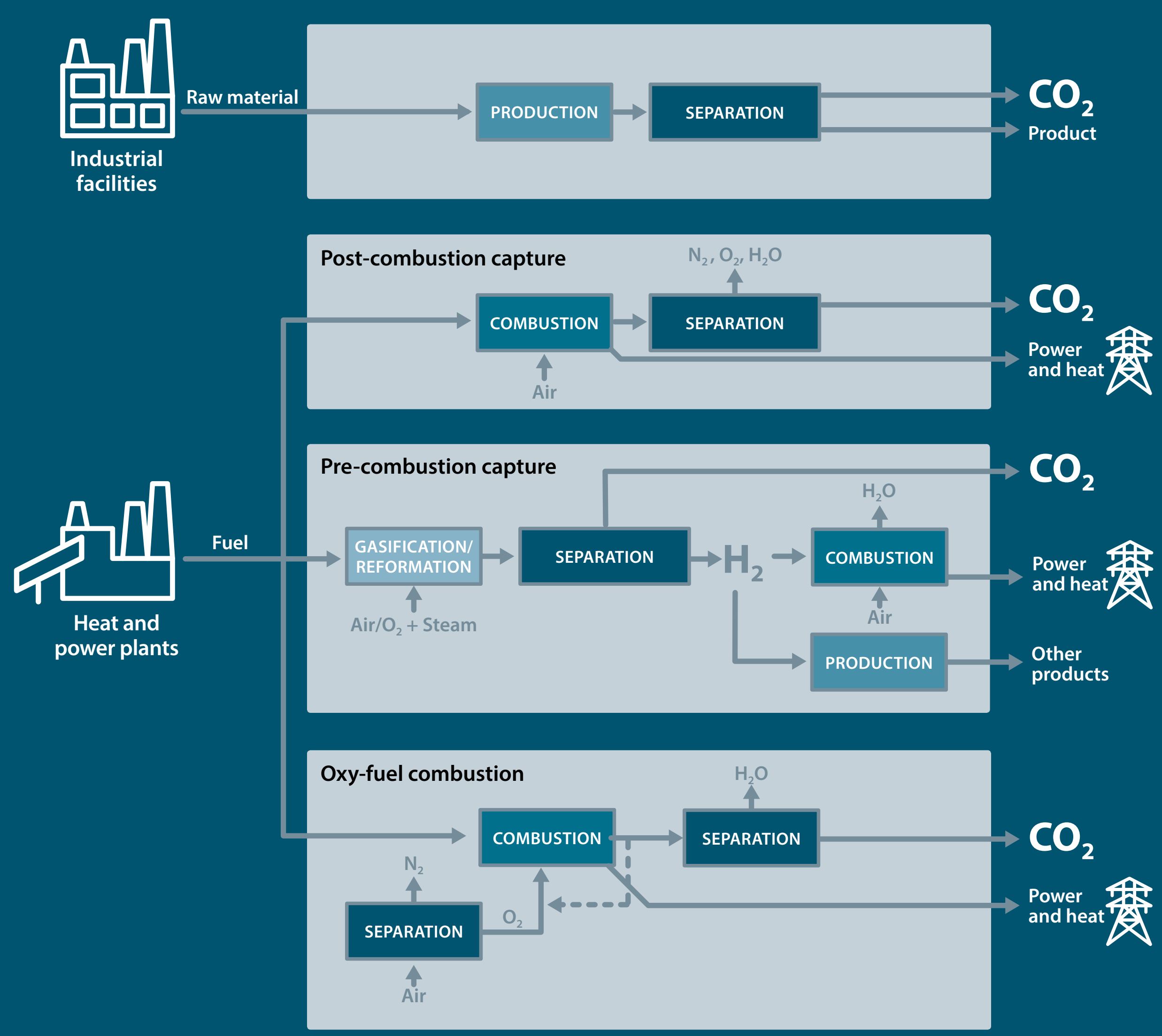
UTILISATION OF CARBON DIOXIDE

Instead of storage, a small share of carbon dioxide could be used as raw material in the production of other – stored or used – materials. Carbon dioxide can, for example, be tied into minerals, mimicking and accelerating their natural decay, or used as a raw material in producing paper fillers.

With regard to utilisation, there is the question of how long the product should tie up carbon dioxide to actually cut carbon dioxide emissions.

"The utilisation of carbon dioxide is not expected to contribute much to the reduction of emissions, but it could play a significant role in the renewable energy systems of the future", Teir says. Carbon dioxide and hydrogen captured in them could be used for producing traffic fuels and raw materials for, inter alia, producing plastics with electricity.

CARBON CAPTURE – MULTIPLE METHODS AVAILABLE



Carbon dioxide is generated when combusting any fuel that contains carbon, and usually it leaves the smoke stack as such into the atmosphere. However, carbon dioxide can be separated and recovered. The methods can be divided into three types:

1. Carbon dioxide is separated from the fuel before combustion. The method is called pre-combustion capture and is used in the production of fertilisers and hydrogen.
2. Pure oxygen is used in combustion instead of air, so the flue gas is almost pure water vapour and carbon dioxide, which can be easily separated from one another. This method is called oxy-fuel combustion. A method under development that uses oxygen contained in metal oxide instead of pure oxygen can also be considered oxy-fuel combustion.
3. Carbon dioxide is separated from the flue gases after combustion. This method is called post-combustion capture and is used in power plants and other industrial plants for producing carbon dioxide for industrial use.

SOLID SCIENCE AND APPLICATIONS

THE CCSP RESEARCH PROGRAMME INVESTIGATED THE TECHNOLOGY OF THE SELECTED CARBON CAPTURE METHODS IN DETAIL, AS WELL AS THE OPPORTUNITIES TO APPLY THESE METHODS IN POWER PLANTS AND OTHER INDUSTRY.

The programme also investigated the preconditions, impacts, development and costs of carbon capture and storage. The research areas were selected from among the core areas of Finnish technological development and industry utilising it.

APPLICATIONS FOR ENERGY PRODUCTION AND OTHER INDUSTRY

In Finland, there is solid expertise in oxy-fuel combustion in particular, which can be used for carbon capture. The oxy-fuel combustion methods are suited for circulating fluidised bed combustion, for example, which is a common combustion method in production, and Finland is a global leader in applying it. By combining these areas of expertise, companies in the industry can achieve a significant position in the carbon capture method market in the future.

Results on pages 22–24 and 26–27

METHODS FOR ANALYSING AND MONITORING ENVIRONMENTAL IMPACTS

Monitoring environmental impacts is an area in which Finnish companies can contribute to the deployment of CCS to a significant extent with special expertise and achieve a significant position in the technology market. The analysing and monitoring methods promote the reliability and safety of carbon capture and storage.

Results on page 25

METHODS FOR THE UTILISATION OF CARBON DIOXIDE

There are multiple minerals and mineral-based industrial by-products and wastes in Finland that can react with carbon dioxide, forming carbonates. The carbonates with the highest quality can be used as raw material in the paper industry, for example. Finland is the leading developer of the method in Europe. Therefore, Finland is exceptionally well suited to test the entire value chain.

Results on pages 28–30

POSITION IN FINLAND'S FUTURE ENERGY SOLUTIONS

Political guidelines guide the capture and storage of carbon dioxide in Finland and the EU alike. Alternative climate scenarios have been used to investigate the suitability of carbon capture methods for Finnish conditions.

Results on pages 18–21

MOST SIGNIFICANT OBSTACLES AND LIMITATIONS

Carbon capture and storage can be deployed on a large scale only when the obstacles to the application of the method have been found and dismantled. The research also serves the creation of support mechanisms.

Results on pages 31–34

38 PEER-REVIEWED SCIENTIFIC ARTICLES

24 MASTER'S THESES

84 CONFERENCE PUBLICATIONS

OVER **90** TECHNICAL REPORTS

8 DOCTORAL DISSERTATIONS

An active cooperation relationship was created with the Nordic and Baltic countries in particular

The foundation of long-term research was strengthened and new pilot equipment resources were created

Connections with international research programmes and organisations were strengthened

MORE EFFICIENT UTILISATION OF BIOMASS AND WASTE

"Fortum is determined to transition from fossil fuels to renewables, and we are among the biggest utilisers of energy wood in the Baltic Sea region. In addition to energy wood, we will also increasingly utilise waste in the coming years. Because of this, the attitude towards the combustion, utilisation and especially refining of biomass in Finland and the rest of the world in the future is particularly important to us. We are also interested in carbon capture and storage first and foremost from the point of view of biomass combustion.

Bio-CCS is not currently profitable, because carbon dioxide released from combustion of biomass is not included in the scope of emissions trading, but we are actively following up the development of EU regulations. For Finland, the intermediate storage of captured carbon dioxide and its transport to the place of final storage are also essential. This requires further investigations."

RISTO SORMUNEN
CTO, Fortum Power and Heat Oy

CCS INEVITABLE – AND EXPENSIVE FOR THE TIME BEING

"The CCSP research programme strengthened the view that major emission reductions in the future will require all possible methods in Finland, including CCS. CCS does, however, require major investments not currently supported by low electricity prices and the structure of emissions trading. Therefore, as an energy producer, it is not currently a topical development project for us in the same way as increasing the use of biomass, for example.

However, the CCSP research programme offered us a good opportunity to learn more about the subject, especially from the Finnish point of view. Finland's special features include combined heat and power production. In it, the increased heat generation of the power plant can cover part of the energy losses caused by capture to electricity generation. We modelled carbon capture in our own power plants and our own energy system, and took a look with a longer term than the next couple of years. We obtained research-based information that is not available by merely following up foreign studies.

From Finland's point of view, bio-CCS seems to offer the most significant opportunities for carbon capture. However, this requires bio-CCS to also be accepted as an emissions reduction measure in emissions trading. Major investments will require a reliable and predictable operating environment. It is important to pay attention to the entire capture and storage chain and related markets and regulations already now so that the system can be adopted later."

TIMO ARPONEN
Head of Energy system development, Helen Ltd

SOLID FOUNDATION FOR FURTHER RESEARCH

"The CCSP research program contributed to the research of carbon capture and storage with solid scientific results. It also provided a thorough techno-economic evaluation to support national policy making. Strong industrial involvement ensured that the achieved results linked well to industrial needs.

The research program included extensive international collaboration, which will also be crucial to future success. International collaboration could advance particularly the demonstration of technologies in large-scale pilot units.

As the CCSP program now ends, research on carbon capture and storage is in a critical phase in Finland. The program highlighted carbon capture and utilization technologies that can lead Finland to the cutting edge in the field as a developer and tester. Commercialization of the technologies will, however, require an increasingly sharp focus on the most promising options. Opportunities are good, but the field is lacking follow-up funding and a clear path for pilot plants.

We recommend future research on most promising, emerging capture technologies, particularly with regard to modelling and associations with bio-CCS. Similarly, we recommend that Finland select one or two of the most promising niche utilization technologies to develop towards commercialization."

MOHAMMAD ABU ZAHRA
Assistant Professor, Masdar Institute

WILLIAM MITCH
Associate Professor, Stanford University

BEN ANTHONY
Professor, Cranfield University

The scientific advisory board visited a pilot plant used for developing oxygen carrier-based combustion at VTT's Bioruukki pilot centre with the program committee and researchers of the CCSP programme in May 2016.

CCSP's research reports and publications are available here:
http://ccspfinalreport.fi/

CONCLUSIONS

OPPORTUNITIES

- Carbon capture and storage (CCS) could profitably cover one-third of Finland's reduction of greenhouse gas emissions by 2050. Over 80% of carbon capture would relate to the combustion or processing of biomass (bio-CCS), the rest to carbon-intensive industry.

- Without carbon capture and storage, the estimated price of emission allowances would more than double in Europe by 2050 compared to a situation in which carbon capture is adopted.

- The utilisation of carbon dioxide can turn out to be a usable method for producing carbon-neutral fuels and other products with electricity. Certain methods, such as converting ashes and slags into mineral products, already seem commercially feasible.

PROPOSALS

- Due to the reasons presented earlier, Finland should continue research and testing related to carbon capture, storage and utilisation.

- Carbon dioxide should be put to test use in Finland in combined power and heat plants firing biomass and peat in particular, as well as at pulp and paper mills. Early application of bio-CCS would provide an opportunity for exporting emission allowances, technology and services.

PRECONDITIONS

- Economic incentives to deploy carbon capture and storage are created in Europe. Technologically, most capture methods can already be taken into use.

- Bio-CCS is acknowledged as a "carbon sink" in the EU's emissions trading, or a support mechanism is created for these "negative emissions".

- Carbon dioxide hubs for facilitating transport are built in Europe.

CCS WILL DECREASE THE COSTS FOR A LOW-CARBON FUTURE

FINLAND HAS STRICT CLIMATE OBJECTIVES, AND REACHING THEM WILL REQUIRE MAJOR INVESTMENTS IN BOTH ENERGY PRODUCTION AND INDUSTRY. CARBON CAPTURE AND STORAGE WOULD DECREASE THE TOTAL COSTS OF THE UNDERTAKING AND SUPPORT THE COMPETITIVENESS OF INDUSTRY.

Finland is well set to reach its climate objectives for 2020 and is preparing for the 2030 objectives. However, it is already evident that the objectives for 2050 cannot be reached without major changes in energy production and other industry.

The CCSP research programme investigated the kinds of changes required for a low-carbon future. The scientists built three alternative routes alongside current policies, leading to the pursued 80% emission reductions by 2050.

"After comparing the scenarios, it seems that carbon capture and storage will be an inevitable part of the low-carbon society. If it is not used, industrial processes in particular must change, or alternatively the production of emission-intensive industry will have to be run down", says **Tiina Koljonen**, team leader at VTT.

ONLINE PROFITABILITY TOOLS

There are interactive tools on the CCSP research programme site for anyone to try that demonstrate how the profitability of carbon capture depends on the market situation. **(http://ccspfinalreport.fi/)**

FINLAND TO BECOME A SELLER OF EMISSION ALLOWANCES

The scientists investigated the most cost-efficient route to the emission reduction objectives by assessing the position of Finland in the EU's emissions trading system in particular. In short, the outcome of the review of the scenarios was that carbon capture and storage will make Finland a net seller of emission allowances, whereas without capture, Finland will be a net buyer of emission allowances. These conclusions assume that bio-CCS, or carbon capture from the combustion of biomass or its processing into traffic biofuels, is accepted in the scope of emissions trading in the future.

"In that case, carbon dioxide captured from biopower plants and forest industry processes will be counted as negative emissions in emissions trading, which would be a significant competitive advantage to us", Koljonen says.

The scenario with the steepest change assumed that Finland will abandon fossil fuels in energy production altogether and also radically renew the processes of industries that generate high carbon dioxide emissions, such as the steel industry. Moreover, the degree of processing of industry was assumed to increase while the volume of production will decrease. Even in that case, carbon capture from the combustion and processing of biomass turned out to be profitable.

"Bio-CCS turned out to be so profitable that fossil fuels were replaced due to economic reasons even in those scenarios in which we had permitted them", Koljonen says.

FROM PILOT USE TO COMMERCIAL USE

Koljonen expects a major increase in carbon capture and storage in 2040–50. "For CCS to be in commercial use after 2030, we should invest strongly in it today. The capture methods have to be demonstrated in large-scale plants, and we will also need clear guidelines on the transport and storage of carbon dioxide", Koljonen says. According to her, it is not crucial from the point of view of development whether carbon dioxide is captured from plants that use biomass or plants that use fossil fuels, as the methods are largely the same. Therefore, a method tested in a Finnish plant combusting biomass is suited for the export market favouring mixed combustion, for example.

GUIDED BY THE PRICE OF EMISSION ALLOWANCES

In the programme, scientists also assessed the profitability of different carbon dioxide capture methods in energy production and industrial processes. Among other things, they investigated how much emission allowances should cost to make it profitable to invest in carbon capture rather than purchasing emission allowances. In comparing the methods the costs of transport and storage of carbon dioxide were also taken into account.

With the price for emission allowances in 2016, clearly under EUR 10 per tonne of carbon dioxide, none of the reviewed methods turned out to be profitable. However, some capture concepts turned profitable at a price of EUR 20 per tonne of carbon dioxide, when the storage cost were neglected and assuming very modest transportation costs. These could be the first sources for carbon dioxide utilisation.

"However, the volume of emissions available among the studied options at a low price is not very large. We are talking about a maximum of one million tonnes

FINLAND'S AND THE EU'S OBJECTIVES

Finland's energy and climate strategy follow the EU's objectives, according to which Finland and the rest of the EU will decrease their greenhouse gas emissions compared to the level of 1990

- by 20% by 2020
- by 40% by 2030
- by 80–95% by 2050

Currently, Finnish legislation extends to the objectives of 2020, and it is based on Finland's energy and climate strategy from 2013. It does not take CCS into account. The 2016 strategy, extending to 2030, is under preparation. The new strategy will take into account the new climate objectives set by the EU for Finland.

The EU's climate and energy objectives are based on limiting global warming to 2°C. However, it was agreed at the Paris climate conference in 2015 that the increase in temperature should be limited to well below 2°C. A report ordered by Sitra showed in 2016 that Finland and the EU will not reach the Paris climate objectives with their current 2030 and 2050 emissions commitments.

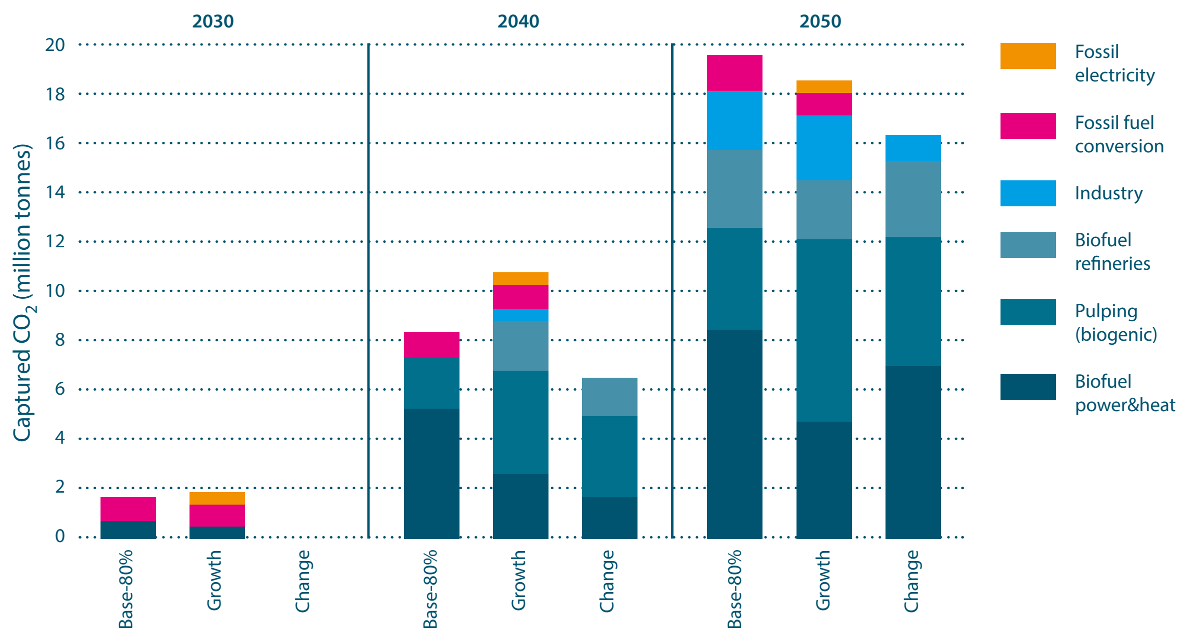
per year", says **Janne Kärki**, Research Team Leader at VTT. Finland's total annual carbon dioxide emissions have been approximately 50 million tonnes in recent years.

If carbon dioxide emissions of 10 million tonnes were to be captured, the minimum price needed for emissions allowances increases to EUR 50 per tonne of carbon dioxide including also transportation and storage costs. In that scenario, also large combined heat and power plants and industrial plants would be included. Transportation and storage costs of CO_2 play a significant role in the total costs – for inland locations up to several tens of euros per tonne. From coastal locations the transportation is much cheaper.

The study found CHP plants fired with biomass, production of liquid biofuels and process industry to be the most cost-efficient for CCS application.

LARGE EMITTERS PLAY A SIGNIFICANT ROLE

Over 50% of the carbon dioxide emissions of the Finnish emissions trading sector are generated by only ten industrial plants. For example, the largest individual source of fossil carbon dioxide in Finland is SSAB's steel mill in Raahe, with annual emissions of approximately four million tonnes.



CCSP PROGRAMME SCENARIOS

- The basic scenario took into account Finland's emission objectives only until 2030 and thereby could not realise the climate objectives for 2050.
- Base-80% took into account the 80% emission reduction objective, but assumed Finland's industrial structure to remain similar to its current structure.
- The Growth and Change scenarios assumed that industry will renew strongly and that new technology will be developed and deployed rapidly. The costs of solar and wind power, for example, will decrease fast. In the Growth scenario, the urban structure became denser, whereas in the Change scenario it fragmented slightly compared to the current structure.
- No low-carbon scenarios in which new technology is not used much were reviewed, as they primarily exclude carbon capture. In the Basic-80% scenario, however, the deployment of technology was slower than in the Growth and Change scenarios.

In the largest plants, capturing carbon dioxide would rapidly yield great benefits to the climate, but the situation is less clear when reviewing profitability. Kärki emphasises that in energy production in particular, emissions can also be decreased by changing the production method, while carbon capture is one of the few options in the steel and concrete industries, for example.

The profitability of carbon capture does not depend only on emission allowances, but also other variables, such as the price of electricity and fuels.

"Therefore, we created interactive tools for reviewing profitability in different market situations", Kärki says.

UPDATING THE SCENARIOS

Finland's Energy and Climate Roadmap 2050 outlined the journey towards a carbon-neutral Finland in 2014 and weighed different options with which Finland could reach its objectives for 2050 while maintaining its competitiveness. Carbon capture and storage emerged as a significant method, and above all, the roadmap emphasised the importance of its commercialisation.

The preparation of the roadmap made use of the scenarios produced in the Low Carbon Finland 2050 platform project in cooperation between VTT, VATT Institute for Economic Research, Finnish Forest Research Institute (currently Natural Resources Institute Finland) and Geological Survey of Finland.

The CCSP research programme, on the other hand, updated the scenarios in 2016 and investigated them from the point of view of carbon capture and storage in particular.

BOILER OPTIMISED FOR CAPTURE READY FOR TEST USE

OXY-FUEL COMBUSTION SUPPORTS CARBON CAPTURE BEST WHEN THE BOILER OF THE POWER PLANT HAS BEEN OPTIMISED FOR IT. EXPERTISE IN THE INDUSTRY IS STRONGLY CENTRALISED IN FINLAND AND BOILER TECHNOLOGY DEVELOPED IN FINLAND.

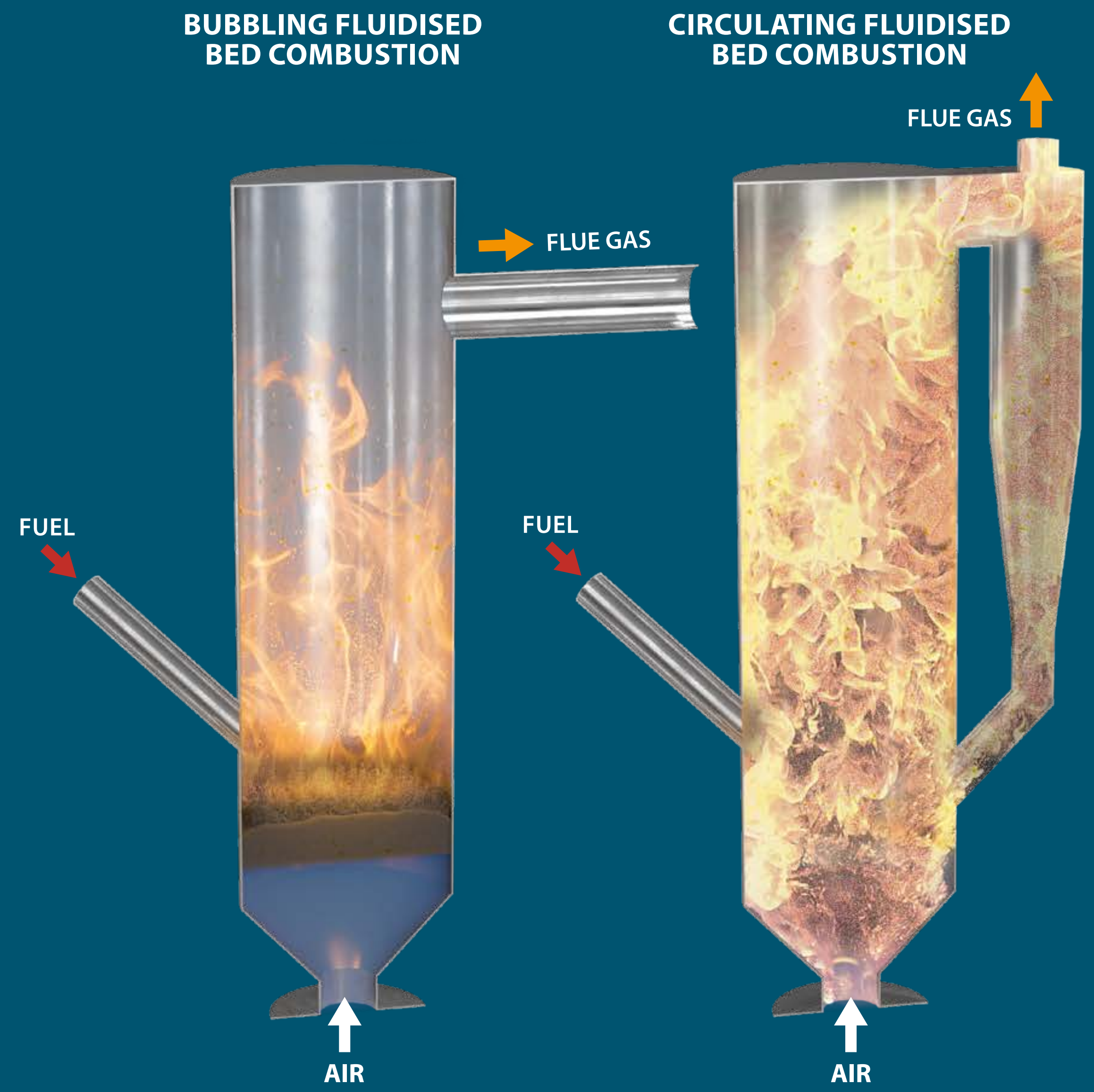
When fuel combusts in air, it creates flue gas that contains also other combustion gases and nitrogen from the combustion air besides carbon dioxide. If pure oxygen is used instead of air, the flue gas is largely comprised of carbon dioxide and water vapour, from which carbon dioxide can be separated easily before capture. Oxy-fuel combustion has been studied closely in Finland for about a decade.

"Oxy-fuel combustion is technologically ready for large-scale test use", says **Reijo Kuivalainen**, project manager at Amec Foster Wheeler Energia Oy. The company is known for circulating fluidised bed boilers used in power plants, among others, and oxy-fuel combustion is adapted for them in Finland.

The CCSP was a natural continuation of the cooperation that companies and research institutions had begun in EU-funded research programmes.

"It is important that research can be continued with roughly the same partners for a long time. This way, we can maintain and develop Finnish expertise even if it is too early to talk about commercialisation", Kuivalainen says.

The research programme focused on modelling what happens in the boiler when combustion air is replaced with oxygen. By combining the models of different research institutions, the scientists built a simulation tool for applying oxy-fuel combustion to circulating fluidised bed boilers of different sizes. "The tools help in assessing the thermal behaviour of the circulating fluidised bed boiler and the formation of emissions, thereby offering a more reliable information base for designing the boiler and specifying its operating values", says **Kari Myöhänen**, senior researcher at the Lappeenranta University of Technology.



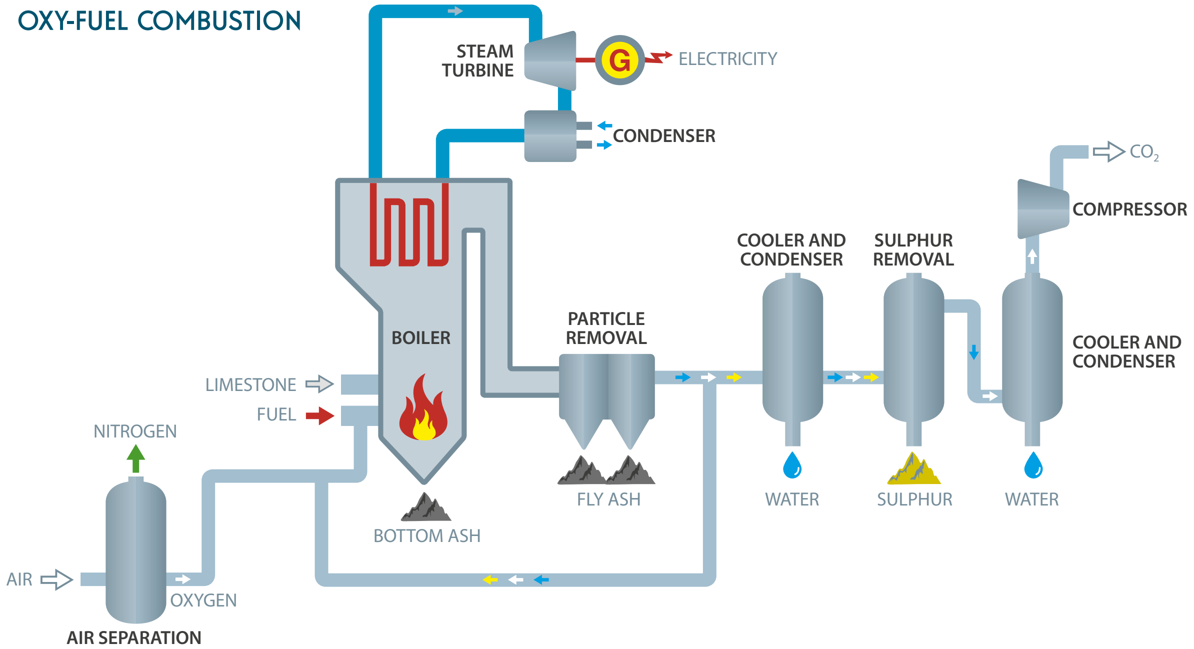
ENERGY PRODUCTION METHOD: FLUIDISED BED COMBUSTION

In fluidised bed combustion, the fuel is fed to the boiler among hot sand functioning as the bed material, which increases the transfer of matter and heat. Moreover, desulphurisation is easy and nitrogen oxide emissions low due to the low combustion temperature and phasing of combustion air. Fluidised bed combustion is actually one of the most important and environmentally sustainable methods in the combustion of solid fuels. Because the method does not set many requirements for the quality of the fuel, such as its humidity or temperature, it is utilised especially in power plants in which fuels are varied or blended. The boilers can incinerate coal, biomass and municipal waste alike.

As versatile utilisers of biomass, Finnish power plants are pioneers in fluidised bed combustion. The method is particularly well suited for combined heat and power production. There are also significant developers of the method and internationally successful equipment suppliers in Finland.

Fluidised bed combustion is realised with two different methods. A low gas flow rate is used in the bubbling fluidised bed boiler, with the sand staying as a bubbling fluidised bed, while the flow rate in the circulating fluidised bed boiler, the flow rate is higher so that the sand goes out of the combustion chamber and is returned to the bottom of the combustion chamber through a separator. Bubbling fluidised bed combustion is typically utilised for wet fuels with a low heat value in relatively small plants, while circulating fluidised bed combustion is also suitable for large plants and almost all fuels.

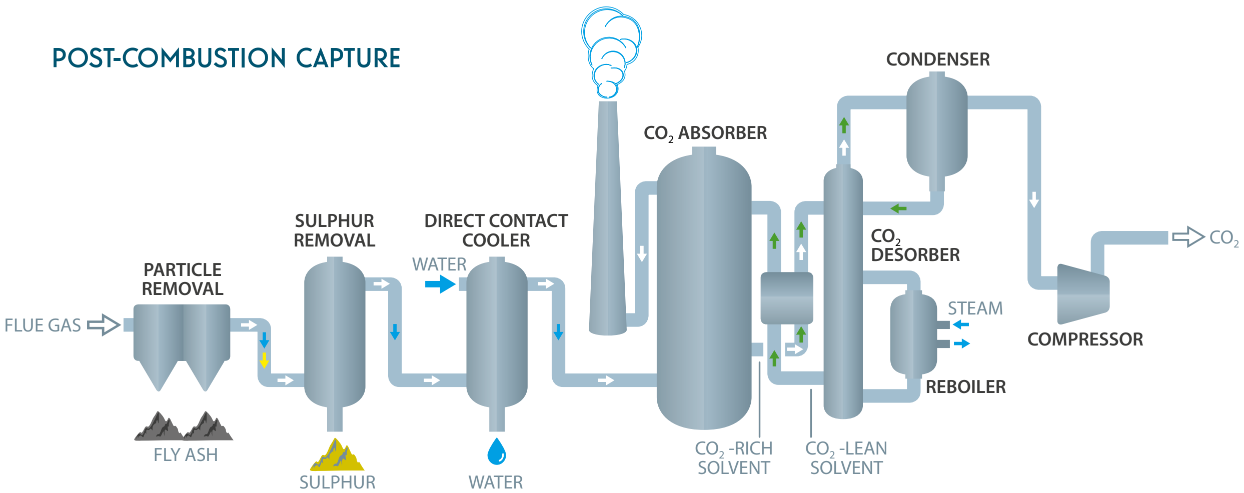
OXY-FUEL COMBUSTION



CARBON CAPTURE METHOD:

- The pure oxygen needed for combustion is produced by separating it from air, which contains nitrogen, and introducing it to the boiler blended into flue gases generated in combustion. This aims for combustion conditions similar to the use of air. Thus, the boiler can be designed to work in both air and oxy-fuel combustion. If the boiler is optimised exclusively for oxy-fuel combustion, the oxygen content can be increased and the furnace made smaller, which saves costs.
- When using pure oxygen in combustion, flue gases are primarily comprised of pure carbon dioxide and water vapour, in which case the carbon dioxide gas is easy to separate by condensing the water vapour. Other impurities are also removed by condensing, which is not possible in conventional air combustion.
- Methods that utilise oxy-fuel combustion are not yet in commercial use, but test plants have been built and tested up to a size of 30 MW.

POST-COMBUSTION CAPTURE



CARBON CAPTURE METHOD:

- Flue gases rising to the stack are guided to a scrubber column in which carbon dioxide is absorbed into a solvent, typically amine. The solution is heated, and the carbon dioxide is released. After this, the solvent is returned to the absorber.
- Industrial scale applications are still quite few, but there are test plants in operation around the world, and at least seven demonstration projects will be launched in the next couple of years.

MEASUREMENT OF EMISSIONS TO A NEW LEVEL

WHEN CARBON DIOXIDE IS CAPTURED AFTER COMBUSTION, AMMONIA OR AMINE EMISSIONS CAN FORM. EMISSION MEASUREMENT METHODS DEVELOPED IN FINLAND SUPPORT THE GLOBAL DEPLOYMENT OF CCS.

A carbon capture plant can be built after the boiler of almost every existing power plant. However, the method consumes a lot of energy and can produce carcinogenic nitrosamines. Carbon dioxide is tied to solvents circulating in the process, such as ammonia or amines, and they can decay forming nitrosamines. Therefore, the CCSP research programme addressed the safety of environment and people alongside the energy consumption of the method.

The scientists assessed the negative environmental impacts of the method above all by measuring amine emissions. Already before the research programme, it was obvious that the concentrations of nitrosamines in the flue gas are very low. It was also known that some of the compounds are quite unstable, and that there is a multitude of them. Because of this, sampling methods were developed in the programme for exhaust gas released into air and the analysis of individual compounds. A method for measuring the combined amount of nitrosamines in the flue gas – more accurately than ever before – was the true breakthrough. The measurement method was also granted an internationally recognised accreditation.

"With the research, we reached such a position in the international network that we are always invited along when scientists or technology developers organise comparison tests between analysis laboratories", says **Eerik Järvinen**, department manager of the Air Quality Unit at Ramboll Finland Oy.

The research programme also addressed the separation of carbon dioxide by reviewing the suitability of various amine solvents and reaction conditions in a scrubber column. The first objective was to cut energy consumption in different phases of the process.

Combining the research of Aalto University and VTT resulted in a model that can be utilised in the selection of solvents and development of equipment in the future.

"We wanted a model that would make it possible to jump directly to a large-scale plant from the laboratory, without building an expensive research pilot. It could be said that the results are strongly inclined in that direction", says **Jussi Laitio**, manager at Neste Jacobs Oy. According to him, the results are also useful in other fields of industry in which acid gases are scrubbed with amine solvents.

NITROSAMINES AT THE PLANT AND HOME

Nitrosamines are carcinogenic compounds that are generated, e.g. when amines disintegrate and react with nitrogen oxides in the flue gases. Nitrosamines are also produced when nitrites or nitrates are present with amino acids, such as in some foodstuffs. Nitrosamines are also regularly detected in cosmetics. It was verified in the CCSP programme that antioxidants, such as vitamin C, prevent the formation of nitrosamines. Even though the matter was not investigated from a medical perspective in the project, this observation encourages adding vegetables to meals containing processed meat.

CARBON CAPTURE WITHOUT WASTING ENERGY

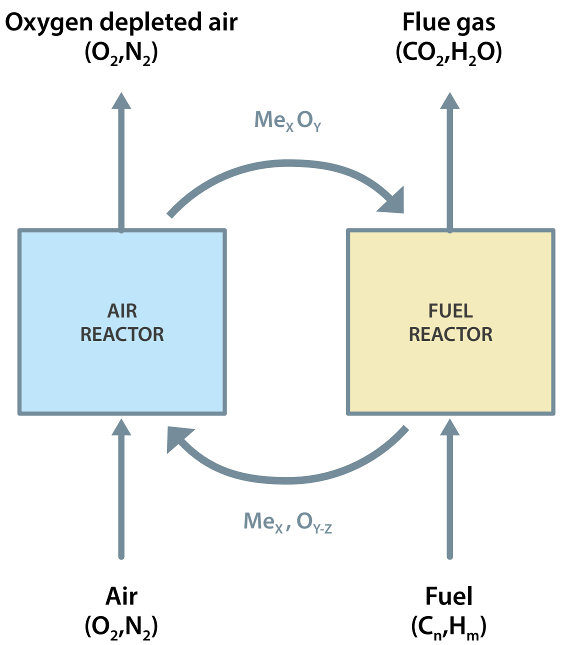
CARBON CAPTURE CONSUMES ENERGY. HOWEVER, CHEMICAL LOOPING COMBUSTION PROMISES MODERATE ENERGY CONSUMPTION.

The separation and capture of carbon dioxide will become easier when the fuel combusts in a gas mix that does not contain nitrogen coming with air. However, producing pure oxygen from air requires a lot of energy. Therefore, oxy-fuel combustion researchers are interested in how the oxygen could be brought to the boiler tied to a carrier material, such as metal oxide.

"The use of metal oxides decreases the efficiency of energy production by only about four percentage points. With other methods, the loss of efficiency is double, even triple that", says **Toni Pikkarainen**, senior scientist at VTT. According to him, the oxygen carrier method, also known as chemical looping combustion, is suitable for a very extensive range of fuels.

Scientists at the Lappeenranta University of Technology developed a reactor model in the CCSP research programme for reviewing how chemical looping combustion, which was successful in the laboratory, could suit large-scale energy production and the use of diverse fuels. The modelling utilised the test results of Austrian and Spanish research institutions obtained through researcher exchange. This way, the Finnish scientists achieved the readiness to simulate carbon capture in an industrial scale and compare the method with other capture methods. In addition, different oxygen carriers were compared in the programme: both natural minerals that contain metals and synthetic materials.

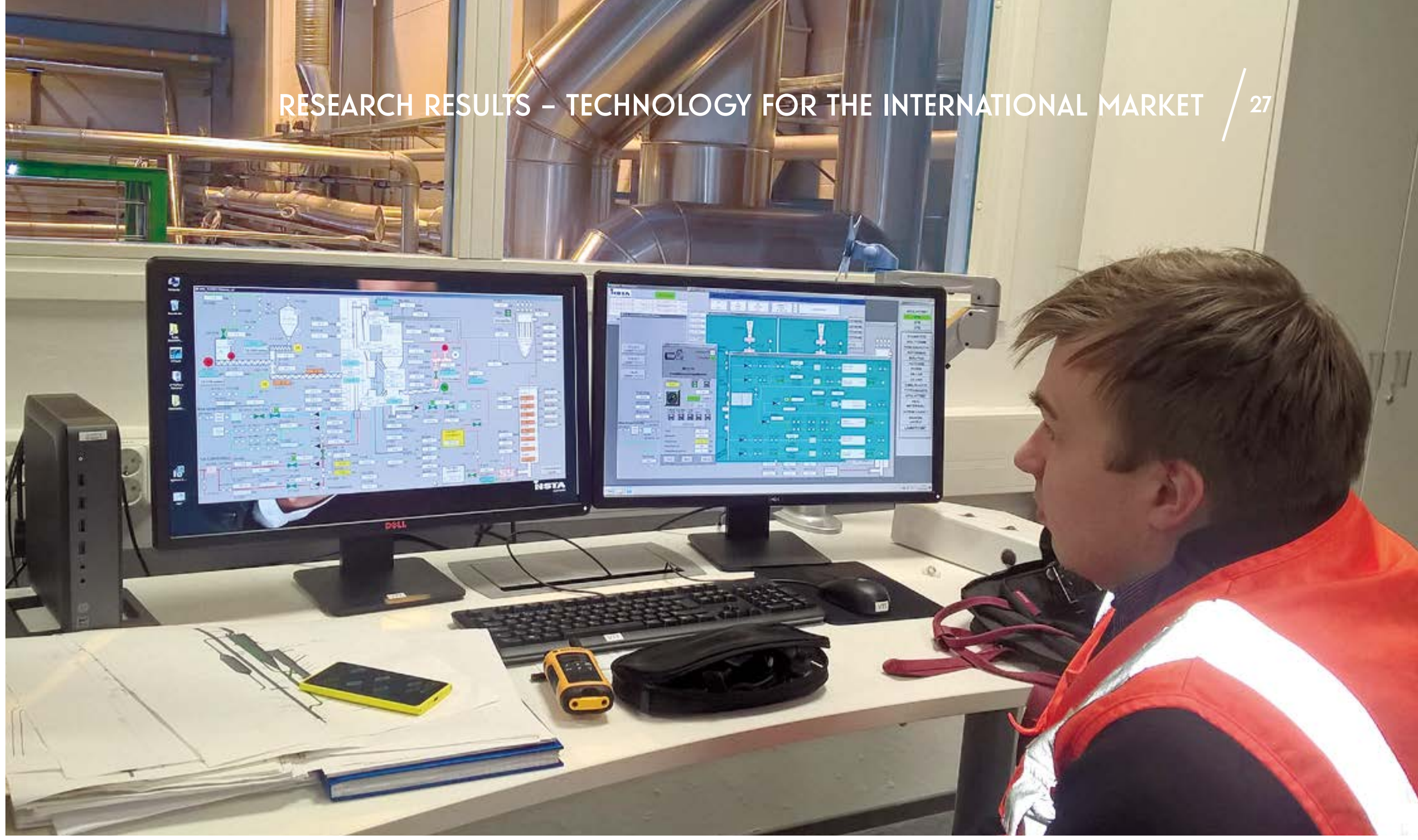
The research work culminated in the construction of a test plant based on bubbling fluidised bed combustion in VTT's new Bioruukki centre. Wood pellets were fired in the tests, and a naturally occurring iron titanium oxide, ilmenite, was used as oxygen carrier.



"We were able to prove that chemical looping combustion works with biomasses. The results are promising, although we can surely achieve even better results by optimising the process and process conditions", Pikkarainen says.

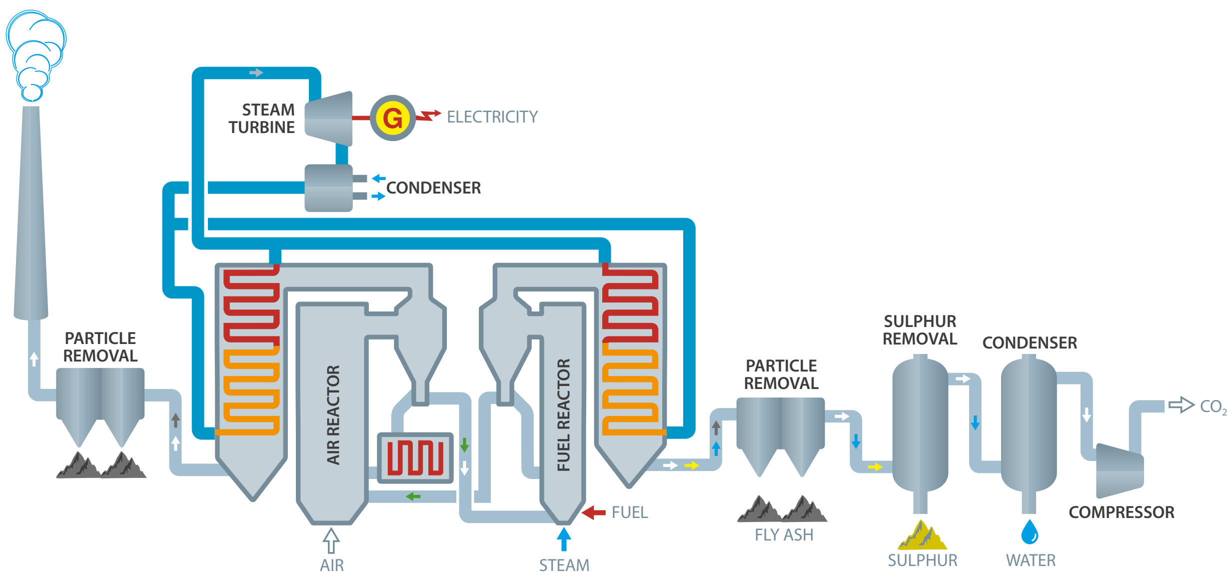
Testing wood pellets at the Bioruukki test plant was unique in the world. Carbon capture methods are not usually associated with biomass plants, as they are excluded from emissions trading and thus do not benefit from capture financially. According to Pikkarainen, however, chemical looping combustion could be profitable in plants combusting biomass in particular, even without the recovery of carbon dioxide.

"The method improves the efficiency of electricity generation in a plant combusting biomass by improving the corrosion resistance of the boiler, thereby enabling higher steam temperatures", Pikkarainen explains. He believes that Finnish biomass combusting plants could be pioneers of the method. This is also the target of a Nordic cooperation project that begun in 2016 and will test the suitability of the method for biomass in a test plant a hundred times bigger than the Bioruukki plant.



Ilkka Hiltunen, head of VTT's Bioruukki test centre, operated the first biomass test combustion with oxygen carriers in February 2016.

CHEMICAL LOOPING COMBUSTION



CARBON CAPTURE METHOD:

- The oxygen is fed to a reactor tied into a solid metal oxide. Once the oxygen has separated from the metal oxide and reacted with the fuel, the reduced oxygen carrier is returned to a separate reactor in which it is oxidised with air.
- Flue gases are primarily comprised of pure carbon dioxide and water vapour, from which carbon dioxide and other impurities can be easily separated.
- Methods utilising oxygen carriers are not yet in commercial use.

MAKING USE OF INDUSTRIAL BY-PRODUCTS

CARBON DIOXIDE PRODUCED IN STEEL PRODUCTION CAN BE REACTED WITH ASH AND SLAG SO THAT THE FINAL PRODUCT IS, FOR EXAMPLE, VALUABLE PAPER FILLER. THE ENTIRE PRODUCTION CHAIN WOULD BE SUITABLE FOR FINLAND.

Steel industry is one of the biggest carbon dioxide emitters, besides energy industry. A small share of the carbon dioxide produced by steel mills can be reacted with slag and ash generated in steel production without having to separate it first from the flue gases.

When calcium-containing slags react with carbon dioxide, very stable compounds, calcium carbonates, are produced, and carbon dioxide will not escape from them in storage. The calcium carbonates with the highest quality can even be used as raw material for various purposes, such as paper filler applications. Carbonates of a slightly lower quality can be used as construction materials.

“In Finland, the steel industry could produce roughly the same amount of calcium carbonate that Finland’s paper industry needs”, estimated Professor **Ron Zevenhoven** from Åbo Akademi.

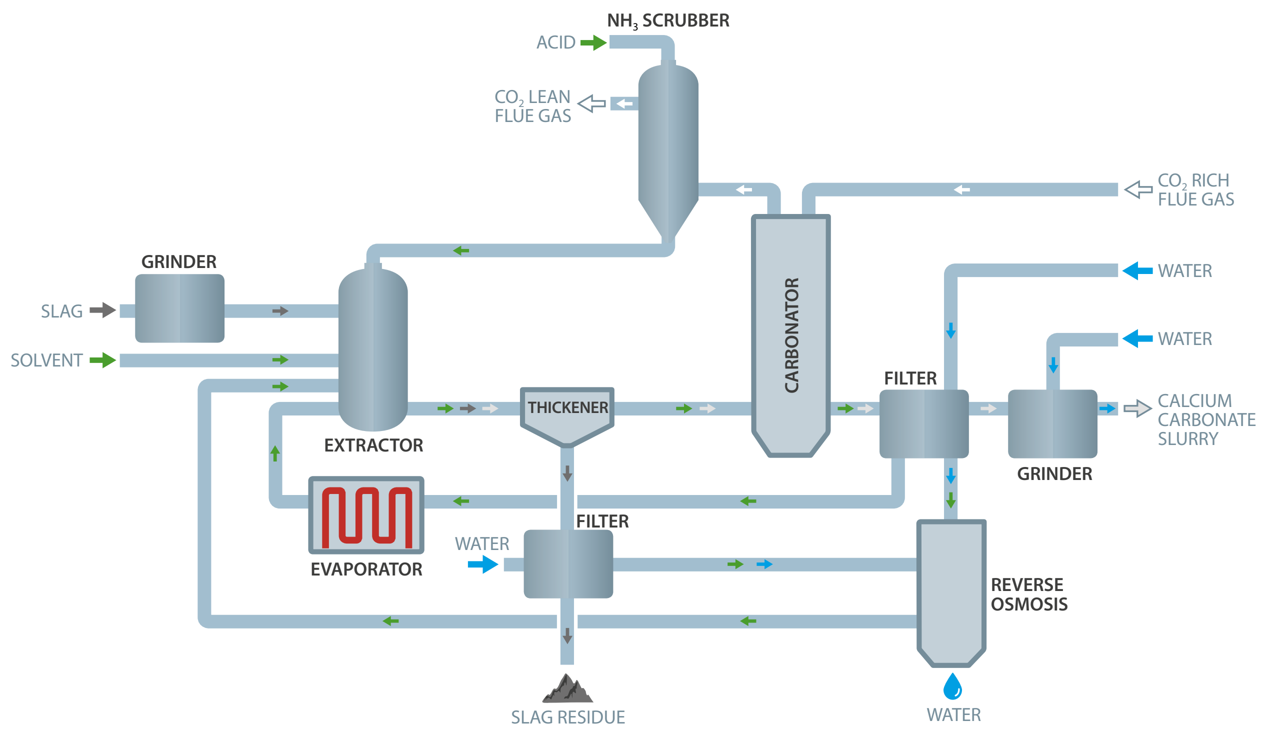
The CCSP research programme continued Aalto University’s and Åbo Akademi’s long-term work with carbonation. Aalto University has patented a manufacturing method for high-quality, precipitated calcium carbonate, and its manufacture has been developed and tested in the test equipment of both universities. In the research programme, the tests were taken to an even bigger scale. During the programme, a laboratory-scale test plant was completed at the Aalto University, able to produce calcium carbonate from steel slag in batches of 3 kg. According to calculations, one tonne of calcium carbonate would tie 300 kg of carbon dioxide.

“The research confirmed the feasibility of the technology.”

CALCIUM CARBONATE FROM LIMESTONE OR SLAG?

Calcium carbonate used by the paper industry is made from limestone, which requires the excavation of minerals and abundant energy use. Recycling could be a more environmentally sustainable solution, such as producing calcium carbonate from steel industry slag. Currently, steel industry slag is utilised in road improvement, for example, and some slag is also still landfilled. The value of calcium carbonate is approximately twenty times that of slag.

Test plant at Aalto University ties carbon dioxide to calcium extracted from steel slag, producing calcium carbonate.



UTILISATION OR PERMANENT STORAGE?

High-quality calcium carbonate produced as a by-product of the steel industry can be used as a coating and filler in paper. At the same time, it ties carbon dioxide and recycles calcium in an environmentally sustainable way. Utilisation does not, however, offer a solution for the long-term storage of carbon dioxide from the point of view of current emissions trading, as the carbon dioxide is released in the combustion of paper – after a few weeks or centuries. Even if EU's emissions trading system supported utilisation, steel industry slag could tie only a very small amount of the world's carbon dioxide emissions.

However, a similar carbonation method can be used for tying large amounts of carbon dioxide into large amounts of natural minerals, such as magnesium silicates, which are abundant in Finland in particular. The method mimics the natural decay of minerals, and chemically stable products, carbonates, are suitable for storage in the soil without monitoring.

However, achieving a sufficient reaction rate requires energy and chemicals. The CCSP research programme succeeded in significantly reducing the need for both.

CARBON CAPTURE CAN DOUBLE THE ENVIRONMENTAL BENEFITS OF BIOMASS

FROM THE POINT OF VIEW OF CLIMATE, CARBON DIOXIDE IS CARBON DIOXIDE, REGARDLESS OF ITS SOURCE. THEREFORE, CARBON CAPTURE IS ALSO JUSTIFIED IN THE CARBON-NEUTRAL COMBUSTION AND PROCESSING OF BIOMASS – AND BEFORE LONG ALSO PROFITABLE.

Carbon capture will not probably make those combusting and processing biomass enthusiastic at the moment, as the EU's emissions trading does not acknowledge negative emissions.

"Yet negative emissions offer a tempting back door for mankind, which seems to be approaching the climate objectives quite slowly. In Finland alone, annual emissions could be decreased by tens of millions of tonnes if the producers of bioenergy were to capture carbon dioxide", says **Antti Arasto**, business development manager at VTT. Finland's annual carbon dioxide emissions have amounted to approximately 50 million tonnes in recent years. Slightly over one half of this is included in the scope of emissions trading.

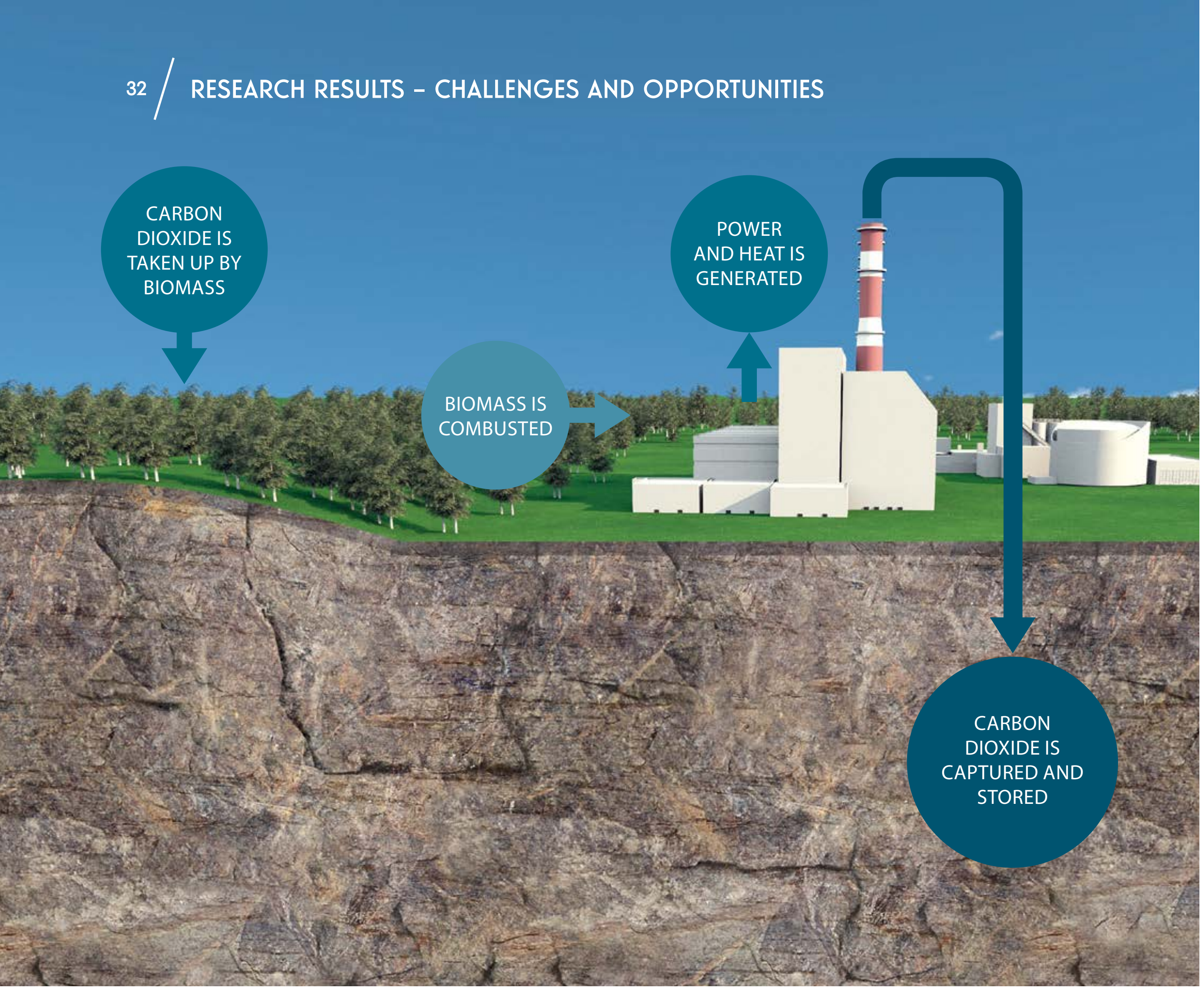
Arasto believes that bio-CCS, or recovery of carbon dioxide from the use of biomass, will inevitably be put forth when the price of carbon dioxide emissions increases significantly in the EU at the latest. He emphasises that technologically, carbon capture is suitable for a plant combusting biomass just as well as for a plant combusting fossil fuels. He thinks that the challenge lies mainly in biomass-combusting plants being typically quite small, as they must be located within a reasonable distance from the sources of biomass. Thus, the investments related to recovery are proportionally higher than in bigger power plants. "The commercialisation of the method will also require credible long-term objectives for reducing emissions", Arasto says.

He considers the manufacturers of liquid biofuels, i.e. refiners of biomass, natural pioneers.

"One half of the carbon goes into the fuel and roughly one half is emitted as pure carbon dioxide in any case. From there, it is very easy to capture", Arasto says. According to him, Finland could also lead the way with its experience in the combustion of biomass. After all, Finland has long traditions in the use of biomass in combined heat and power production, while in southern parts of Europe, biomass combustion mainly refers to the parallel incineration of biomass in coal boilers.

Arasto deems it important that VTT was able to strengthen its international cooperation and survey the outlook of biomass use in the EU through the CCSP research programme.

"Now, the work will continue with the International Energy Agency IEA and the European Commission, guided by VTT and CCSP."



NEGATIVE EMISSIONS – CARBON SINK

Carbon dioxide emissions are produced in the combustion of fuel. However, it is customary to calculate that the carbon dioxide ending up in the atmosphere in the combustion of biomass will be tied again into the biomass as it grows. Because of this, biomass is considered a carbon-neutral fuel, and only the users of fossil fuels must pay for their carbon dioxide emissions or recover them. However, if carbon dioxide produced in the combustion or refining of biomass is captured and stored, it is actually removed from the atmosphere. Bio-CCS can therefore produce negative emissions and drive the world towards the international climate objectives. However, EU's emissions trading system does not currently acknowledge negative emissions.

WILL CAPTURE OFFER ADDITIONAL TIME FOR FOSSIL FUELS OR A NEW CARBON SINK?

Carbon capture and storage offers users of fossil fuels a way to decrease emissions. However, some suspect that it could increase the use of fossil fuels. The CCSP research programme shows that increasing the use of fossil fuels will not probably be attractive in Finland. Based on analyses, the adoption of carbon capture would be considerably more profitable for plants that use biomass than plants that fire fossil fuels in Finland.

TOWARDS EMISSION CUTS – OVERCOMING OBSTACLES

CARBON CAPTURE AND STORAGE WILL MITIGATE CARBON DIOXIDE EMISSIONS SIGNIFICANTLY IF THE METHOD IS ADOPTED AND BECOMES COMMON. SO WHAT'S HOLDING IT BACK?

Carbon capture and storage can become an important method for reducing carbon dioxide emissions once the limitations and obstacles are overcome. The CCSP research programme investigated the sustainability of different methods, taking into account their ecological, economic and social impacts. Legislation and general attitudes were considered as aspects of social sustainability, among others.

"The shortcomings in legislation can be corrected. Economic profitability is the biggest challenge", **Eemeli Tsupari**, senior scientist at VTT, sums up.

ECOLOGICAL IMPACTS CAN BE MANAGED

The effects of carbon capture on environment depend largely on the capture method. What is common to the methods is that the energy consumed by capture increases fuel consumption and thereby influences emissions either at the same plant or elsewhere in the energy system. In addition, when solvents are used in separating carbon dioxide, compounds created from the solvents can end up in the environment with the flue gases. On the other hand, when carbon dioxide is separated by increasing its concentration, such as by oxy-fuel consumption, the concentrations of impurities also increase in the flue gases, even if the absolute amounts remain unchanged. Both separation methods lead to the need for removing impurities effectively before the recovery of carbon dioxide. Therefore, it is likely that several other emissions into air from the plant decrease in connection with carbon capture, but some emissions could increase.

"It is largely a question of what the acceptable emission amounts are, how the different environmental impacts are weighed, and how certain emissions can be measured and controlled in a reliable way", Tsupari says. He emphasises that many chemicals used for capture are already well known in various industries. The risks of accidents related to the handling of solvents and pure oxygen are also well known.

"When carbon capture is viewed from an ecological point of view, it is very important to consider the entire life cycle, including the effects on the energy system and other emissions alongside carbon dioxide emissions", Tsupari adds.

ECONOMIC LOSSES CAN BE PARTIALLY COVERED

The efficiency of energy production is considered especially when assessing the economic profitability of carbon capture and storage.

"The loss of efficiency caused by recovery has a strong effect on the profitability of power production, while combined heat and power production can utilise part of the heat generated by capture and cover the efficiency loss partially with it", Tsupari says. He emphasises that the efficiency losses vary between methods and applications. "Profitability can also be significantly improved if the carbon dioxide can be utilised instead of storage."

OBSTACLES OF EMISSIONS TRADING CAN BE OVERCOME

In Europe, the profitability of carbon capture and storage is largely determined by emissions trading. According to Tsupari, there are at least two aspects in legislation on emissions trading whose reform could significantly promote carbon capture in Finland. They have to do with fuels and the transport of carbon dioxide.

EU's emissions trading system is currently focused on carbon dioxide emissions, which are generated when combusting fossil fuels. It is not economically profitable for a plant combusting biomass to mitigate its emissions by capturing carbon dioxide.

Currently, the emissions trading system also ignores carbon capture when carbon dioxide is transported to storage by ship and not through a pipeline.

"The shortcomings related to biomass combustion and transportation by ship affect the position of Finland in particular, as there is a lot of biomass combustion in Finland, but no possibility of storing carbon dioxide in our own bedrock."

PROPOSALS FOR LEGISLATION ON EMISSIONS TRADING

The scientists offer a solution model to address the shortcomings of emissions trading. "Emission allowances issued in the emissions trading system could be given to those that store carbon dioxide for free based on the amount stored. This way, there would be compensation for a carbon sink where the sink is created. In this case, the storing party would begin to need to purchase carbon dioxide from carbon dioxide emitters included in the scope of emissions trading, who would not otherwise be refunded for capture in this model. This way, it would not be necessary to agree separately on transportation methods or negative emissions or the details of their supervision", Tsupari says.

According to Tsupari, the situation would also be clarified by allowing the utilisation of carbon dioxide as an alternative to storage, provided that the application ties the carbon dioxide for decades or centuries.

"For example, when tied into paper filler as calcium carbonate, carbon dioxide remains out of the atmosphere for quite a long time. Perhaps it could be considered to offer some benefit", Tsupari thinks.

REMOTE TO PEOPLE, LARGELY POSITIVE

The research programme also investigated the attitude of the Finnish public towards carbon capture and storage. The research focused on stakeholder interviews and articles in mass media during the last ten years. The majority of them treated the subject in a positive or neutral way.

"The subject is quite remote to Finns, and it does not give rise to strong feelings", Tsupari states. In Germany, for example, citizens were intimidated a few years ago by the idea of storing carbon dioxide in the bedrock on the continent and not under the seabed. With the Finnish bedrock, storage would not even be possible.

In Finland, the negative attention concerned mainly costs, challenges of storage and the fact that carbon capture and storage will make the use of fossil fuels possible in the future as well, and might even increase it.

"Defenders, on the other hand, appreciated us being able to reach the climate objectives faster and more cost-efficiently if fossil fuels could be combusted without increasing carbon dioxide emissions", Tsupari reports. He also says that it was also considered positive that many capture methods and also some storage methods are based on technology already known from other industry.

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