Impetus from the Kopernikus Projects | 2019

PAVING THE WAY FOR A SUSTAINABLE ENERGY SYSTEM

KOPERNIKUS PROJEKTE
Die Zukunft unserer Energie

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Published by
Kopernikus Project Energy Transition Navigation System | ENavi
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Last updated September 2019

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Printed by
Printsystem GmbH, Schafwäsche 1-3, 71296 Heimsheim

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TIPPING POINT

The targets of Germany's climate and energy policies are ambitious. Relative to levels in 1990, greenhouse gas emissions must decline by 55 percent by 2030 and by 80–95 percent by 2050. 90 percent of the population supports the transition to clean energy, though the majority have criticised the way it has been implemented.

A Copernican revolution in energy research

Since the autumn of 2016, the Federal Ministry of Education and Research (BMBF) has funded four Kopernikus Projects for studying the energy transition: ENSURE, P2X and SynErgie advance innovation and technological development, while ENavi integrates these advances into the existing systemic, socio-economic, institutional and cultural context.

These projects serve as research workshops for the practical implementation of the energy transition. Their aim is to create pivotal impetus for the establishment of a low-carbon energy system. Researchers in the Kopernikus Projects are cooperating with over 240 partners from science, industry and civil society.

For more information, see www.kopernikus-projekte.de

P2X encourages the use of renewable electricity in the transport and chemicals sectors. **ENSURE** sheds light on new energy supply structures. **SynErgie** explores strategies for enabling more electricity demand flexibility in the industrial sector. **ENavi** links scientific analyses to political and social requirements.

1. IMPETUS FOR THE ENERGY TRANSITION

P2X

Today, more than one-third of electricity generated in Germany today comes from renewable sources such as wind and solar power. This achievement represents an important step towards creating a clean, low-carbon energy system, in which renewables will replace fossil energy sources such as coal or natural gas. The burning of fossil fuels releases carbon dioxide (CO_2) into the atmosphere, which drives global warming. In contrast, renewables do not release CO_2 when used. Their downside is that they are only generated when the sun is shining or the wind is blowing. For this reason, more than 330 scientists and engineers are developing technologies in the Kopernikus Project Power-to-X (P2X) to convert CO_2 and water into fuels and chemicals using electricity from renewable sources. In the future, these technologies can be used to lower CO_2 levels in the atmosphere.

ENSURE

Sustainable, multimodal energy system structures must meet today's requirements and demands with regard to supply reliability, flexibility, stability and system security. In addition, they must also be able to provide energy that is CO_2-neutral, economically viable and highly flexible. The digitisation of supply structures will enable new methods and strategies to be implemented in a volatile environment, thus contributing to the reliability, stability and economic efficiency of energy system management in the future. With these aims in mind, the results of the ENSURE project's work are of particular importance for the successful realisation of the energy transition. The project enhanced the identified network structures and its investigation of new system management concepts with the parallel development of primary and secondary technologies.

SynErgie

The Kopernikus Project SynErgie contributes to the energy transition by comprehensively identifying, developing, and quantifying the flexibility potential of electricity demand in Germany's industrial sector. SynErgie researchers developed and tested technologies that help industry exploit its full flexibility potential. In addition, they identified recommendations for reducing regulatory obstacles that stand in the way of this goal. Two training initiatives for young researchers, the Doctoral Seminar and the Visit-the-Best programme, help ensure that the next generation is ready to continue the work towards a clean energy future.

ENavi

The Kopernikus Project ENavi, short for Energy Transition Navigation System, approaches the transition of the energy system into a largely CO_2-free and renewable energy-based system as a process of societal change. ENavi links scientific analyses to political and social requirements. The project's key product is a navigational aid that the researchers will use to gauge the effects and side effects of economic, political, legal and social measures in advance. ENavi brings together system knowledge (what causes what?), orientational knowledge (where to go?) and transformation knowledge (how do we best get there?).

2. P2X: CONVERSION OF ELECTRICITY INTO HIGH-VALUE ENERGY SOURCES

- **Electrolysis** is a chemical reaction in which a starting material is split into higher-energy building blocks by means of electric current.
- A **catalyst** induces a chemical reaction, accelerates it or determines which of the possible products is formed (selectivity of the products) and remains unaltered after the reaction.
- **Synthesis gas** is an industrially produced gas mixture of carbon monoxide and hydrogen.

The core technologies of Power-to-X are based on electrolytic and catalytic reactions. Electrolysis converts CO_2 and water into intermediate products, which are then converted into chemically higher-value compounds such as synthetic fuels or plastics.

The umbrella term Power-to-X comprises various processes for conversion of electricity:

- Power-to-gas: production of gaseous substances such as hydrogen and methane
- Power-to-liquids: production of liquid energy sources such as fuels
- Power-to-chemicals: production of raw materials and products for the chemicals industry

In the first three-year funding period of the project which ended by mid-2019 the researchers developed promising P2X technologies and concepts. In the subsequent funding phase, they intend to develop these further in order to make the technologies market-ready and to test them within the context of value chains for the production of chemical products.

Water electrolysis – how to save costs and materials

The electrolysis of water into hydrogen and oxygen is a very energy-consuming Power-to-X process. In order to make it more economical and cost-effective, scientists at the Technical University of Munich (TUM) are developing new electrode materials that contain less expensive precious metals and, if possible, improve the performance.

This can be achieved by intelligent material design such as increasing the active surface in which the chemical reaction takes place. In proton exchange membrane (PEM) electrolysis, where a proton exchange membrane separates the two electrodes, hydrogen is formed at the cathode and oxygen is formed at an iridium-based anode. In the first funding phase of the project, researchers reduced the amount of Iridium by a factor of ten while maintaining the same performance.

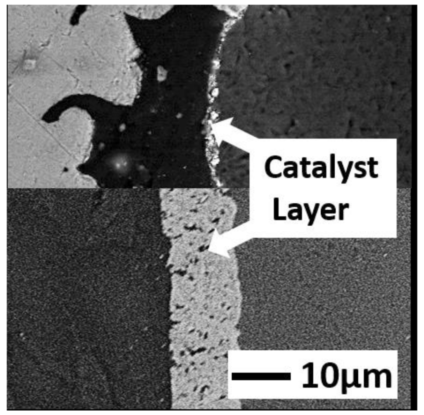

Figure 1: Scanning electron microscope image of the interface of electrode and membrane material (Technical University of Munich)

The scanning electron microscope image (figure 1) shows the cross section of an electrode prepared with a commercial catalyst material (upper part of the figure) and compares it to an electrode with the same loading (0.2 mg Iridium per cm²) produced with a novel catalyst material (lower part of the figure). Thanks to the intelligent design of the new catalyst material, it is possible to produce a homogeneous electrode layer despite lower levels of the precious metal.

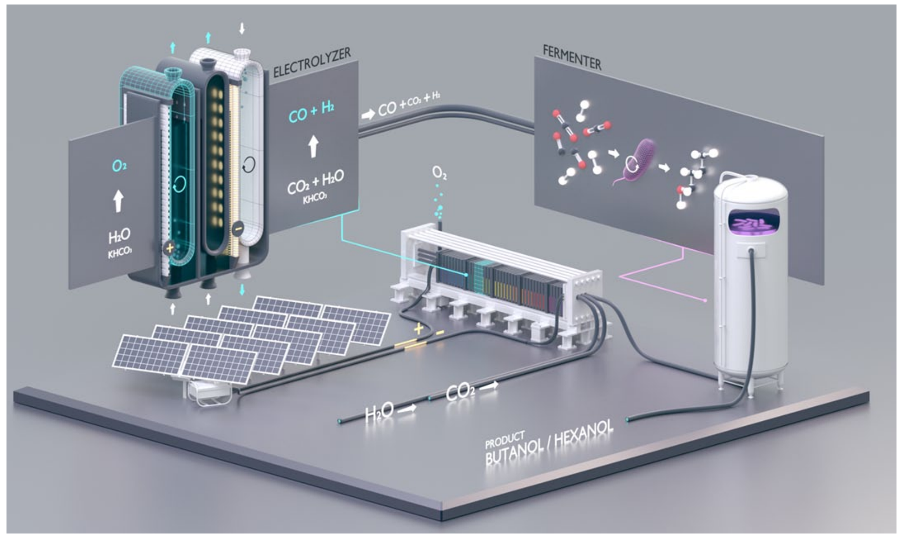

Figure 2: Rheticus – Establishing a value chain by combining co-electrolysis and fermentation (Haas, T.; Krause, R.; Weber, R.; Demler, M.; Schmid, G. (2018) in: Nature Catalysis 1, 32–39)

Rheticus – a Power-to-X idea becomes reality

The Rheticus research project was co-founded by Evonik and Siemens on the basis of very promising initial results in the first phase of the Kopernikus Project P2X. Evonik and Siemens are developing a pilot plant that will use bacteria to produce „green" chemicals from CO_2 and electricity from renewable sources. The specialty chemicals produced in this way – such as butanol and hexanol – are important precursors for specialty plastics and dietary supplements. Other chemicals and synthetic fuels could also be possible products. The independent project started in early 2018 as a satellite project of the Kopernikus Initiative and is funded by the Federal Ministry of Education and Research.

Award-winning start-ups

The start-ups participating in the research network have further developed their technologies and are now successfully offering market-ready solutions. Two of the start-ups have received awards for their work.

INERATEC GmbH has developed micro-reactors with which various Power-to-X processes can be implemented more compactly than ever before. The reactors convert synthesis gas into compounds and mixtures, such as synthetic diesel fuel. INERATEC installs the micro-miniature reactors into mobile container systems which can be readily transported to places with abundant quantities of renewable energy or where fuel shortages are likely due to the absence of infrastructure. In 2018, the company was awarded first place in the „Start-up" category of the 2018 German Founders' Award.

Hydrogenious Technologies offers solutions for safe hydrogen storage, hydrogen transport and its release. The company uses LOHCs (liquid organic hydrogen carriers) which are non-toxic, barely flammable liquid substances to bind hydrogen chemically and release it again at the place of application using special catalysts. The company was among the top three shortlisted nominations for the German Future Prize in 2018.

High-temperature co-electrolysis – turning CO_2 into a valuable raw material

The Jülich Research Centre studies high-temperature co-electrolysis, a direct one-step process using electrolysis to convert CO_2 and steam into synthesis gas. The reaction is conducted at very high temperatures – around 800 degrees Celsius. The resulting gas mixture of CO and hydrogen contains the building blocks carbon, oxygen and hydrogen, and is therefore an important intermediate product in numerous petrochemical processes. During the first Kopernikus project phase, researchers showed that the H_2-CO ratio in synthesis gas can be adjusted over a range of four-to-one to one-to-one by varying the composition of the steam-CO_2 mixture, making it possible to produce tailor-made synthesis gas. The process can very efficiently produce desired gas compositions using high electric current density.

Dehydrogenation of LOHCs – a new catalyst facilitates the release of hydrogen

A further highlight of successful research and development in the Kopernikus Project P2X is a new form of catalyst generation for the dehydrogenation of perhydro-dibenzyltoluene (LOHC+) in industrial applications.

The new approach was tested by the research unit Decentral H_2 Logistics: Storage and Distribution using Liquid Hydrogen Sources. This new technology was a result of the close cooperation between Friedrich Alexander University (FAU), Karlsruhe Institute of Technology (KIT), RWTH Aachen University and the industrial partners Hydrogenious Technologies and Clariant. The university partners conducted the fundamental work on reactions and spectroscopy. Hydrogenious Technologies was responsible for the industrial application tests, while Clariant successfully developed the production of the catalyst and now manufactures it on a commercial scale. The new dehydrogenation catalyst is known by the product name EleMax D101. Due to its superior release rates, high precious-metal efficiency and outstanding selectivity, EleMax D101 represents the new industrial standard for the technical release of hydrogen from LOHC+.

Modular and compact Power-to-X facilities

At the Karlsruhe Institute of Technology, scientists and engineers from the Institute for Micro Processing Technology (IMVT) and from the companies Climeworks AG, Sunfire GmbH and INERATEC GmbH built a modular container system for decentralised use and are currently in the process of putting it into operation. The plant is the world's first fully integrated P2X system. It carries out all process steps, from the capture of CO_2 from the ambient air to the synthesis of the end products – CO_2-neutral synthetic fuels.

All steps are synergistically coupled: the capture of CO_2 from the air, the high-temperature co-electrolysis of CO_2 and steam to synthesis gas, its conversion into hydrocarbons via the Fischer-Tropsch synthesis and the hydrogenation of hydrocarbons to maximize the yield and quality of the liquid fuels. The material and thermal coupling of the individual steps enables high energy efficiency and nearly 100 percent conversion of the CO_2 obtained from the air into liquid fuels. In the trials it will be possible to continuously produce about 10 litres of synthetic fuel per day. In the next phase of the project, improved modular systems based on a variety of reactor concepts will be able to produce different products. For example, a production facility near a petrol station could supply synthetic fuels and a facility near a plastics manufacturer could supply the required specialty chemicals.

Roadmap

A roadmap was drawn up by DECHEMA to accompany P2X research. It follows the developments of the various P2X technologies and evaluates them in terms of their ecological, economic and social sustainability. The results of the evaluation feed into the further development phases and shape the resulting technologies with regard to these three issues. The roadmap describes the potentials of Power-to-X fuels and classifies them within the existing energy system. If the clean energy transition is to be successful and accepted by society at large, it is important that the ongoing research be discussed openly, inside and outside the project. Together with a well-informed public smart decisions can be made for shaping the clean-energy transition. Public dialogues will take place as part of the roadmap, with a special emphasis on the opinions of young people.

3. ENSURE: VIABLE ENERGY NETWORK STRUCTURES

The decentralised production of renewable energies (RE) will play a decisive role in the energy network structures of the future. This will necessitate modifying power grids into heavily interconnected structures requiring intelligent network components for installing and operating hybrid AC and DC grids. The growing number of generation plants, storage facilities and power-to-x plants that feed into the low, medium and high-voltage grids will further compound this effect, making bidirectional load flow necessary. However, the specific requirements of this "energy network of the future" will differ significantly, depending on which transformation path Germany takes.

During the first funding stage of the ENSURE project, which ended in mid-2019, researchers identified the socio-economic conditions and socially acceptable transformation paths for this type of grid modification, which they then used as a basis for developing possible system structures in the "energy network of the future". They subsequently compared these scenarios in a comprehensive system study, which took into account all relevant energy sources and factors in Germany. At the same time, researchers developed a holistic concept for managing future energy network structures and intelligent network components. In order to demonstrate the feasibility of transforming the energy network structures, researchers at ENSURE have proposed constructing a test facility, "ENSURE energy cosmos", which will merge the various strands of research into a common workable concept and make them tangible for a wider public.

Transformation paths to clean energy transition

Together with representatives from leading social and industrial organisations, ENSURE researchers have created potential development paths for energy supply, resulting in four storylines. Storyline A ("Reference") is based on Germany's 2017 Network Development Plan (NEP) for electricity. In this storyline, greenhouse gas (GHG) emissions in Germany should decrease by 52 percent by 2030, relative to 1990. By contrast, storyline B ("Ambitious CO_2 reduction") aims to reduce GHG emissions by 78 percent by 2030, in order to restrict the effects of climate change to a rise in temperature of 1.5 degrees Celsius. Storyline C ("Decentralised")

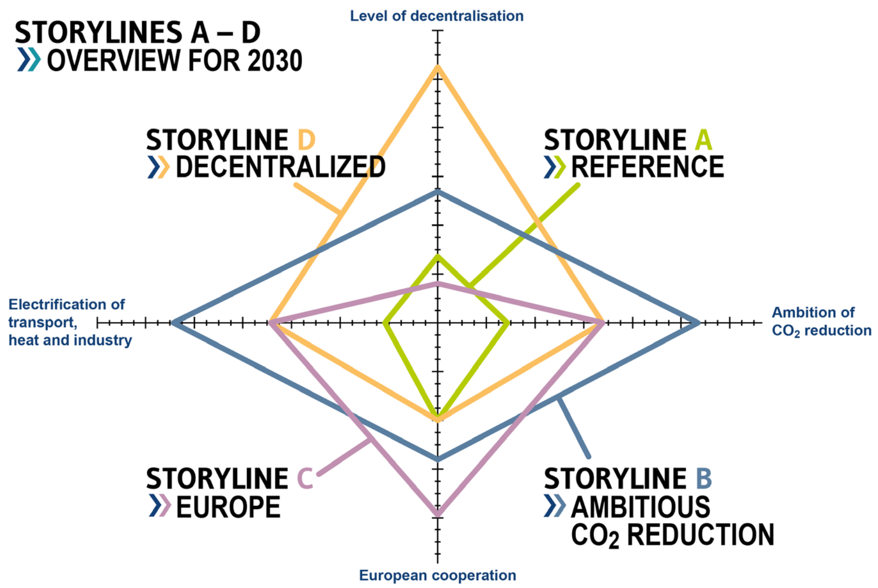

Figure 3: Schematic procedure for assessing centrality and decentrality of a grid structure (SH-Netz AG)

and storyline D ("Europe") both aim to achieve the minimum requirement of the Paris Climate Agreement, according to which GHG emissions fall by 67 percent.

The overwhelming majority of involved stakeholders prefers storyline B, which indicates a strong emphasis on climate protection among the professional organisations involved in the project. The studies accompanying the storylines describe a comprehensive scope of interaction up to 2030. They discuss issues ranging from the public acceptance of new network installations, the incentive-driven design of the energy market and the regulatory framework, as well as the problem of the lack of skilled labour for energy-focused building requirements. The results emphasise the extent of measures required across all sectors. All storylines thus require renewable energy facilities beyond the targets defined in the Renewable Energy Act.

Design of new network structures

In a broad system study, researchers differentiated four possible designs for energy supply systems to implement the clean energy transition, based on the four storylines. The energy sources electricity, gas, heat and liquid fuels were taken into account. The storylines defined the market structure, primary energy input, final energy consumption and the required expansion of systems for energy storage and energy conversion. The remaining two variables in the development of the system structures – the precise design of networks, as well as of information and communication technology (ICT) – were used for optimal spatiotemporal distribution of energy and power.

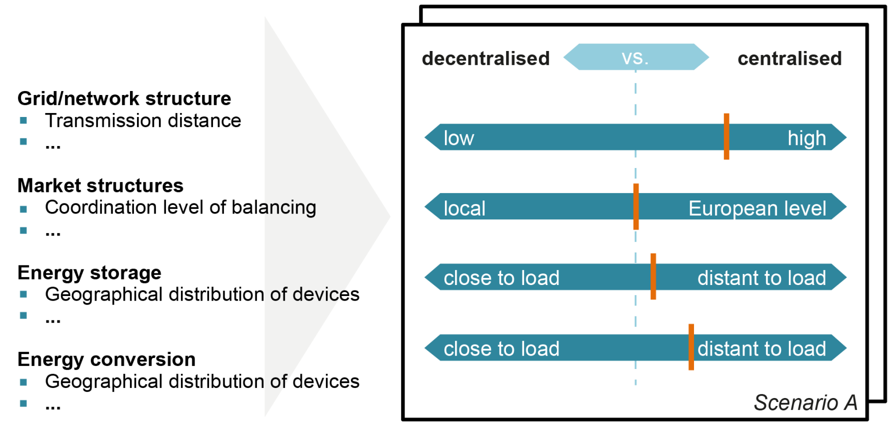

Figure 4: Schematic procedure for assessing the centrality and decentrality of a grid structure

Researchers then assessed the system structures resulting from the storylines with regard to centrality and de-centrality. To this end, they enhanced the predominantly qualitative estimates from the storylines with quantitative parameters identified in simulations. These parameters were derived for each feature and assessed with regard to a more central or decentral characteristic. As a result, researchers could now compare four different system structures with regard to centrality and de-centrality, based on various values in specific parameters. In this context, business models for network operators and flexibility providers, which supported behaviour beneficial to the network, were also proposed.

System operation in novel power grids

ENSURE's researchers have also worked intensively on the operation of future energy network structures, developing an overall ICT concept for future flexible network structures with integrated power electronics components. This enables integrated management of sector-coupled systems (gas/electricity coupling, cogeneration of heat and electricity and power-to-heat systems), which in turn helps to calculate, evaluate and better plan available flexibility. Limit violations and congestion in the existing network can thus be avoided "by design", even during the planning phase.

Researchers have established new methods for evaluating supply reliability and system stability, in order to maintain a resilient overall system. While these methods provide the basis for ensuring secure operation, they also permit a systematic analysis of the interaction between the existing infrastructure and new components. This includes the "worst case" scenario – a novel protection concept, known as the Digital System Protection Design (DSPD), is a modular tool chain that enables safe operation with new, flexible operating concepts through routine, automated protection technology adaptation.

New technologies for the „power grid of the future"

The technological development of network components is a further essential aspect of a successful clean energy transition. On the one hand, they enable meshed and hybrid network structures to be implemented, as well as more efficient integration of renewable energies. On the other hand, they increase flexibility and thus enable reliable control of the network operation.

A central aspect of these components lies in the research of innovative converters for flexible and hybrid AC and DC distribution networks as well as the transformer stations required for this purpose. In this regard, researchers investigated various new concepts for different power converter topologies for medium-voltage networks. In addition to the traditional multi-level power converters with distributed DC link structures, they also focused on new variants. Cost-effective, high-performance 3-level power converter could thus be combined with active filters, for example, reducing the volume and weight of the network filter by more than 60 percent, while an increase of only 11 percent was required in the installed semiconductor area.

Researchers also examined the beneficial network properties of network couplings for potential separation, such as power electronics-based transformers. For example, they developed a HVDC-MVDC converter with 44 percent fewer power semiconductor components and 49 percent fewer capacitors than state of the art topology. Typically, semiconductors and capacitors account for most of the costs, as well as being responsible for volume and weight, so using these types of new components makes operation of a DC network with different voltage levels attractive. In addition, researchers developed versatile control hardware-in-the-loop systems for all applications, topologies and voltage levels, which they can use to study the network properties of various power converters at an early stage of development.

The technological and economic development of superconducting cables for use in extra-high voltage grids constituted a further key area of technological development during ENSURE's initial funding phase. Researchers performed a comprehensive study showing that the creation of a superconducting cable system could be economical, even with today's technology. In the field of ICT technologies, they focused on secure, high-performance communication structures as well as monitoring and diagnostic systems. In one case, they developed a thermal monitoring system for medium-voltage substations as well as a dynamic availability management system for HV transformers that uses thermal models. This demonstrated the potential of developing new operating components that are much more flexible and network-friendly than conventional technologies.

Preparing the way to ENSURE's "energy cosmos"

During the first funding phase, developers proposed the creation of a test facility known as the "energy cosmos", implementation of which is planned for the third funding phase of the project. As part of their preparations, researchers used the research results of their technological project developments and compared them with technical, economical and social requirements, as well as the requirements of the target region.

Specifically, researchers selected a range of suitable technologies, concepts and procedures ("use cases"). To select the location, they used a five-step process to identify a suitable region for the network demonstration in Schleswig-Holstein. For this purpose, they considered technical, economic and social criteria, as well as the integration of the region in the European context and the subsequent transferability of the results. In the final step, they coordinated the feasibility of the "use cases" with the region, and identified standards as well as test specifications. These tests will take place during the second funding phase, in order to ensure the safe operation of the "ENSURE energy cosmos" in the third phase.

4. SYNERGIE: ELECTRICITY DEMAND FLEXIBILISATION IN THE INDUSTRIAL SECTOR

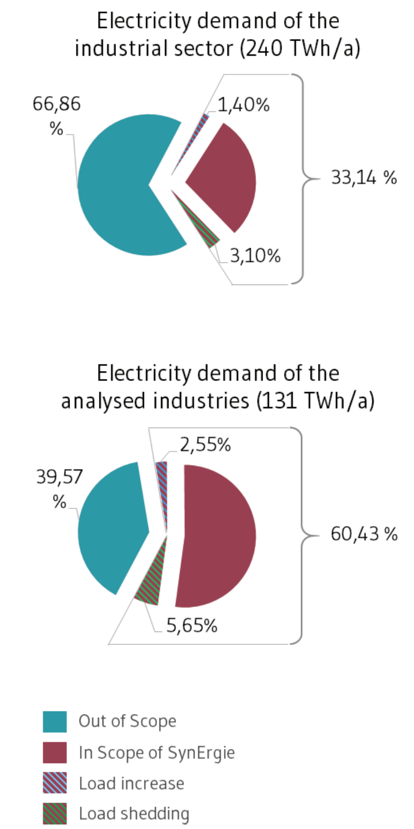

Figure 5: Electricity demand of the industrial sector and the analysed industries in SynErgie (EEP, University of Stuttgart; Database of Destatis, reference year 2016)

Synchronisation in the industrial sector

From September 2016 to August 2019, the Kopernikus Project SynErgie sought to identify the technological and market-based conditions for synchronising industrial electricity demand with a fluctuating electricity supply, while taking into account important legal and social aspects.

The project's researchers examined 17 key production processes along with the production infrastructure in eight industries[1] to determine their potential for electricity demand flexibilisation. These processes were used to estimate Germany's future potential for flexibility. SynErgie found that for periods of up to 15 minutes this potential can total at least 2.5 gigawatts for reduced electrical load and at least 1.1 gigawatts for increased electrical load[2]. This roughly corresponds to the installed capacity of Germany's largest pumped storage power plant and about 1.2 times the installed capacity of Germany's largest gas-fired power plant. The annual volume of displaceable energy amounts to 1.7 terawatt hours for increased loads and 6.7 terawatt hours for reduced loads. This means that two-thirds of generation from German pumped storage power plants in 2018[3] could be replaced. In sum, German industrial sector could contribute significantly to the success of the energy transition by making electricity demand more flexible. SynErgie developed and tested new technologies and market models that could utilise the increased flexibility in the medium to long term. Based on their findings, the researchers made recommendations for adapting the regulatory framework.

1 *Chemical products; metal production and processing; production of glassware; ceramics; processing of stones and soils; production of motor vehicles and motor vehicle parts; production of food and feed; production of paper, cardboard and paper goods; production of metal products; and mechanical engineering*

2 *For shorter periods of 1.2 minutes, there is a flexibility potential of 2.7 gigawatts for increased electric load – more than double – and five minutes for a reduced electrical load of 4 gigawatts.*

3 *This amounted to ten terawatt hours in 2018 (SMARD).*

More flexible demand in power-intense aluminium production

The production of aluminium is one of the most electricity-intensive processes in the German industrial sector. The only way to produce aluminium is the Hall-Héroult process, a technique patented in 1886 in which dissolved aluminium oxide is electrolysed in a molten salt bath at temperatures of around 960 degrees Celsius.

Ideally, traditional electrolysis plants operate around the clock. Any fluctuations in power supply would make this type of operation impossible. SynErgie thus developed technologies that make aluminium electrolysis more flexible. Therefore, an approach to minimise and compensate disturbing effects of the magnetic field has been developed.

To further increase flexibility in aluminium production, researchers developed controllable heat exchangers and installed them along with electromagnetic field compensators in 120 electrolysis furnaces at the TRIMET Aluminium SE manufacturing site in Essen. The SynErgie technologies made it possible to carry out aluminium electrolysis with ± 22.5 megawatts in one direction for up to 48 hours.

Successful FLEX electrolysis

The development of technologies for flexibility in industrial processes is an important, cost-effective and socially accepted driver of the transition to clean energy. In October 2018, TRIMET Aluminium SE carried out a successful test run of "FLEX electrolysis" in Essen. Operators executed electrolysis with a load of +19 megawatts for two hours. Then they throttled down demand by -14 megawatt, and continued for another two hours – all without a hitch. By the approach of FLEX electrolysis volatile supply and households' demand could be virtually balanced. Thus, TRIMET's FLEX electrolysis can provide enough surplus volatile electricity to power 25,000 three-person households and 50,000 one-person households, all without changing consumer behaviour. In this way, TRIMET Aluminium SE can accommodate the by-the-second difference between volatile generation and the typical demand of households.

Market design limits potential

Despite these technological advances, the current design of Germany's electricity market and electricity system restricts the exploitation of flexibility in aluminium electrolysis and in other industrial processes. As a result, the current potential for flexibility cannot deliver the desirable level of system stabilisation. In order to overcome the regulatory barriers, further incentives will be needed in the future to reduce or increase power consumption at appropriate times.

Currently, electricity markets provide certain (sometimes contradictory) incentives for beneficial system/grid behaviour to only a few energy-intensive industries. In the short and medium term, it is important that flexibility is not be hindered by market conditions. Furthermore, flexibility options must be improved in order to increase flexibility for electricity demand in the industrial sector. In the long term, policies must enable much of the industrial sector to provide more flexibility, regardless of their energy intensity or size, while taking into account the complex interactions of the electricity system. These proposed regulatory changes were published in a position paper in according with the three Kopernikus sister projects. The proposed amendments lay the foundations for a greater use of demand flexibility in the industrial sector and thereby make an important contribution to the energy transition.

Visit the Best

SynErgie research is supplemented by two formats for young researcher education: the Doctoral Seminar and the Visit-the-Best programme, each of which take part once a year. In the Doctoral Seminar, doctoral candidates present their work and discuss it with an interdisciplinary audience of specialists. The Visit-the-Best programme gives doctoral candidates and industry representatives the opportunity to visit companies that employ energy flexibility measures, including the BMW plant in Leipzig, TRIMET Aluminium SE in Essen and UPM Communication Papers in Schongau. Both initiatives make an important contribution to training outstanding young researchers in the implementation of the clean energy transition.

5. ENAVI: IN DIALOGUE WITH SOCIETY

TEN SUSTAINABILITY CRITERIA

ENavi is a navigation tool for a systematic transition to clean energy. It organises political decisions, government subsidy programmes, regulations and other instruments into a road(s)map for transforming the energy system. The Decision Theater, ENavi's interactive format for multi-actor dialogue, visualises discussion results in real-time on five monitors using a database-driven application. This allows discussion participants to compare baseline scenarios with a variety of solution options.

ENavi helps stakeholders evaluate proposed measures on the basis of ten central criteria: effectiveness, cost efficiency/total costs, and resilience gauge whether and at what cost individual measures contribute to key energy and climate targets. Political instruments are reviewed to determine how they contribute to the public good and/or impact the ability of economic actors to engage in reliable planning for the future (whether in a positive, negative, intended or unintended fashion). The criteria also assess measures with regard to health and environmental protection, resource conservation, the promotion of social cohesion, legality, ethical acceptability and the legitimacy of energy system interventions.

CO_2 pricing: the most efficient solution

ENavi analysed sector-wide scenarios for how to reach a 90 percent reduction of greenhouse gas emissions by 2050 – the goal defined by Germany's Climate Action Plan. The analysis took into account the targets of the heat and transport sectors and the changes in electricity demand that would result. After discussions with stakeholders from all sectors of society, ENavi researchers focused their complex simulations on two primary strategies:

› A rapid phase-out of coal that is ordained by regulators in accordance with a specified timetable (KAS scenario).

› The implementation of a minimum price for CO_2 in the European Emissions Trading System (ETS) for energy-related plants in the German trading area (COP scenario).

Both options for action come with measures that reduce unwanted side-effects (KAS+ or COP+): (a) a national elimination of remaining CO_2 certificates after emission reductions in the German energy industry (ZS); and (b) a reform of the Renewable Energy Act (EEG) that accelerates the expansion of renewable energies (EE) by increasing the volume available at auction (+EE).

The analysis found that, without supplementary measures, the KAS scenario recommended by the BMWi's Commission on Growth, Structural Change and Employment would generate considerable costs and fail to reduce emissions. Only supplementary measures can address this problem. By contrast, it found that appropriate CO_2 pricing would make the decarbonisation of electricity generation more economically and ecologically efficient.

A minimum CO_2 price in Germany would also counteract the rebound effect that occurs when the decommissioning of old coal-fired power stations leads to an increased use of modern plants and natural gas. Otherwise, the CO_2 saved by decommissioning coal-fired power plants would be simply be emitted elsewhere[4].

ENavi also showed that minimum CO_2 pricing in Germany must be accompanied by supplemental EU policy measures in order to avoid unintended consequences such as the "waterbed effect", which causes increased emissions in other European countries. Because the ETS defines a constant level of emissions, any emissions that one EU country saves results in increased CO_2 emissions from more coal and gas consumption in other countries. If extra emission certificates (carbon credits) in Germany are cancelled and the expansion of renewables is accelerated, then this undesired effect can be reduced.

The introduction of minimum CO_2 pricing – 30 EUR/t in 2020, 60 EUR/t in 2030

4 *Pahle, M.; Zabel, C.; Edenhofer, O.; Fahl, U.; Fischedick, M.; Hufendiek, K. et al. (2019): Interdisziplinärer Synthesebericht zum Kohleausstieg: ENavi informiert die Kohlekommission. In: GAIA – Ecological Perspectives for Science and Society 28 (1), p. 61–62*

and 120 EUR/t in 2050 – along with the supplemental measures of COP+, achieves the same objectives as the KAS+ scenario overall, but at significantly lower overall costs for the economy. By comparison, in the KAS + scenario, the specific reduction costs through 2050 amount to around EUR 82/t of carbon dioxide equivalent (CO_2e), whereas in the COP+ scenario those costs are only around EUR 50/t CO_2e.

It is crucial that policies mitigate the financial burden on citizens, especially those in the lower to middle income brackets. Each month, an average household would have to pay an extra EUR 15.70 for the KAS scenario, EUR 23.20 for the KAS+ scenario and EUR 13.80 for the COP+ scenario, provided that the federal government compensates households using some of the additional revenue generated from higher CO_2 prices.

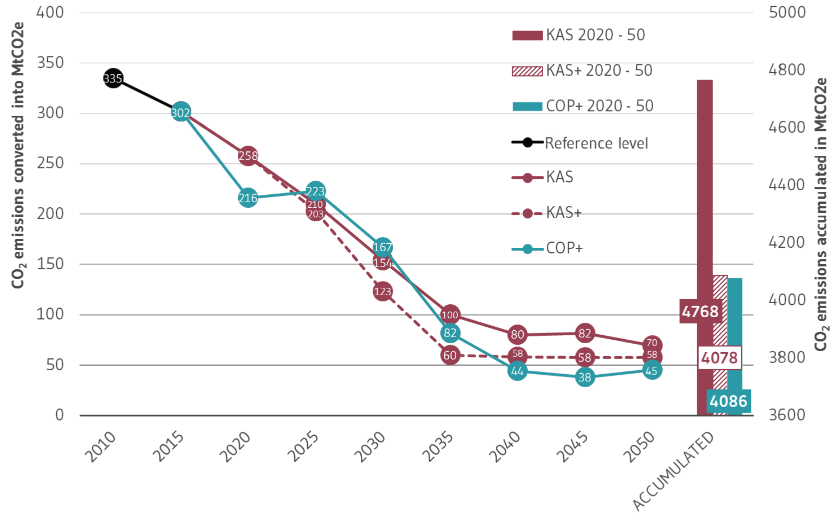

Figure 6: Greenhouse gas emissions in the ENavi scenarios (Stuttgart Research Initiative on Integrated Systems Analysis for Energy / IER)

Demand for alternative fuel vehicles on the rise

The Climate Action Plan 2050 envisages a 40 percent reduction of greenhouse gas emissions in the transport sector relative to 1990 by 2030. Motor vehicles with internal combustion engines cause 60 percent of the CO_2 emissions in road traffic. ENavi has developed measures to boost demand for low-emission vehicles.

An ambitious CO_2 limit for vehicle manufacturers and a CO_2 price for fossil fuels aim to augment demand for alternative drive technologies. According to ENavi projections, however, a price of 150 EUR/t CO_2 in 2030 will only slightly increase the rate of new electric car registrations. Apparently, the higher acquisition costs of electric vehicles have a greater impact on purchase decisions than their higher costs of use. A doubling of the CO_2 price to 300 EUR/t CO_2 could significantly increase new registrations. Likewise, the imposition of a CO_2 limit on car emissions stands to increase vehicle availability while reducing costs.

In addition to these policies, ENavi proposes the introduction of higher parking fees and a reform of vehicle taxes to make conventional vehicles more expensive. Its analysis also projects that the expansion of intelligent charging stations, combined with public information campaigns, could help eliminate misconceptions about the ranges of electric cars and increase the popularity of alternative fuel vehicles.

An agent-based model for analysing household investment decisions shows that when people buy a car, it's not just the purchase price that matters, but also their individual preferences and social networks. In the case of early adopters, who embrace technical innovations at an early stage, positive attitudes to innovation, social status and social networks determine whether they buy an electric-, diesel- or petrol-powered car.

Long-term developments in the heat sector

The heat supply in the industry and in the trade, commerce and services sector is responsible for more than half of total final energy consumption in Germany. In principle, the core elements of a lower-emission heat supply are well-known. ENavi has analysed the impediments to their implementation on a technical, economical, societal, political and legal level in order to develop market- and actor-specific approaches for reducing emissions in heating.

ENavi examined the long-term steering effects of CO_2 pricing on the business models of sector-coupling technologies and on system flexibility. ENavi researchers worked together with stakeholders to analyse and systematise the causes of long innovation cycles and information gaps.

Comprehensive measures are needed to reduce energy consumption and CO_2 emissions in the heat sector. These include CO_2 pricing, better information, stricter specifications, bans on certain practices, green retrofits across much of the building stock, and intelligent building technologies such as digital smart metering and the coordination of energy systems between buildings. A near complete switch to renewables will require the installation of district heating and heat pumps and the phase-out of conventional heating technologies based on oil and natural gas.

In individual buildings, heat pumps will play a particularly important role, in addition to the use of solar thermal energy, geothermal energy, or bioenergy. For dense areas, city planners must utilise the potential of low-emission, multi-source district heating. As for industrial process heat, closed material cycles, renewable energy, innovative production techniques and the reuse of emitted CO_2 will help mitigate climate change. If renewables are used in the building and industrial sectors, then demand for renewable power will increase. ENavi projects that Germany's total demand for renewable electricity will increase from 220 terawatt hours in 2018 to between 800 and 1000 terawatt hours in 2050.