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https://www.kopernikus-projekte.de/projekte/p2x/#roadmaps

2nd Roadmap of the Kopernikus project "Power-to-X": Flexible use of renewable ressources (P2X)

OPTIONS FOR A SUSTAINABLE ENERGY SYSTEM WITH POWER-TO-X TECHNOLOGIES

Sustainability effects – Potentials – Development opportunities

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KOPERNIKUS PROJEKTE
P2X
The Future of Our Energy

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PREFACE

Dear reader,

with climate change, the consequences of our lifestyle are taking on tangible form. Mitigating these consequences to a "tolerable" level presents humanity with unprecedented challenges, as the causes cut across all aspects of society. This starts with the conversion of energy, affects the production routes and distribution of goods, and ends with the individual choices of each consumer. Our economic system is currently based on the use of fossil carbon and is designed for constant growth.

In 1997, the Kyoto Protocol laid the foundation for internationally binding climate protection. The implementation of the Kyoto Protocol and the current Paris Agreements is the responsibility of each participating country. However, due to opposing developments, which are related to economic and population growth (increased energy demand, increased transport services, etc.), these agreements are difficult to comply with. The concerns of many citizens, especially the younger generation, are expressed through actions such as the Fridays for Future demonstrations. They are intended to increase the pressure on politics, business and society to make the necessary changes quickly in order to protect the climate.

Germany is committed to international climate protection targets and in its 2016 national climate protection plan has set itself the goal of becoming largely greenhouse gas (GHG)-neutral by 2050. The energy transition is an integral part of this path and foresees a radical transformation of the energy system that specifically promotes the expansion of renewable energies.

With the renewable energy sources of wind power, photovoltaics and biomass, a clear solution path has been defined for the electricity sector. The continuous expansion of renewable power generation plants shows the steady progress on this path. For other sectors, such as industry, heat supply and transport, a number of approaches exist, but it has not yet been possible to define an unambiguous solution path.

In order to address the technological and political challenges of the energy transition through new options, four so-called Kopernikus projects funded by the Federal Ministry of Education and Research (BMBF) were launched in 2016. The SynErgie project deals with the flexibilization of industrial processes, ENSURE develops new grid concepts and the ENavi project addresses the socio-political aspects of the energy transition.

The Kopernikus project P2X deals with technologies for sector coupling, which make it possible to transfer energy from renewable power generation to other sectors that are still primarily based on fossil fuels. The consortium of 50 partners from universities, research institutions, industry and civil society is pursuing the goal of developing power-to-X technologies to the point of market maturity, if possible, and thus making an active contribution to the success of the energy transition.

This can be done either by direct electrification or by transferring the electrical energy to material-based energy carriers. These technologies are summarized under the term Power-to-X (PtX). The use of these synthetic energy carriers provides the option of transforming the other sectors, which cannot be electrified directly, towards a more sustainable energy system.

The challenges are considerable:

- Process chains are prone to losses and the overall efficiency is low.
- Electricity demand is correspondingly high and would have to be met by additional expansion of renewable power generation.
- Some of the technologies are still in their early stages. Operational experience in these cases is therefore limited.
- The estimated costs of producing the energy sources significantly exceed the costs of their fossil counterparts.

Ultimately, the different technologies are at different levels of development and target different applications ranging from the sustainable supply of feedstocks for the chemical industry to energy carriers for applications in transportation or energy storage.

The progress of the project is accompanied by the so-called roadmapping process, which attempts to track the development of the various technologies and evaluate them in terms of ecological, economic and social sustainability. These assessments form the basis for a systemic classification under the current regulatory and political circumstances, with the aim of making the dedicated analyses more comprehensible. Active participation in this roadmapping process has been open to all project partners.

It is crucial that technological development is not carried out in isolation, but accompanies public debates, because the energy transition is a task for society as a whole. This could be achieved by conducting the discussion openly, both within and outside of the project. This transparency can contribute to a well-informed society, and ultimately result in active support of the decisions necessary for the energy transition.

The work before you marks the end of the first funding phase of the Kopernikus P2X project. However, as the technologies as well as the societal and political debate are in constant evolution, this should also be considered as a living document. It is not to be understood as a conclusive description of the technologies and a final assessment of their respective future viability, but rather as a snapshot of the current state of development. The collected findings on the technological side as well as on the technology assessment side are to be transferred to the second funding phase and further developed in order to support the energy transition in this way.

In this spirit, we wish you an informative read, the preparation of which would not have been possible without the constructive cooperation of the project partners. The exchange and lively discussions lead to controversies in some places, which fertilized the work in the project and thus have helped to examine the technologies in their overall impact. Therefore, we would like to take this opportunity to thank all project partners and especially the colleagues who provided the data and results for this roadmap.

Florian Ausfelder

Hanna Ewa Dura

EXECUTIVE SUMMARY

The Kopernikus-project P2X „Flexible use of renewable resources" unites 50 partners in research and development and aims to reach market entry level of chemical power-to-X-technologies (PtX). The progress of the research and development is continuously monitored, documented and analysed using the roadmap-process. PtX-technologies are evaluated based on economical, ecological as well as societal aspects and discussed in the wider context of the energy system. An initial version of the roadmap was published in August 2018 and presented the preliminary evaluation of the project's work. This present document is meant to be a continuation of the first document and is also considered to be a reference point for the planned work in the upcoming next funding phase of the project.

The Paris Climate Agreement puts climate protection as the main issue on the global political agenda. The goals outlined in the agreement won't be achievable without fundamentally changing our energy system and therefore the agreement requires social acceptance. In particular, the current use of fossil fuels, coal, oil and gas has to be severely curtailed, with the perspective of coming to an end in 2050.

The energy requirements will still have to be met by renewable sources, i.e. mainly energy from solar radiation (photovoltaics, solar thermal), wind, hydropower and biomass. Only biomass, CO_2 and recyclables from organic materials will be available as carbon carriers for the production of materials, chemicals and fuels.

PtX-technologies can provide synthetic products to cover a broad range of applications and thereby facilitate the replacement of fossil-based energy sources in certain applications, where alternatives to fossil-based substances and processes are otherwise not readily available. These include parts of the transport sector (e.g. aviation, marine, heavy-duty vehicles and long-distance transport), as well as the chemical industry.

From a technical point of view, PtX products could in principle replace fossil-based energy sources in most applications (heat supply, fuels and chemical raw materials). However, in order to identify the best applications in terms of ecological effects, economic efficiency and societal impact, a more comprehensive analysis of their effects, as presented in this document, is essential.

Within this Kopernikus-project a number of different PtX-processes and -products are developed. **Figure 0.1** shows an overview of the processes and products that are examined within P2X and evaluated within the roadmap process regarding their economic, ecological and societal impact.

A simplified energy model, which defines the electricity mix as well as the available full-load hours for the target year 2050 and the interim year 2030, was used for the evaluation. Within the barrier limits and assumptions of the model, it provides rather high full-load hours that are available to the PtX-processes, especially for the year 2050. Consequently, the results of the ecological and economic analyses have to be classified as rather optimistic.

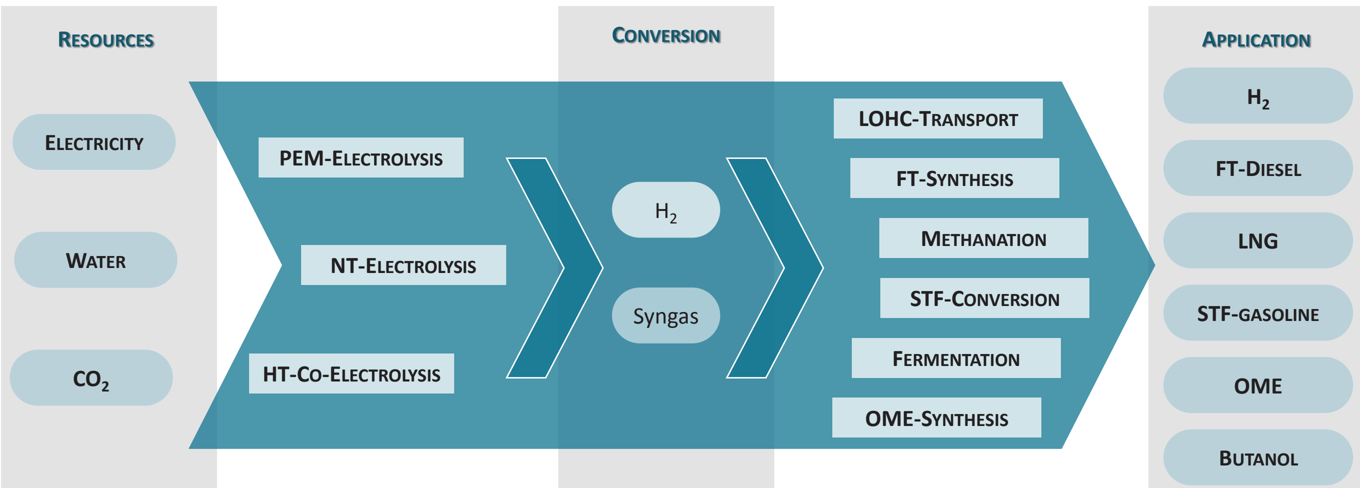

Figure 0.1: Overview of the PtX-production chains and -products subject to the analysis within the roadmap process.

In order to demonstrate the full range of possibilities of PtX-technologies, different modes of operation were investigated:

- A remote scenario with Norwegian hydropower (with 4,500 full-load hours)
- Flexible operation to support grid stabilisation (with 1,000 full-load hours in the interim year 2030 and 3,000 full-load hours in 2050 for lower GHG reduction ambition (KS 80) and 6,500 full-load hours for a higher GHG reduction ambition (KS 95) respectively)
- Continuous operation (with 8760 full-load hours)

TRENDS OF THE RESULTS OF THE LIFE CYCLE ASSESSMENT (LCA)

The previous statements, made in the first edition of the roadmap document (Ausfelder; Dura 2018) regarding the cumulative energy demand (CED) and the greenhouse gas potential (GWP), have been confirmed by the accompanying assessment in line with the progress of the project. The ecological assessment (based on life cycle assessment, LCA) of the investigated processes has been extended with additional relevant criteria: Metal Depletion Potential (MDP), Photochemical Ozone Creation Potential (POCP), Particle Matter Formation (PM), as well as water and area consumption. In addition, an initial assessment of the expected demand for critical raw materials was made. This extension gives a better insight into the environmental footprint of PtX-technologies compared to their fossil counterparts, but can by no means be considered exhaustive with respect to all possible ecological aspects.

The biggest lever for greenhouse gas reduction is to reduce the CO_2 burden stemming from electricity generation. A largely CO_2-free electricity generation is a precondition to reduce GHG_{LCA} emissions from PtX-products to the level of their fossil counterparts. Significant additional GHG emission reductions of PtX-products can only be achieved by accounting for the emission burden of the CO_2 utilised on the original production process. Further reductions may be achieved by increasing the efficiency of the transformation processes. However, as the results of the CED-analysis show, there is a limit to possible efficiency gains. The analysis shows that the production of PtX-products inherently leads to a higher energy demand compared to their fossil counterparts. This is due to the low energy content of the feedstock CO_2 as well as the conversion losses of the individual processes and the length of the process chain – the more conversions and process steps are required, the larger the conversion losses. A reduction of CED that occurs in line with an increasing share of renewable electricity is not due to increased efficiency of the PtX-processes, but to the accounting methodology of the CED (see Chapter 3.2.2), where fossil fuels and renewable electricity are subject to different barrier limits. The consumption of metallic resources is also significantly higher compared to the fossil counterparts, which is to be expected for an energy system based on renewables. Overall, the Photochemical Ozone Creation Potential (POCP) and the Particle Matter Formation (PM) are also higher for all investigated PtX-routes. This is mainly due to emissions originating from conventional power plants used for electricity generation. Consequently emissions decrease with increasing renewable electricity supply. The remaining emissions stem from the upstream chain of renewable electricity generation, i.e. the production of e.g. photovoltaic panels or wind turbines, which still use conventional electricity. Hence, a reduction in emissions is foreseeable if the electricity used for the production of photovoltaic panels and wind turbines comes from renewable power sources.

Particularly in connection with water and land consumption, but also PM emissions, it should be noted that the LCA results have only limited value with regard to the ecological sustainability of different options, as these are local indicators that can be subject to strong regional (and seasonal) fluctuations. However, the aggregated display of results regarding the environmental impact from the LCA does not provide any such information.

TRENDS OF THE TECHNO-ECONOMIC ASSESSMENT

In the techno-economic assessment PtX-products show uniformly higher production costs compared to the prices of the respective fossil references. Even with a strong decrease in investment costs assumed, large savings are possible compared to today's production costs, however, they still remain at a higher level than the costs of the fossil counterparts. The production costs show very high sensitivity to the capacity utilisation of the PtX-plants and consequently also to fluctuating electricity prices. Although sensitivity to fluctuating CO_2 prices is also observed, it is not as pronounced as the dependence on electricity costs.

A transparent comparison of PtX-fuels to conventional fuels should be made either on mileage or energy content and the cost comparison to the procurement costs of the conventional fossil fuels. This is required due to the different energy contents of synthetic fuels investigated and the distinct pricing structure of fossil fuels used in transport applications in Germany. Only 29–35 % of the fossil fuel price is attributable to product procurement costs, while the majority of the consumer price consists of taxes and levies. It can be expected that some taxes and levies will also be levied on PtX-fuels. Since neither the tax rates nor the amount of levies is foreseeable, a comparison of the production cost with the product procurement costs remains the best approximation.

TENDENCIES OF SOCIAL ACCEPTANCE

In order to analyse the social acceptance of PtX-products, an appropriate methodological framework is required. Within the project, an acceptance matrix was developed which comprises a compilation of evaluation factors derived from the similar work in the field of energy infrastructures and adapted for PtX-technologies. The assessments within the acceptance matrix were initially carried out by the respective technologists within the project and further elaborated in workshop discussions. The central challenge is confirmed by the fact that a detailed assessment is difficult due to the overall low TRL or the not yet widespread use (compared to e.g. renewable energies). As a result, many categories showed a tendency towards a neutral assessment. In addition, results show that many concrete assessments or future developments of the technologies and the associated potential acceptance effects are dependent on developments in the surrounding political and economic framework conditions.

Furthermore, technological differences tend to be insignificant for the assessments from an acceptance point of view (e.g. there are hardly any differences in acceptance for PEM electrolysis, low temperature or high temperature co-electrolysis).

PERSPECTIVES OF DEVELOPMENT AND POTENTIALS OF PtX-TECHNOLOGIES

The development of technologies raises the question of their potential for implementation and deployment. For the time period up to 2035, it is most likely that merely particularly advantageous niche applications for PtX processes will be deployed, rather than a large-scale roll-out of the technologies, at least in Germany. This is caused by the demand of renewable electricity, high specific production costs and low technological readiness level.

With regard to the provision of fuels, the hydrogen transport technology via liquid organic hydrogen carriers (LOHC), the provision of liquid synthetic natural gas (LNG) and artificial fuels via the STF-Ottokraftstoff process, FT diesel and OME are being developed. LOHC has the potential to significantly support the roll-out of hydrogen mobility, as it requires minor changes to the existing fuel supply infrastructure. Thus, the challenge remains on the side of the availability of fuel cell vehicles. STF-Ottokraftstoff and FT-Diesel can be added as drop-in fuels to the corresponding fossil fuels in any mixing ratio up to the pure substances used in both passenger cars and heavy-duty vehicles. No fundamental adaptations of infrastructure or vehicles are necessary, but local emissions continue to occur. It should be noted, however, that admixtures to fossil fuels can only represent a transformation path, since mixed fuels still require a fossil component, creating CO_2-emissions that are not compensated. Thus, this is not in line with GHG reduction targets for 2050.

Two basic approaches can be pursued for applications of PtX-products in the (petro-)chemical industry: (1) the use of synthesis gas at the beginning of the value chain, which allows for a large impact, as synthesis gas is a precursor of multiple products further downstream, or (2) direct production of high value specialty chemicals. For the former, the relevant size scales and low production costs must first be reached in order to compete with current fossil supply. On the other hand, market entry for specialty chemicals may be easier, as it is a higher priced segment with smaller volumes.

The contribution that PtX-technologies and -products can make to the defossilisation of the respective sectors and to the energy system transformation as a whole depends not only on the specific ecological and economic characteristics, but also on their production potential, i.e. the quantities, that can be arguably produced under certain conditions. The chosen example of Norwegian hydropower shows that different conclusions can be drawn from the analysis. On the basis of the evaluated ecological indicators (THG_{LCA}, PM, POCP, etc.), hydropower could be classified as the most advantageous energy source from an ecological point of view. However, the techno-economic analysis shows that, from an economic point of view, Norwegian hydropower would not be the most favorable production side due to the relatively low full-load hours (IRENA o. J.). Compared to the (optimistic) model assumption used, lower production costs could be achievable with constant operation within the KS 95 ambition. Assuming the still available but not yet developed hydropower potential in Norway would be available solely for PtX-fuel production, about 7.5 % of today's annual passenger car fuel demand in Germany could be covered by PtX (see chapters 2.3.1 and 4.3.1). Similar local restrictions apply to water demand, as it is also a local resource: the supply of 1 % of the German car fleet with PtX-fuels for one year corresponds to a required water quantity of 770,000 t/year. This comparison clearly demonstrates that the investigations on a specific basis (LCA, techno-economic analysis) must be complemented by a corresponding analysis of the available potential in order to adequately estimate the possible contributions of a technology to the overall system.

Usually, an analysis of available potentials describes a static situation, such as a given amount of renewable energy, energy demand, available technologies, etc. Based on these statistics the potential of a given technology can be derived adequately. However, this potential merely represents a snapshot in time based on the assumptions made, e.g. the quantity of PtX-products in 2050. Thus, this potential is inadequate to describe the necessary transition trajectory up to 2050. In addition, such scenarios often assume the unique access to this potential for a sole purpose, e.g. that all PtX-fuels produced are available for Germany. Such surveys of potentials should not disregard the fact that, should a country decide to manufacture PtX-products, these are in principle available to different markets, including local or regional markets, in accordance with the investor's interests. These interrelationships show the need for further analysis to assess possible potentials and to put specific environmental influences and techno-economic analyses into perspective.

ROLE OF REGULATORY FRAMEWORKS

The current results of the LCA and techno-economic analyses are already impacted by the relevance of the regulatory framework, as briefly described in the respective sections. The regulations relevant for PtX include the EU ETS (mainly relevant for the industrial sector), the EU ESD (mainly relevant for the transport sector) and the RED II (also relevant for the transport sector). So far, however, only RED II has taken PtX-fuels specifically into account at the European level. The sector coupling nature of PtX-technologies and -products leads to a convergence or even an overlap of different regulatory regimes, such as the EU ETS, EU ESD and RED II.

It has not yet been clarified how these regimes will interact with each other and what concrete consequences may arise from the interaction of different regulatory frameworks. However, these effects have most likely the most significant influence on development of emissions, as well as the implementation of PtX-technologies. It is important to understand these interrelations in terms of compliance with GHG emission targets in order to avoid any undesirable developments.

Within this context, the question of which CO_2 sources should be used in PtX-technologies is also relevant. Both outside and within the project consortium there are contrary positions with regard to this question:

- Position 1: The approval of industrial (i.e. fossil) CO_2 sources is viewed as dangerous in terms of strengthening or further delaying the already existent lock-in (continued dependence on fossil raw materials). The supporters of this position are therefore in favour of restricting the allowed CO_2 sources to biogenic sources or direct air capture.

- Position 2: The approval of industrial (i.e. fossil) CO_2 sources is viewed as an opportunity to reduce CO_2 emissions early on, deploy the technologies and thus initiate the transition to a renewable and largely GHG-neutral economy.

Details on these two positions and their possible impacts are set out in Part D.

As already described in the section on techno-economic analysis, there is still a need for clarification with regard to the production costs and taxation of PtX-fuels in particular. By offsetting the CO_2 used as a raw material, which is regulated by RED II, the question of how the German energy tax is to be levied must be answered. The energy tax varies depending on the type of fuel and depends on the environmental footprint of the respective fuels (BMF 2019). The interaction between these regulations has not yet been investigated.

The investigations with regard to system operation of the plants have shown that the production costs of the PtX products are very high at low utilisation rates, which places profitability into question. The current market for grid stabilising services is not yet designed to address flexibility as a structural development. In addition, the current legal framework favours constant power consumption through the reduction of grid fees. By offering flexibility, there is a risk that grid fees will be raised in full. In addition, for the conversion of electricity into other energy sources, the PtX process is defined as a final consumer and is therefore subject to full taxes and levies, unless the energy source produced is used exclusively for re-generation of electricity. Consequently, flexibility as a grid service, which is expected to be more and more required for a transition towards a system based on predominantly intermitting and fluctuating renewable sources, is not supported by the current legal framework, which is based on a fossil and permanent energy generation.

There is a need for „dynamic" regulatory frameworks that actively support the transformation from a fossil-based to a renewable, flexible energy system. Only uniform framework conditions that account for the complexity of PtX, can provide the certainty necessary to implement these technologies.

The institutions listed below are funded or associated partners in the P2X consortium. Based on the technological developments in the project, the authors of the Roadmap 2.0 have developed the contents of this document based on their own work and under their own responsibility. Therefore, the opinions expressed in the texts do not reflect the position or a opinion of partners in the P2X consortium.

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FULL VERSION (GERMAN) AND TECHNICAL APPENDICES
https://www.kopernikus-projekte.de/projekte/p2x/#roadmaps

Made within the roadmapping activities in the Kopernikus project **"Power-to-X": Flexible use of renewable ressources (P2X)** sponsored by the German Federal Ministry of Education and Research.
FKZ: 03SFK2WO
(DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.)

IMPRINT

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Design and typesetting
Lindner & Steffen GmbH,
Nastätten

Image Credits
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Sponsored by the
German Federal Ministry of Education and Research

Supervised by
Projektträger Jülich

Published in Frankfurt am Main on May 31, 2023
1. Edition

ISBN: 978-3-89746-240-3