This document is an excerpt of the 1st Roadmap of the Kopernikus project P2X. You can find the full (German) version on the project's website:

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

1st 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

Challenges – Potentials – Methods – Impacts

Editors:
Florian Ausfelder
Hanna Ewa Dura

KOPERNIKUS P2X PROJEKTE
The Future of Our Energy

SPONSORED BY THE
Federal Ministry of Education and Research

PREFACE

Dear reader,

Climate change poses an unprecedented global challenge to humankind. Anthropogenic emissions of greenhouse gases into the atmosphere since industrialization are the primary cause. As the consequences and impacts of our actions and our consumption patterns slowly take tangible shape, the search for solutions becomes ever more urgent.

International policy makers have responded, and new target agreements to implement climate goals are being adopted continuously. The European Union is negotiating on behalf of its member states and has adopted measures for implementation within its area of jurisdiction. The member states implement these resolutions and also exercise the leeway they have for shaping their own policies.

Germany's approach to meeting the European climate goals initiated a radical restructuring of the energy system that specifically promotes the expansion of renewable energies. According to the Climate Protection Plan of 2016, Germany has pledged to be greenhouse gas neutral by 2050 while ensuring security of supply and affordability in accordance with the energy policy triangle.

The electricity sector has seen strong growth in renewable power generation, which is to be expanded even further, particularly in the area of wind power and photovoltaics. In contrast, the other sectors which traditionally rely more heavily on material energy sources - industry, heat and transport – are finding it difficult to increase the share of renewables because, apart from the limited availability of biomass, there are few direct options open to existing technologies. In turn, new electricity-based solutions rely on the availability of larger amounts of renewable electricity.

In order to address the technological and political challenges of the energy transition through new options, four so-called Kopernikus projects, funded by the 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 carry 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 further developing power-to-X technologies to market maturity, if possible, and thus making an active contribution to the success of the energy transition.

A successful transition can either be achieved by direct electrification or by transferring the electrical energy to material energy carriers. These technologies are summarized under the term Power-to-X (PtX). The use of synthetic energy carriers enables another option for transforming the other sectors towards a more sustainable energy system.

The challenges are considerable:

- The 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 electricity generation.
- The technologies are often still in their early stages.
- Operating experience is limited.
- The estimated costs of producing the PtX-based energy sources significantly exceed the costs of their fossil equivalents.

The various technologies are at different levels of development and target different applications, ranging from the sustainable supply of raw materials for the chemical industry to energy carriers for applications in transportation.

The progress of the project is accompanied by the so-called Roadmapping process, which attempts to track the development of the various technologies. The criteria on which different projects are evaluated are 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 transparent. Active participation in this roadmapping process has been open to all project partners.

Since the energy transition is a task for society as a whole, it is crucial that technological development is not carried out in isolation but accompanies public debates. 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 an active support of the decisions necessary for the energy transition.

The work presented is a living document that will be adjusted periodically to reflect new findings from the project and changes in the political and societal context. It should therefore neither be seen as a conclusive description of the technologies nor as a final assessment of their respective future viability, but rather as a basis for discussion based on the current status of the project.

With this in mind, we hope you will enjoy reading this report, which would not have been possible without the constructive cooperation of the project partners. The exchange and lively discussions fertilized the work in the project and thus helped to arrive at robust results in the end. We would therefore like to take this opportunity to express our sincere thanks to the authors and the editorial team.

Florian Ausfelder

Hanna Ewa Dura

EXECUTIVE SUMMARY

The Kopernikus-project P2X "Flexible use of renewable resources" unites 50 partners in research and development to reach market entry level of chemical Power-to-X technologies (PtX).

This development is continuously monitored and evaluated via the roadmapping process, which includes all partners analyzing and documenting the respective progress in research and development, and puts the results into context of the energy system. This document presents the current state of the work in the project and its preliminary results.

Chemical PtX technologies have the potential to significantly contribute to "sector-coupling" by transferring renewable electricity into chemical energy of synthetic energy carriers. This is especially valuable in areas of the energy system that do not have many options for using renewable energies directly.

These areas encompass aviation and marine fuels, fuels for high-temperature industrial applications as well as the chemical feedstock as raw material basis for the chemical industry. Possible priorities and implementation strategies will be presented and discussed.

Chemical PtX energy carriers can in principle contribute towards greenhouse gas (GHG) reduction and thereby support the national political targets of the energy transformation (Energiewende) and the implementation of international climate agreements. However, a detailed analysis of individual process chains is required, since synthetic energy carriers are not a priori more sustainable than their respective fossil counterpart. This is done using life cycle assessments (LCA). Within this context, the transferability of LCA results to political goals and interactions between different European regulations aiming for GHG reduction are discussed.

A precondition for using PtX technologies is the availability of the respective resources (electricity, CO_2 and water), which is discussed in some detail.

The following PtX technologies are studied in this project:

› **Electrolysis**
  – Polymer Electrolyte Membrane (PEM) water electrolysis
  – Low-temperature co-electrolysis
  – High-temperature co-electrolysis

› **Liquid organic hydrogen carriers (LOHC)**

› **Production of liquid fuels**
  – Synthetic kerosene and diesel via Fischer-Tropsch processes
  – Gasoline via production of synthetic methanol and a subsequential Methanol-to-Gasoline (MTG) process
  – Oxymethylene ether (OMEx) as diesel substitute

› **Production of gaseous fuels**
  – Hydrogen (via PEM)
  – Synthetic liquefied natural gas (LNG)

› **Production of chemical feedstock**
  – Syngas in various compositions
  – Long-chain alcohols

These technologies and their respective value chains are evaluated on the basis of a simplified power generation model. The technologies are investigated using two operation modes "system assist operation", i.e. operation when renewable electricity is available and "continuous operation".

Methodologies for sustainability evaluation applied in this project are life cycle assessments (LCA) for ecological sustainability, techno-economic evaluations to cover economic aspects and the evaluation of social acceptance. The methodologies are presented and their uncertainties discussed in light of the generally low technology readiness level of the processes under investigation. Furthermore, the technologies are investigated with respect to their system compatibility, possible routes for development and application as well as utilization potentials. Additional aspects include possible logistical structures for LOHC applications in the transport sector and reduction of local NO_x and soot emissions when using OME_x as fuel.

Preliminary results from LCA include the indicators "cumulative energy demand" (CED) and "global warming" (GW) for "system assist" and "continuous" operation for all investigated technologies and their respective references. Furthermore, expected developments for these indicators are assessed, as the technology becomes more advanced. CED values are displayed with their fossil and renewable contributions. Since the allocation of CO_2 bound in PtX energy carriers is not treated consistently in all relevant regulations, its emissions are displayed separately.

No technologies under investigation in the project perform better on the CED and GW indicators than their fossil references at the current state of their technological development. Foreseen improvements and "system assist" operation however have the potential to shift these indicators into better performance than their fossil reference.

Ballpark future potentials for PtX applications are evaluated via a comparative study of different scenarios and based on current demand of fossil fuels in the respective application area. As a result, the foreseen required amount of PtX energy carriers makes a production solely based in Germany unlikely. Therefore, technology export and import of PtX energy carriers seems to be a more probable future development.

There are some subjects under discussion, for which the project partners have not reached a common position yet. Controversial aspects and their lines of argumentation are presented explicitly. These include:

- Achievement of the national climate targets within the corridor of 80 % to 95 % of GHG reduction in 2050 relative to emissions in 1990
- Requirements and assumptions and the validity of the power generation models
- Evaluation of emissions for PtX production from the power sector subject to EU ETS regulation
- Allocation of CO_2 bound in the PtX energy carrier at the original CO_2 source or in the energy carrier
- Function of PtX plants as sector-coupling technologies in the energy system

The institutions listed below are funded or associated partners in the Kopernikus project P2X consortium. The partners have contributed to the contents of this publication to different extents. Based on the technological developments in the project, the authors of this roadmap 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 opinion of all partners in the P2X consortium.

CONSORTIUM

Areva H_2Gen GmbH
Arge-Netz GmbH & Co. KG
AUDI AG
BASF New Business GmbH
Bund für Umwelt und Naturschutz Deutschland e.V.
Chemieanlagenbau Chemnitz GmbH
Clariant Produkte (Deutschland) GmbH
Climeworks Deutschland GmbH
Covestro Deutschland AG
DECHEMA-Forschungsinstitut
DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.
Deutsches Institut für Wirtschaftsforschung e.V.
Deutsches Zentrum für Luft- und Raumfahrt e.V.
ERC Additiv GmbH
Evonik Creavis GmbH
Ford-Werke GmbH
Forschungszentrum Jülich GmbH
Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.
Friedrich-Alexander-Universität Erlangen-Nürnberg
GETEC green energy AG
GETEC heat & power AG
Greenerity GmbH
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH
Heraeus Deutschland GmbH & Co. KG
HYDROGENIOUS TECHNOLOGIES GmbH
ifeu – Institut für Energie- und Umweltforschung GmbH
INERATEC GmbH
innogy SE
Karlsruher Institut für Technologie
Leibniz-Institut für Katalyse e.V.
Linde AG
Ludwig-Maximilians-Universität München
Öko-Institut e.V.
OMV Refining & Marketing GmbH
RWTH Aachen University
Shell Global Solutions (Deutschland) GmbH
Siemens AG
sunfre GmbH
Technische Universität Bergakademie Freiberg
Technische Universität München
thyssenkrupp Industrial Solutions AG
Volkswagen AG
Wacker Chemie AG
Wissenschaftszentrum Berlin für Sozialforschung gGmbH
Wuppertal Institut für Klima, Umwelt, Energie gGmbH
WWF Deutschland
ZAE Bayern
Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

PROJECT COORDINATION

Kurt Wagemann (DECHEMA e.V.), Walter Leitner (RWTH Aachen University), Rüdiger Eichel (Forschungszentrum Jülich)

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

Editors
Dr. Florian Ausfelder
Hanna Ewa Dura

DECHEMA Gesellschaft für Chemische
Technik und Biotechnologie e.V.
Theodor-Heuss-Allee 25
60486 Frankfurt am Main
Germany

Responsible according to the German Press Law and the Media
Dr. Florian Ausfelder
DECHEMA Gesellschaft für Chemische
Technik und Biotechnologie e.V.
Theodor-Heuss-Allee 25
60486 Frankfurt am Main
Germany

Design and typesetting
PM-GrafikDesign, Peter Mück, Wächtersbach
english version: Lindner & Steffen GmbH, Nastätten

Image Credits
U1: ipopba – stock.adobe.com

Sponsored by the
German Federal Ministry of Education and Research

Supervised by
Projektträger Jülich

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

ISBN: 978-3-89746-239-7