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Integrating Power-to-X Technologies and Methanol Synthesis into Chemistry Education: Curricular Innovation for Sustainable Development

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Abstract

The current challenges posed by global climate change and the energy transition call for innovative and sustainable solutions that are effective at both the technological and societal levels [1]. Power-to-X (PtX), in particular methanol synthesis, is a prime example of how chemical processes can be coupled with renewable energies to reduce CO_2 *emissions [2]. In the context of school education, the integration of these technologies opens up new ways of linking scientific content with social relevance and education for sustainable development [3]. The aim of this project is to develop and empirically evaluate experimental and conceptual learning modules on methanol synthesis [4]. The modules are designed according to the principle of curricular innovation research and are geared towards the requirements of competence building in chemistry lessons and the professionalisation of teachers [5]. A particular focus is placed on teaching skills in the areas of sustainability, energy and climate in order to sensitise pupils to the challenges of the future and enable them to take action [6], [7]. The accompanying empirical research is conducted using a design-based research approach and combines qualitative and quantitative methods to test and continuously optimise the effectiveness and acceptance of the teaching and learning materials developed [8]. The project thus contributes to innovative teacher training and the sustainable anchoring of future-relevant technologies in the school curriculum [9].*

Keywords: *Power-to-X-Technology, Methanol Synthesis, education for sustainable development, chemistry teaching innovation, sustainable energy supply*

1. Social Relevance of the Topic and School Compatibility – Education for Sustainable Development as a Curricular Necessity

The energy transition and global climate protection require a comprehensive transformation of energy systems towards a sustainable, low-carbon economy. In this context, PtX technologies are increasingly becoming the focus of research and industry. These processes offer innovative approaches to efficiently utilising renewable energy sources and converting them into chemical energy carriers or valuable raw materials that can be used in a variety of ways [4].
The term PtX encompasses a variety of technologies based on the conversion of electricity from renewable energy sources, particularly wind and solar energy, into other forms of energy or products. Central to this is the electrolysis of water, in which water is broken down into hydrogen (H_2) and oxygen (O_2) using renewable electrical energy. The "green" hydrogen produced can be used directly, stored or used as a starting material for further synthesis reactions [10], [11]. In the context of the energy transition, power-to-liquid, power-to-gas and power-to-chemicals pathways play a particularly key role. Against this background, it is clear that PtX is not only significant from a technical perspective, but also has a pronounced social relevance. They open up opportunities for reducing greenhouse gas emissions, integrating fluctuating renewable energies and developing long-term storage strategies [2], [12]. At the same time, current analyses point to challenges such as high energy requirements, efficiency losses and the need for sustainable CO_2 sources, which must be reflected in social negotiation processes [12], [13].
The international education agenda emphasises that such transformation processes cannot be achieved through technological innovation alone, but require appropriately targeted education [14]. UNESCO describes Sustainable Development Goals (SDG) as an approach that enables learners to make informed decisions and act responsibly to promote sustainable development [15]. At the national level, the orientation framework for global development education within the context of education for sustainable development specifies this objective and emphasises that pupils should acquire the skills to make future-oriented and sustainable decisions [3]. Chemistry lessons offer particular opportunities

for this, as they deal with fundamental concepts such as material and energy conversion, resource and emission issues, and material cycles. Burmeister et al. [6] show that combining green chemistry and SDG in chemistry lessons can help to systematically link the ecological, economic and social dimensions of scientific content, thereby promoting sustainability-related action skills [6]. Rubner et al. [16] argue that the energy transition can be used as teaching material to embed chemical content in socially significant contexts, thereby highlighting the relevance of science education for current energy and climate policy issues. Methanol synthesis, as a central component of PtX technologies, offers an ideal opportunity to achieve these educational goals through its combination of chemistry, energy transition and sustainability. Despite its high relevance, however, there is a lack of didactically prepared experimental formats, materials and empirical studies on the effectiveness of corresponding educational offerings in a school context [17]. Although initial models, simulation games and digital learning environments for PtX have already been developed in higher education, these are primarily aimed at scientifically trained target groups and hardly take into account the specific requirements of school teaching, such as time constraints, safety regulations and curricular framework conditions [17].
Although sustainable energy topics are receiving increasing attention in teacher training, the methodological and didactic design of such topics often remains vague or limited to theory-heavy approaches. In order to successfully integrate PtX processes into chemistry lessons, a didactic approach is needed that takes into account both the subject content and the learning requirements of the pupils, as well as the demands of everyday teaching [7]. The concept of curricular innovation offers a promising theoretical basis here, enabling a close connection between subject content, the learning requirements of students and targeted didactic modelling [5], [18]. Against this background, curricular innovation is defined as a central task in this project. The aim is to gradually reconstruct PtX processes from a chemistry teaching perspective, model them experimentally and research them empirically, with a focus on the storage of "green" hydrogen in the form of methanol [19]. The focus is on developing and testing experiments that are as simple, safe and inexpensive as possible, which represent key sections of the industrial PtX process chain in a didactically reduced and action-oriented manner so that they can be used in schools. Both technical and ecological and social aspects are to be taken into account in order to enable a multi-perspective approach to the topic [20]. At the same time, education for sustainable development requires pupils to acquire the skills to make future-oriented and sustainable decisions [1], [3]. This is where the project comes in, linking current social challenges with chemical content and aiming to integrate the topics of climate protection, energy storage and sustainable technologies into schools and universities [2].
Against the backdrop of the Sustainable Development Goals, in particular SDG 4 (quality education), SDG 7 (affordable and clean energy) and SDG 13 (climate action), it is clear that the rapid integration of Power-to-X and methanol synthesis into chemistry curricula is not an optional extra, but an educational policy necessity [3], [15]. The proposed work contributes to this by addressing the existing discrepancy between social relevance and implementation in schools and developing empirically based teaching and learning arrangements that systematically link SDG, scientific literacy and current energy technologies [21], [22].

2. Use of Hydrogen and State of Scientific Research

The transformation of energy systems towards a sustainable, low-carbon economy has brought PtX technologies into the focus of research and industry. They enable the conversion of renewable electrical energy into chemical energy carriers and basic chemicals that can be used across sectors [4]. A key aspect of this is the provision of "green" hydrogen through the electrolysis of water, in which renewable electricity is used to split water into hydrogen and oxygen [10]. The hydrogen obtained in

$$CO_2 + 3H_2 \xrightarrow[\text{CuO/ZnO}]{\text{480-520 K / 5-10 MPa}} CH_3OH + H_2O$$

Fig. 1. Chemical Equation Methanol Synthesis from H_2 and CO_2

this way can be used directly, stored or used as a reactant in synthesis processes [11].
Power-to-liquid and power-to-chemicals processes are particularly important. Power-to-liquid focuses on liquid energy carriers such as synthetic fuels [13], while power-to-chemicals provides basic chemicals such as methanol, which serve both as platform chemicals and for energy storage [4]. The synthesis of methanol from hydrogen and carbon dioxide or carbon monoxide is a key reaction

pathway in this context; methanol is relatively easy to store and transport and has a wide range of industrial applications [4].

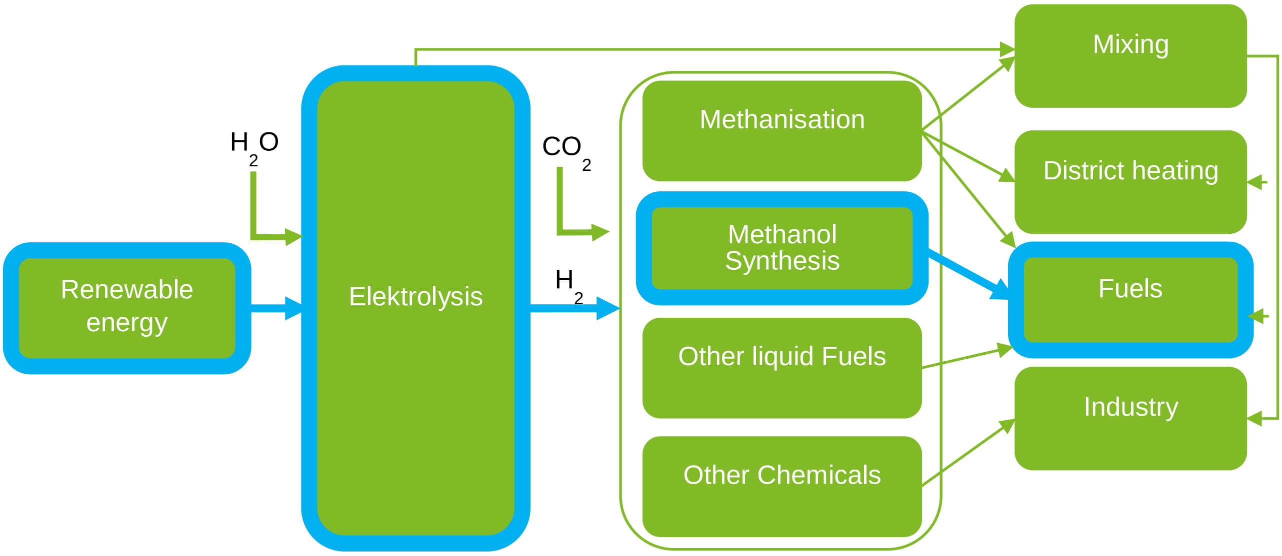

Fig. 2. Overview of PtX product manufacturing

Current research focuses on optimising catalysts and process conditions. At the Fraunhofer Institute for Interfacial Engineering and Biotechnology, Copper/Zincoxide/Zirconiumdioxide catalysts are being developed for industrial conditions [23], while the Fraunhofer Institute for Solar Energy Systems is investigating catalysts for dynamic operating modes in conjunction with H_2 electrolysis [24]. In addition, novel systems such as Copper/Zinc/Palladium are being researched for detailed analysis of the reaction pathways of methanol formation [25], as well as alternative preparation methods for highly active, bifunctional catalysts, for example via mechanochemically produced palladium-containing nanomaterials [26].
In addition, alternative conversion paths are coming into focus, such as biomass-based processes or electrochemical approaches for direct CO_2 reduction to methanol [27], [28]. These concepts open up additional options for the use of renewable resources, but still face challenges in terms of scalability, stability and economic efficiency [28]. Review articles show that numerous European demonstration projects are testing various PtX pathways, including methanol synthesis, in real-world applications, thus providing important insights into technical feasibility and system integration [2]. At the same time, reference is made to the geographical and energy potential of renewable-based PtX concepts, but also to the high demands on sustainable H_2 and CO_2 supply [12] and to persistent problems such as high energy requirements, efficiency losses and infrastructure costs [10], [13]. These developments form the scientific basis for the didactic reconstruction undertaken in the project and the discussion of key principles and challenges of the hydrogen and methanol economy in schools [4].

3. Introduction of Power-to-X – Specifically Methanol Synthesis – Into Schools

The integration of Power-to-X technologies, in particular methanol synthesis, into school chemistry lessons represents a curricular innovation that aims to teach future-relevant content in a practical and socially relevant way. The focus is on the development of experimental-conceptual learning modules that address technical, ecological and social aspects and are supplemented by digital materials to enable a multi-perspective approach to the topic [20].

3.1 Curricular Innovation and Development of Learning Modules

Implementation is carried out in line with curricular innovation research. The aim is to develop teaching and learning materials in which innovative topics are prepared in an experimental and conceptual manner and embedded in meaningful technical and social contexts. The newly developed experiments must also be as simple, safe and inexpensive as possible so that they can be used without hesitation in a school context [19]. These materials depict key steps in the industrial PtX process chain, in particular methanol synthesis, in a way that is suitable for schools, and are designed and developed for use in teaching and learning laboratories as well as in chemistry lessons. In addition, digitally enriched teaching and learning materials and didactic comments are being created that take different learning requirements into account and promote research-based learning [20]. These will be tested and optimised/further developed. Dissemination will take place within the framework of teacher training courses, through which they will also be disseminated in regular lessons.

3.2 Empirical Accompanying Research and Evaluation

The effectiveness of the developed modules will be empirically investigated using a mixed-methods design, combining qualitative methods (e.g. interviews, observations) and quantitative methods (pre/post questionnaire surveys). The evaluation focuses on the acceptance, competence development and self-efficacy expectations of teachers and learners [29]. In addition, the experiments and materials developed are tested at a scientific level using instrumental and wet chemical methods to ensure their practical suitability and safety in a school context.

3.3 Iterative Implementation Process

The project is divided into several iterative steps: First, the experiments and their conceptual embedding are developed and piloted before a sufficiently mature version is tested in the teaching-learning laboratory. This is followed by an in-depth conceptual design of the learning modules and another pilot test with teacher training students and teachers. In a further step, the materials will be used in teacher training courses to disseminate the concepts and, at the same time, to provide scientific support and evaluation. A possible further iteration involves the use of the materials in regular school lessons [8], [9].

3.4 Multiperspective and Sustainable Anchoring

The aim is to sustainably anchor innovative energy technologies and socially relevant issues in chemistry lessons in order to teach pupils skills in the areas of sustainability, energy and climate and to sensitise them to the challenges of climate change [7], [29]. By combining experimental approaches with digitally supported learning materials and contextual references, the aim is to achieve a practical, motivating and competence-oriented implementation in the classroom.

3.5 Dissemination and Quality Assurance

The results and concepts are presented and published at relevant subject-specific conferences to ensure broad dissemination and quality assurance of the teaching and learning modules. Teacher training courses serve as a central instrument for promoting professional skills and the sustainable implementation of innovations in everyday school life [9].

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