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Short version

**Technology and market study:
Overview of technologies for
bio-inspired CO₂ fixation and utilization
as well as of actors in Baden-Württemberg**

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Starting point and objective

By the year 2050 the state of Baden-Württemberg wants to be climate gas neutral. To this end, it becomes necessary to defossilize extensively i.e. do without using fossil raw materials in favor of renewable and climate gas neutral energy carriers. On the other hand, an efficient sink for carbon as a component of climate gases, as for example carbon dioxide (CO₂), must be built up which should be decoupled from the surface area. In addition, circuit management of the industrial raw material carbon should be attained - among others by using carbon dioxide (CO₂) as raw material.

The study "Technology and market study: overview of technologies for bio-inspired CO₂ fixation and utilization as well as actors in Baden-Württemberg" identified and assessed CO₂ fixation and utilization processes, either biotechnological processes, or processes inspired by biological knowledge. These processes inspired by the principle of biological photosynthesis are an important approach within a sustainable bioeconomy. They comprise at least one biotechnological step and facilitate a sunlight-driven conversion of CO₂ into energy carriers and chemicals. Processes were identified which could within a few years' time be mature enough to become pilot and demonstration plants and bear the potential to be utilized in industrial processes within a sustainable bioeconomy.

In this area Baden-Württemberg could become a role model. A roadmap is shown how an application-oriented development hub for biotechnological/bio-inspired CO₂ recycling should be designed which contributes to the climate protection targets 2030/2050 and which supplies industry with carbon raw materials. Such a development hub is planned as a measure in the Baden-Württemberg "State Strategy for a Sustainable Bioeconomy" as well as in the "Integrated Energy and Climate Protection Concept (IEKK)" and serves as an attainment of the states' sustainability targets.

CO₂ utilization and recycling processes inspired by the principle of photosynthesis

A broad spectrum of approaches is available for the sunlight-driven conversion of CO₂ into energy carriers and chemicals: it extends from purely biotechnological processes via hybrid processes which combine technical and biotechnological steps to a purely technical process such as power-to-X and artificial photosynthesis (illustration).

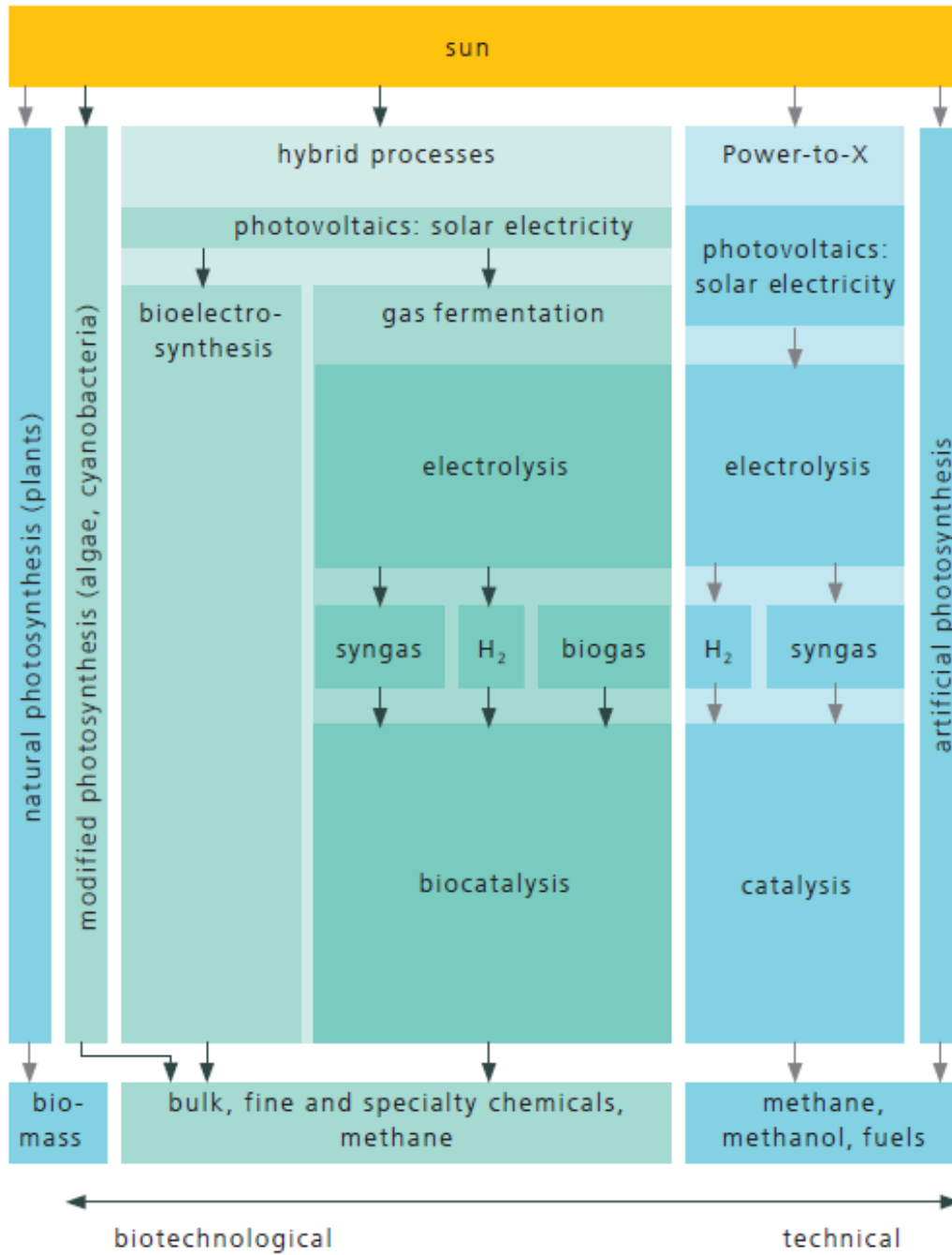


Illustration: CO₂ utilization and recycling processes, inspired by the principle of photosynthesis, for a sunlight-driven conversion of CO₂ into energy carriers and chemicals. Green: processes with at least one biotechnological step

Currently most biotechnological and hybrid approaches (marked green in the illustration) are still in the research and development phase. Modified photosynthesis, various types of gas fermentation and in the long term electro-biosynthesis, however, could within a few years become mature enough to be tested in pilot and demonstration plants. Therefore they could complement and broaden the spectrum of other technologies for CO₂ recycling (reference processes, marked blue in the illustration) in order to be able to provide solutions for different challenges. For example, biotechnological and hybrid processes can extend the product spectrum towards valuable i.e. long chain and highly functionalized organic molecules whereas power-to-X processes mainly provide simple organic compounds, for example methane or methanol as chemical energy carriers and fuels. Synergies and complementarities between these different approaches have to be actively explored and exploited.

Potentials for and in Baden-Württemberg

Baden-Württemberg with its universities, non-university research institutions and companies has excellent and relevant competences in life science, energy and climate-related research that is relevant for biotechnological and bio-inspired CO₂ fixation and utilization.

Excellent scientific-technological expertise goes hand in hand with an early political-strategic focus on CO₂ recycling with biotechnological and bio-inspired approaches both in the State Strategy "Sustainable Bioeconomy Baden-Württemberg" and in the "Integrated Energy and Climate Protection Concept (IEKK)". Therefore, Baden-Württemberg has very good preconditions to take the lead in this technology field, to shape it nationally and internationally and in the medium term to benefit from it economically.

In the state's economy biotechnological or bio-inspired processes for CO₂ utilization can in the long term be of interest to various industries: to CO₂ emitting industries as an option for climate protection technology, to producers of components, machines and plants who could supply CO₂ recycling process equipment, to the chemical industry utilizing CO₂ as a feedstock, as well as to the manufacturing industry as a processor of chemicals and materials produced from recycled carbon. Actors in Baden-Württemberg can position themselves as nationally and internationally important experts and sought-after cooperation partners with the aim to become technology leaders. However, companies are currently rarely aware of these options and their potentials.

The power-to-X and hydrogen technology communities in Baden-Württemberg are already well established and networked, their technologies having reached the pilot and

demonstration stage. On the other hand, the taking up of biotechnological and bio-inspired processes for CO₂ recycling in research and development and the formation of a corresponding community, which is connected with the Power-to-X and hydrogen technologies, has to be brought about actively in order to explore the innovation potentials present in Baden-Württemberg in an interdisciplinary and cross-sectoral approach.

Recommendations

1. Research and funding needs. Several years of R&D are still required to develop the processes of biotechnological and bio-inspired CO₂ fixation and utilization to industrial application maturity. A funding gap exists in Germany as well as on the level of the EU - beyond the funding of individual projects - which should be closed by a larger application-oriented development hub in Baden-Württemberg.

2. Development hub. Such a development hub for biotechnological and bio-inspired CO₂ fixation and utilization should be established jointly with research and industry. The requirements for such a hub are listed in the table below.

Table: Requirements for a development hub for biotechnological/bio-inspired CO₂-recycling in Baden-Württemberg

Requirements
Application-oriented and industry-relevant research and development with the aim of reaching the development stage of pilot plants (technology readiness level TRL 4-5) or demonstration plants (TRL 6-7) within a few years
Joint elaboration of application-oriented and industry-relevant R&D topics and objectives by research institutions and industry
Consolidation of the required competences across all disciplines and institutions
As biotechnological approaches mature, increasing role of companies in the funded projects
Funding instruments take into account the current different stage of development and the probable different speed of development of the various biotechnological and bio-inspired approaches
Support for consortia and network building
Openness for new R&D topics and integration of new R&D competences and actors
Comparative assessment of biotechnological and bio-inspired processes for CO ₂ utilization with complementary or competing approaches as an integral part of the development hub
Regular review and adjustment of R&D topics and objectives, of the necessary competences as well as the funding instruments due to the dynamically changing framework conditions (e.g. climate protection targets, development of other technologies, actor landscape, international developments)

On this basis a holistic concept is recommended which encompasses several interconnected modules which are staggered over time (illustration). The concept is designed for a period of approximately 8 to 10 years. The core of this development hub has several successive funding phases for interdisciplinary R&D projects. They are flanked by different measures which are planned in the State Strategy "Sustainable Bioeconomy Baden-Württemberg".

The objective of the development hub is to attain demonstration maturity of promising processes of biotechnological and bio-inspired CO₂ fixation and utilization, to establish an internationally visible and competitive community and to lay the foundation for new cross-sectoral value networks.

3. Funding phases and interdisciplinary R&D joint projects. Core of the development hub are R&D activities in the shape of interdisciplinary joint projects on biotechnological and bio-inspired CO₂ fixation and utilization which are conducted in several successive funding phases. By passing through these funding phases, it is the objective to bring the respective process to pilot and demonstration plant maturity. The joint projects must address industry-relevant R&D topics and must bring together the required competences of bio- and bioprocess engineering R&D, regenerative electricity production and electrolysis, chemical catalysis, scale-up, system integration and sustainability assessment.

It is recommended to implement a phase prior to the actual joint projects, in which the potential grantees for joint projects as well as potential relevant companies jointly identify application-oriented, industry-relevant R&D topics in workshops. They also specify the requirements for the applications which are to be developed, identify collaboration potentials and form consortia. Concrete project applications for joint projects could be elaborated in pre-projects with a duration of about 6 months and could then, in a competitive process, be selected for funding.

4. Information module. An information module should be implemented before the beginning of the actual development hub and should run in parallel to the first joint projects for a certain period of time. It contains several measures of the State Strategy "Sustainable Bioeconomy" and addresses biotechnological and bio-inspired processes for CO₂ utilization. The objective of the information module is to make the options for biological and bio-inspired CO₂ fixation and utilization known to all stakeholders of the relevant value networks. It is also to motivate them to participate in workshops for R&D topic identification and consortium formation or in a corresponding professional initiative (measure M26) or in industry dialogs (measure M24). Corresponding information can be conveyed on the one hand at virtual or physical events of research institutions,

associations, networks and initiatives that are taking place anyway, and on the other hand through information materials and activities within the framework of the information initiatives (measure M35).

5. Strategic reflexion. The foci and goals of the R&D activities and the composition of actors that are involved in the development hub should be reviewed and, if necessary, adjusted at regular intervals. This should be done in the light of the changing political and economic framework conditions, the developing competitive or complementary technologies and also national and international developments. This could be carried out, for example, in the form of status seminars or interim reviews.

6. Visibility and international networking. The development hub should be presented regularly within the International Bioeconomy Congress (measure M29).

7. Legal framework conditions. There should be regular reviews whether the (legal) framework conditions for CO₂ recycling are impeding or conducive. Their further development could possibly be conducted with the approach of the "regulatory innovation zone" (measure M3).

8. Training. Topics and activities of the development hub on biotechnological and bio-inspired CO₂ fixation and utilization should also be part of training measures (measure M30), of measures for imparting of knowledge and awareness-raising of sustainable bioeconomy (measure M27).

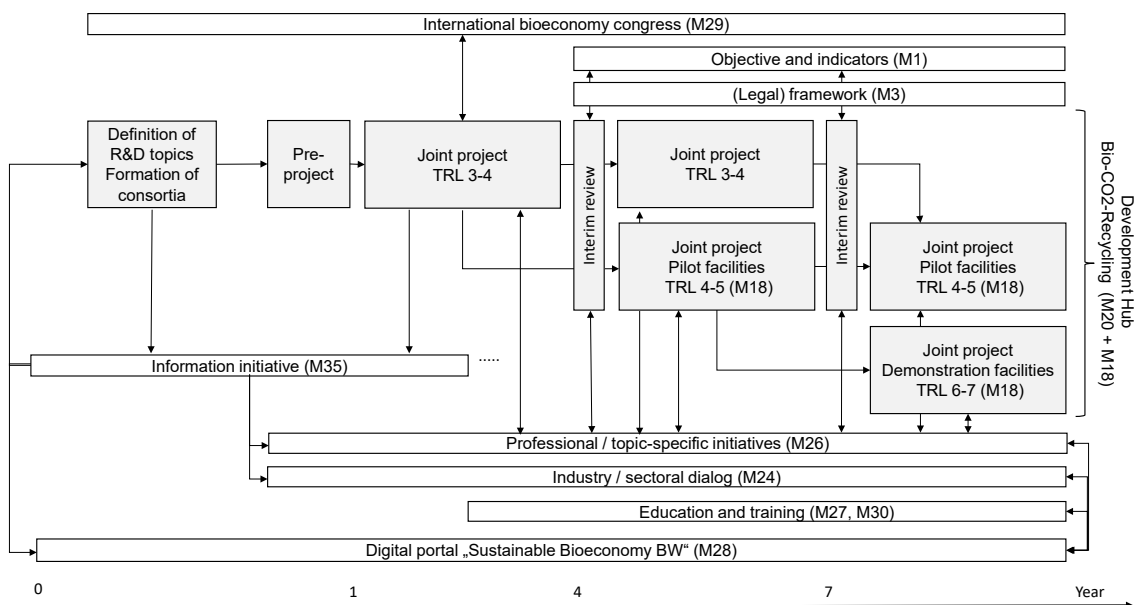


Illustration: Roadmap for a development hub on biological/ bio-inspired CO₂ recycling in Baden-Württemberg and networking with other measures of the State Strategy "Sustainable Bioeconomy".