„Potential of Hydrogen Production by Wastewater Treatment Plants (WWTPs) - Technologies, Benefits, Challenges and Limitations using the Example of the Wastewater Treatment Plant Straubing“

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Abstract

Due to an ever-increasing change towards a circular economy and energy self-sufficiency, the energy production and the use of it must be redefined. This does not stop at the water- and wastewater industry, which is responsible for a large amount of a municipality's energy consumption. However, WWTPs can also make a significant contribution to the energy transition and circular economy. Sustainable hydrogen, produced decentrally, regionally and for regional consumers, will play a important role in the future energy supply. The aim of this study is to identify possible potentials and technologies for local hydrogen production, conceivable alternative uses, research programmes, funding opportunities, but also challenges and limits with regard to the possibilities of hydrogen production at the approximately 10,000 municipal WWTPs in Germany.

Key words

Hydrogen production, regionality, wastewater management, circular economy, sustainability

1. Hydrogen demand and production options

In order to reach climate goals and achieve deep decarbonisation of the society, transformation of our entire industrial landscape towards a circular economy, sustainable production, and renewable energies is needed. Of course, the wastewater sector must also be considered and contribute to the energy transition. Some sectors already have obligations to save energy, recycle raw materials by comitted recovery rates or using a certain proportion of recyclates. In Germany and Switzerland, for example, phosphorus will have to be recovered from sewage sludge in the future. In other areas of wastewater treatment further research and development are being carried out so that wastewater management contribute further towards sustainable industries, including nutrient recovery (Nitrogen) excess energy usage (Heat or hydrodynamic) (Qadir, M. et al., 2020; Nagpal, H. et al., 2021).

Here, the revision of the Urban Wastewater Directive (in German - Kommunale Abwasserrichtlinie) will bring about a lot of positive changes across Europe in terms of circular economy, Electricity consumption, reuse, recycle and the production of green energy to cover self-consumption. However, this will also lead to major challenges for wastewater treatment plant (WWTP) operators. Many innovations are to apply to WWTP with a size of 10,000 PE (Population equivalents; in German - Einwohnergleichwerte/EWG) or more. Financially, in terms of personnel and organization, all of this must be managed.

The availability of sustainable hydrogen as an energy carrier and as an indispensable raw material is an important key technology. For example, the German National Hydrogen Strategy focuses on green hydrogen (Schuberth, J., 2023) and its production potential. By 2030, instead of 5.000 MW (5 GW), 10.000 MW (10 GW) of Electrolyser capacity must be created (Federal Ministry of Education and Research – BMBF et al., 2023). There are various ways to produce hydrogen in wastewater treatment. Several ways and possible synergies, but also their disadvantages, will be shown.

Apart from providing suffient amounts of hydrogen by centralized or decentralized production sites, the hydrogen distribution is also a very demanding task. The transition of natural gas pipelines to be “hydrogen-ready” will cost 45 billion Euros (DVGW, 2021). For the transition period, short and long term storage options and conversion methods für hydrogen will play an important role.

For this purpose, biomethanation is an interesting area of application, in which hydrogen and carbon dioxide are converted into methane. We would also like to take a closer look at this in this study.

Green hydrogen can be produced at WWTP and thus synergies, such as the use of the resulting oxygen or wastewater as a raw material, can be used.

In addition to green hydrogen as a possible energy carrier, the oxygen also obtained during water electrolysis can be used in the biology of the WWTP or as a starting material for a so-called fourth purification stage in order to remove further pollutants from the wastewater stream. The resulting wastewater is purified in the sewage treatment plant and thus serves as an additional raw material. The electrolyser waste heat can also be used in the wastewater treatment plant. Nitrogen-rich side streams in the WWTPs have great potential to produce hydrogen from them. This also applies to the biogas produced y digestion of raw and/or excess sludge. Furthermore, wastewater or sewage sludge can also be used as sources of supply for extraction via biological or thermal processes. The potential hydrogen production and therefore the optimal production technology is heavily depending on the situation of the WWTP, like influent, sludge composition, biogas production, or synergies on site.

In addition, using synergies with nearby industries, cycles can be closed in the sense of the circular economy. WWTPs are given great potential (Jentsch, M. F. et al., 2019). Regional electricity surpluses can also be used, and CO_2 emissions and energy dependencies are reduced.

The mentioned technologies are presented in more detail in the study and their feasibility in municipal WWTPs is evaluated. The findings can also be used as a basis for industrial wastewater treatment plants.

At the end of the introduction, however, a distinction should now also be made as to what type of hydrogen is involved. The most common term is grey hydrogen. The grey hydrogen is produced from fossil fuels. Blue hydrogen, on the other hand, is when the carbon dioxide produced during hydrogen production from fossil fuels is used and not simply released into the environment. Green hydrogen means that no additional carbon dioxide is produced during its production process (Federal Ministry for Economic Affairs and Climate Action – BMWK et al., 2023).

Current estimates assume that up to 800 TWh of hydrogen will be needed in Germany alone by 2050 (German Bundestag et al., 2022), whereby green or at least blue hydrogen in particular should be purchased and used in order to achieve the climate targets.

Germany was produced and consumed around 55 to 60 TWh of hydrogen in 2020, but this is mainly grey hydrogen from natural gas and only about 5% green hydrogen (Noack, C. et al., 2015; Merten, A. et al., 2020).

In 2019, German WWTPs produced around 1.515 GWh or 1.5 TWh of electricity (Federal Statistical Office – Destatis et al., 2020).

To calculate the amount of hydrogen that can be produced with 1.5 TWh of electricity, we assume an efficiency of 75%. Depending on the type of electrolysis, the efficiency is around 70% to 80%.

$$Amount\ of\ hydrogen = \ Electricity\ in\ TWh\ x\ Efficiency$$

$$Amount\ of\ hydrogen = \ 1{,}5\ TWh\ x\ 0{,}75$$

$$Amount\ of\ hydrogen = \ 1{,}125\ TWh$$

This would allow the WWTPs to cover around 0.14% of the hydrogen demand forecast for 2050. As a rule, however, the WWTPs use the self-generated electricity themselves, which would make the proportion for hydrogen even lower.

The following text shows the various technologies, research projects, funding opportunities, corresponding laws and obstacles.

2. Presentation and explanation of the different technologies

a. Electrolysis of water

Various processes and technologies can be used to produce hydrogen. This study explains how electrolysis of freshwater, treated wastewater, desalinated seawater, or direct electrolysis of saltwater works. Alkaline water electrolysis (AEL) is very widespread. It is the most established technology among the proven electrolysis processes. However, it has the most problems in intermittent operation associated with renewable energy. Polyelectrolyte membrane electrolysis (PEM), also known as proton exchange membrane electrolysis, is therefore becoming increasingly important. Very large research efforts are being made in the field of anion exchange membrane electrolysis (AEM) and high-temperature electrolysis (HTEL). The efficiency, the lifetime of the electrodes and the operating costs of the electrolysers vary greatly depending on the technology used. In addition, the operating costs are influenced by the purity of the water, which material is used for the electrodes (Aluminum, Copper, Iron, Nickel, Zinc), whether the waste heat from the electrolyser can be used and how high the electricity demand is.

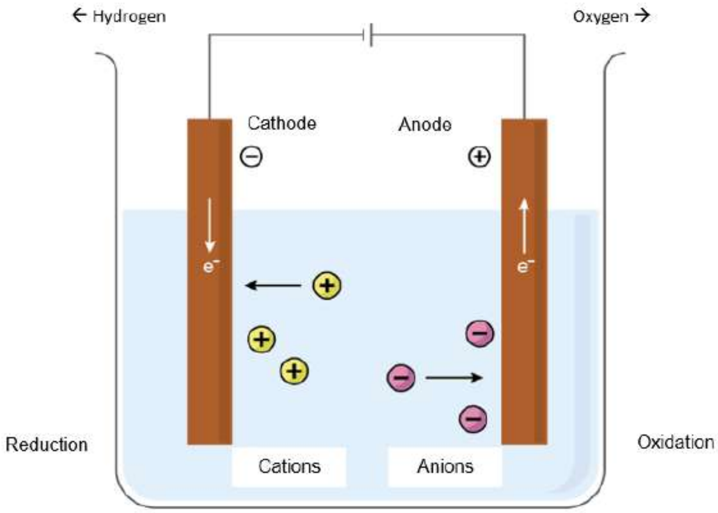
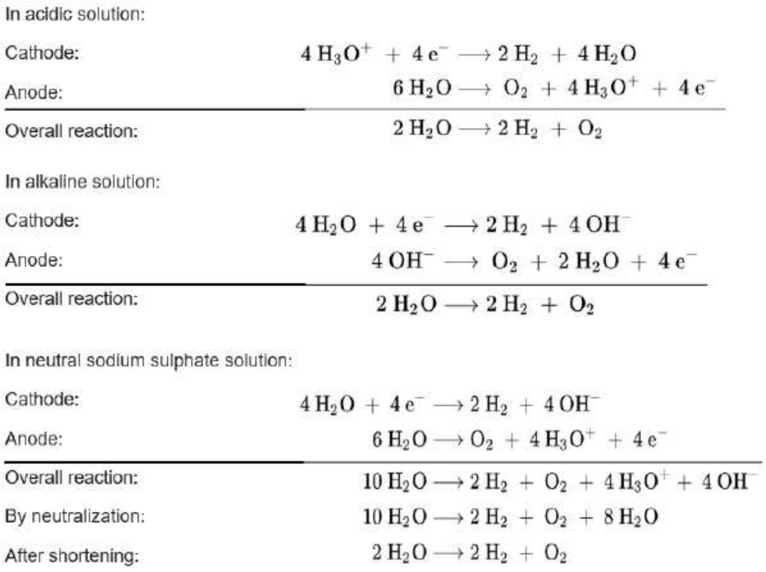


Figure 1: Basic design for water electrolysis (Vögtil, Dr. A., 2024), with own modifications

Electrolysis is the process of using electrical energy in the form of electric current to break down water into hydrogen and oxygen, as you see in figure 1. Electrolysis can take place in an acidic, alkaline and neutral solution. Figure 2 shows the three different electrolytes.



In acidic solution:

Cathode: $4\,H_3O^+ + 4\,e^- \longrightarrow 2\,H_2 + 4\,H_2O$
Anode: $6\,H_2O \longrightarrow O_2 + 4\,H_3O^+ + 4\,e^-$
Overall reaction: $2\,H_2O \longrightarrow 2\,H_2 + O_2$

In alkaline solution:

Cathode: $4\,H_2O + 4\,e^- \longrightarrow 2\,H_2 + 4\,OH^-$
Anode: $4\,OH^- \longrightarrow O_2 + 2\,H_2O + 4\,e^-$
Overall reaction: $2\,H_2O \longrightarrow 2\,H_2 + O_2$

In neutral sodium sulphate solution:

Cathode: $4\,H_2O + 4\,e^- \longrightarrow 2\,H_2 + 4\,OH^-$
Anode: $6\,H_2O \longrightarrow O_2 + 4\,H_3O^+ + 4\,e^-$
Overall reaction: $10\,H_2O \longrightarrow 2\,H_2 + O_2 + 4\,H_3O^+ + 4\,OH^-$
By neutralization: $10\,H_2O \longrightarrow 2\,H_2 + O_2 + 8\,H_2O$
After shortening: $2\,H_2O \longrightarrow 2\,H_2 + O_2$

Figure 2: Representation of different electrolytes (Kurzweil, P. et at., 2022), with own modifications

To produce one kilogram of hydrogen, you need about 9 to 10 liters of water. In addition, you need about 53 kWh of electricity. The degree of utilization is about 60 - 85% (GASAG et al., 2022).

Probably the best known and most widespread electrolysis application is the electrolysis of fresh water (drinking water or well water).
Before that, however, the drinking water must be purified of disturbing minerals, i.e. salts. Only ultrapure water can be used to prevent salt deposits on electrodes or the membranes. As a result, the service life can be shortened and the service life of the system components can be increased (Jabs, F., 2021).
Important in terms of utilization: The calculated efficiency depends on how the energy content of the hydrogen is calculated. You can use the HHV (Higher Heating Value) or the (significantly lower) LHV (Lower Heating Value). In relation to the HHV (Higher Heating Value), this results in correspondingly higher values.

b. Electrolysis of treated wastewater

Due to the ever-increasing shortage of freshwater, attempts are being made to utilize treated wastewater instead of freshwater in electrolysis. However, it should be noted that due to the substances still contained in the treated wastewater, such as organic compounds, bacteria and salts, a great deal of effort must be made in the purification of the wastewater. Tests at the Straubing sewage treatment plant have shown that the wastewater from a partial flow of the sewage treatment plant after the normal purification cycle and an additional ultrafiltration overloaded the test downstream test activated carbon filter within a very short time, making it no longer possible to regenerate the activated carbon. Thus, ultrafiltration with an activated carbon filter is unsuitable for providing water for desalination and further for the supply of an electrolyser, at least in WWTPs with trickling filters. Alternative pretreatment technologies of wastewater are nanofiltration or reverse osmosis before the water can be fed to the desalination plant and an electrolyser. This not only increases the energy requirement, but also the amount of water, because, for example, process-related water losses have to be compensated for during reverse osmosis. Electrolysis would then take place in the same way as freshwater electrolysis.

c. Electrolysis of desalinated seawater

Here, too, the salt water must be specially pre-treated. There are, especially in the Arab world, many seawater desalination plants that desalinate the seawater to supply of potable water and also for the supply of electrolysers. However, a lot of energy is needed for desalination and hydrogen production, which is mostly obtained from fossil fuels. Therefore, it is mainly grey hydrogen that is generated here. In addition, the degree of utilization is even lower, as the purification of the salt water is time-consuming. Certainly, many more countries and regions will be dependent on saltwater desalination plants in the future due to global warming and the lack of precipitation. Therefore, this would be a way to combine both, i.e. the provision of drinking water and ultrapure water for electrolysis.

d. Direct electrolysis of salt water

Recent research and experiments have shown that direct electrolysis of salt water is quite possible, at least on a smaller scale. For this purpose, Tianjin University in China operates a pilot plant that produces about 40 liters of hydrogen per hour from salt water (Klatt, R., 2023).
The main challenges in seawater electrolysis are that the chlorine (Cl-) contained in seawater has an extremely corrosive effect on the electrodes. In addition, there are many other components that attack the electrodes and membranes. These include calcium and magnesium, which are deposited as hydroxide precipitates on the cathode and anode, thus

reducing performance and service life. Tianjin University has protected the electrodes from these influences with a special nickel coating.

WWTPs are usually the largest energy consumer in a municipality. In 2021, 31.6 kWh were needed to treat approx. 82 m³ of wastewater per PE (Population equivalents; in German - Einwohnergleichwerte/EWG) per year. The share of self-generated electricity generated by the WWTPs participating in the performance comparison is less than 40% (DWA Working Group BIZ-1.1 "Wastewater Treatment Plant Neighborhoods" et al., 2022). If, in the future, electrolysers are also to be established at WWTPs for the production of hydrogen, the demand for electricity will increase significantly. If the supply of green electricity cannot be secured, hydrogen production will not produce green hydrogen and should therefore be viewed critically. In addition, WWTPs will have to supply themselves with green energy in the future in order to achieve their own energy self-sufficiency. As a result, there may be a certain amount of competition between the company's own energy supply and the production of hydrogen. The investments must be covered by subsidies, or at least largely covered, to minimise negative effects on wastewater charges for the inhabitant of a municipality or city. Of course, it would also be conceivable to install hydrogen-capable CHP (Combined Heat and Power) units on the wastewater treatment plant, which would then convert the hydrogen produced in-house into electricity and heat. However, the usefulness, cost-effectiveness and operational safety of all concepts must be carefully examined. Likewise, the safety of handling hydrogen, the effort required for certifications and the need for qualified specialists must not be ignored.

e. Hydrogen production from nitrogen-rich material flows

i. Wastewater Plasmalysis

By means of the so-called wastewater plasmalysis, hydrogen can be obtained from effluent from sewage sludge dewatering, slurry or vapours from sewage sludge drying. These media contain high nitrogen-rich loads, mostly ammonia, which are ideal for the process. Graforce has developed, patented and implemented an established process in various plant sizes.

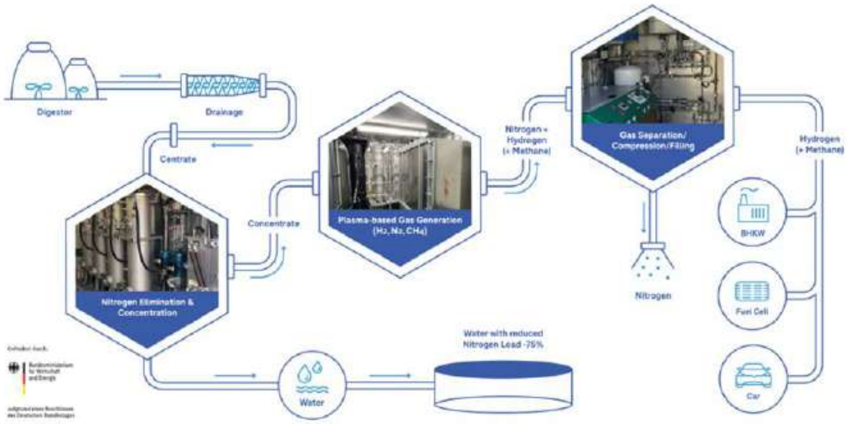


Figure 3: Production of green hydrogen from ammonium-containing wastewater (*Cronenberg, A. 2020*)

In this process, which is shown in detail in figure 3, a plasma is generated from (green) electricity. In this high-frequency plasma field, the nitrogen and carbon compounds in the water are split. In fact, the reverse reaction of the Haber-Bosch process occurs in the case of nitrogen compounds:

$$2\ NH_3\ (g) \xrightarrow{Plasmalysis} N_2(g) + 3\ H_2\ (g)$$

The energy requirement of this process is significantly lower than that of conventional electrolysis. Such a process reduces the Nitrogen chargeback from sludge treatment and facilitates the subsequent treatment of this effluent and produces green hydrogen. Prerequisite is obtaining chemically pure and concentrated soluten of ammonia, impurities can produce unwanted by-products and hamper the hydrogen production. A corresponding plant is operated in Berlin Waßmannsdorf as a demonstration plant for the treatment of the centrate of sewage sludge dewatering.

ii. Plasmalysis of biogas

Here, too, there is great potential to produce hydrogen and also to establish a solid carbon dioxide sink. The so-called carbon black can be obtained as carbon in solid form for other branches of industry, e.g. for asphalt or tire manufacturers. The company Graforce has also developed a corresponding process here.

Clearly explained in figure 4, in this process, a plasma is also generated from (green) electricity. In this high-frequency plasma field, methane, which is contained in biogas (or natural gas), is split into its two molecular components, hydrogen and carbon. Thus, 4 kilograms of methane and an additional 10 kWh of electricity produce 1 kilogram of hydrogen and 3 kilograms of elemental carbon. The hydrogen produced in this way is also known as turquoise hydrogen. Such a system is operated on the roof of the MOA Hotel in Berlin. Here, natural gas is split into carbon and hydrogen by means of plasmalysis, the hydrogen fires a heating boiler, and the carbon is collected and reused for further processes.

The application for biogas is more efficient, if the methane content is high. WWTPs can raise the methane yield by adding high caloric wastes like fat float to the biogas digester.

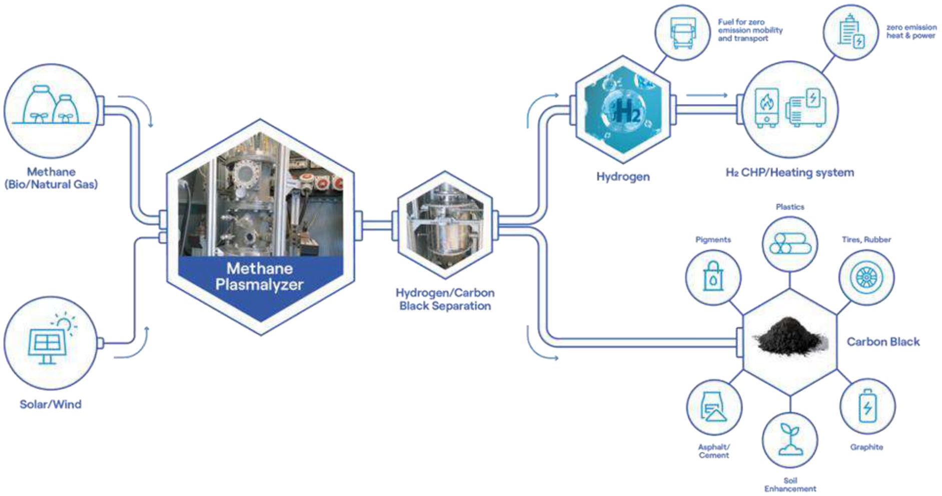


Figure 4: Production of green hydrogen from methane plasmalysis (Graforce GmbH, 2020)

f. Thermal sewage sludge treatment

Sewage sludge contains large amounts of organic compounds. Non-stabilized sewage sludge contains up to 75%, anaerobically stabilized sewage sludge contains 50 – 55% organic compounds. These can be converted into hydrogen, carbon monoxide, carbon dioxide and methane by substoichiometric combustion or gasification. Water vapour is a suitable oxidizing agent here, a large part of the hydrogen produced also results from the water, not from the organic compounds. Air is also possible, but not favored due to the dilution of the product gas with nitrogen and nitrous oxides.

Gasification takes place optimally at temperatures higher than 850°C and in a fluidized bed reactor, analogous to thermal combustion. Ideally, this also makes it possible to recover phosphorus from sewage sludge ash, as required by the Sewage Sludge Ordinance (in German - Klärschlammverordnung - AbfKlärV), which was amended in 2017, for sewage treatment plants > 100,000 PE or > 50,000 PE from 2029 or 2032. The necessary heat can be provided by simultaneous incineration of part of the sewage sludge in the combustion chamber or by separate incineration of sewage sludge or other energy sources and the subsequent transport of the heat by means of heat pipes or heat exchangers.

In addition to the gaseous compounds, the flue gas also contains tar compounds, which must be condensed. The gas must then be purified, and the hydrogen yield can be increased by means of water gas shift. The hydrogen must then be removed from the gas mixture. Possible methods for this are pressure swing absorption or organometallic frameworks. The lean gas must be treated, for example by off gas burning, in order to prevent the emission of harmful gases.

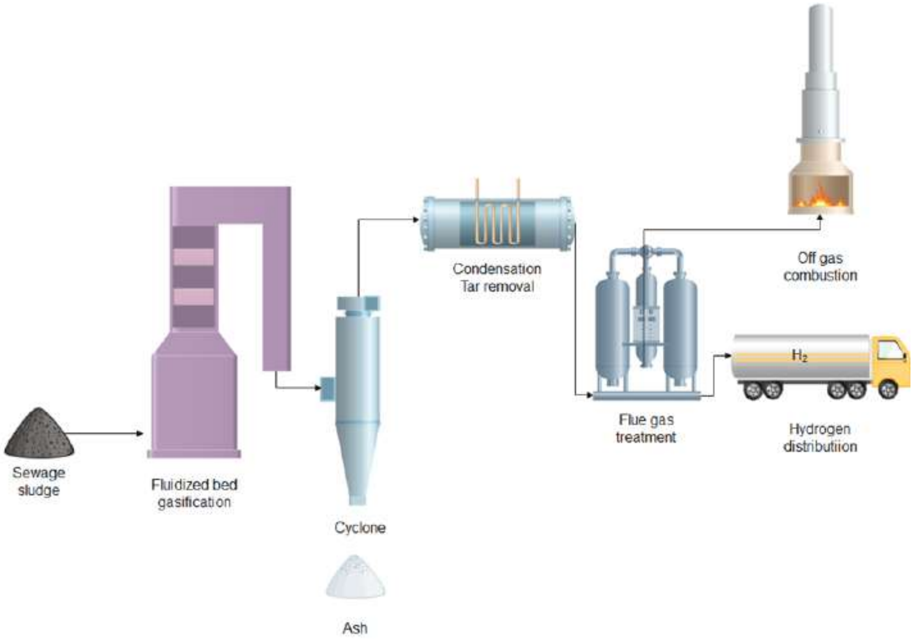


Figure 5: Schematic structure of sewage sludge gasification, own scheme by Jürgen Pettrak

As can be seen from the figure 5 above, many process steps are required to produce renewable hydrogen from sewage sludge. The advantages are that raw materials such as phosphorus can be recovered and the production of hydrogen can contribute to the energy transition. However, studies currently suggest that economical operation for gasification is only possible in very large plants (Lumley, N. P. G., 2013), with hydrogen separation being added as an additional treatment step. The gas quality depends strongly on the composition of the sewage sludge and therefore has a very strong influence on economic efficiency. Depending on the process technology, up to 50% hydrogen can be achieved in the gas mixture.

For this purpose, suitable locations must be sought and found, as is currently often planned with mono-incineration plants for sewage sludge, in which sufficiently large quantities of sewage sludge are available and there are customers for the hydrogen produced. To comply with german or swiss legal regulations, phosphorus recovery must be possible, in order to be able to carry this out economically, sewage sludge with high phosphorus contents is necessary, and in addition, little or no bed material may be discharged so as not to further dilute the phosphorus content. Economic feasable operation of such plants either require centralized sites or close proximity to WWTPs.

There are some pilot plants in operation, such as Green Hydrogen Technology in Leoben, but there are currently no large-scale plants planned.

g. Biological processes

Sewage sludge or wastewater can also be used to produce hydrogen via biological processes.

The principle in a nutshell:

Microorganisms break down organic compounds and produce hydrogen under anaerobic conditions. These microorganisms can represent pure cultures, i.e. a selected strain, co-cultures, i.e. several selected strains, or a mixed flora. Hydrogen is already produced in the digester during normal operation of a biogas plant and is needed to convert CO2 into methane. By acidifying the fermentation substrate to pH 5-6, methane formation can be inhibited and only CO2 and hydrogen are produced (Cai, M. et al., 2004).

There is a variety of hydrogen-producing microorganisms, from mesophilic (25 - 40°C) clostridia to hyperthermophilic (65 - 90°C) thermotogales (Kengen et al., 2009). The greater the load of organic matter in the water, measured by the chemical oxygen demand (COD), the higher the theoretical yield, but bioavailability, which can be determined by the biological oxygen demand (BOD), also plays an important role here.

The hydrogen yield from sewage sludge decreases rapidly with the degree of sewage sludge stabilization (Kim, S., 2004). This is not surprising, since the easily degradable organic load has already been metabolized in both aerobic and anaerobic sewage sludge stabilization, making the residue difficult to degrade.

For both sewage sludge and raw wastewater, pre-treatment of the substrate is therefore necessary to increase gas yields (Mohan, S. V. et al., 2008). The most efficient pre-treatment depends on the type and composition of the substrate. For example, larger aggregates are broken down into smaller, more easily accessible flakes by physico-chemical processes such as thermal pressure hydrolysis or acid treatment. Longer, difficult-to-degrade molecules can, for example, be broken down into shorter molecules by acidification, which are then more bioavailable.

For biological hydrogen production, it is also promising not to focus on municipal WWTPs, but rather to use wastewater streams rich in organics, such as wastewater from breweries, milk processing industries, oil mills, or similar industries that produce oil, protein and/or sugar-rich material streams, which can then be used for hydrogen production by means of selected cultures. Often, an increase in efficiency can be expected through pre-treatment, but the gas yields are much higher than with wastewater or sewage sludge (Preethi et al., 2019).

i. Biomethanation

Biomethanation uses the methane-forming microorganisms of the Archeen type. They can withstand extreme living conditions, such as high temperatures and pressures (Bär, K. et al., 2015). However, the process usually takes place between 30–70 °C in the technical reactor and a distinction is made between the in-situ and the ex-situ process:

In the in-situ process, the hydrogen produced from electrolysis is introduced directly into the digester (Bär, K. et al., 2015). This has the advantage that existing fermenters can be used for power-to-gas concepts without additional reactors. However, since other steps take place in anaerobic fermentation in parallel to methanation, the conditions in the fermenter are not specifically tailored to the archaea. This results in lower methane formation rates. In addition, large quantities of hydrogen are needed immediately, as the volumes of the fermenters are very large.

External reactors (ex-situ methods) are quite efficient (Bär, K. et al., 2015). This has the advantage that the microorganisms can obtain the perfect framework conditions and the use of hydrogen can be better regulated. In addition, the required carbon can also be used from external sources. The most relevant reactor concepts for process engineering are stirred tank, trickle bed and bubble column reactors (Manig, R. et al., 2023).

Another advantage of biomethanation is the elimination of hydrogen storage facilities, which are not available in Germany in the required quantity and size. Either disused salt caverns, exhausted oil or gas fields are used, or containers built above ground that first have to be produced and erected. Among other things, lengthy planning procedures are necessary for both, and the metabolism of hydrogen by microorganisms in the exhausted oil and gas production fields is another problem. There is an urgent need for further research efforts with regard to underground storage options, as many safety questions and which chemical reactions take place, among other things, remain unclear (Heinemann, N. et al., 2021). In addition, the biomethane obtained can be used directly as fuel for agricultural vehicles, for city buses or the waste collection fleet of cities or companies.

3. Hydrogen Research projects at wastewater treatment plants

As the use of hydrogen as a clean energy carrier becomes increasingly important worldwide and efforts to combat climate change and reduce dependence on fossil fuels are intensified, WWTPs are of course also increasingly becoming the focus of research and technology companies in this context. They are trying to optimize the purification of wastewater and also to harness the potential for the production and use of hydrogen.

Research projects on hydrogen production at WWTPs are the focus of this chapter. These projects aim to optimise wastewater treatment processes by using innovative technologies to produce hydrogen from biological waste streams. Not only are environmentally friendly alternatives to conventional energy generation being explored, but synergies between wastewater treatment and the renewable energy industry are also being created.

Table 1 takes a closer look at the various research projects on hydrogen production in WWTPs.

Project Name	Project Partners	Goal	Technology	Performance	Synergies	Project Status	Reference
ARRIVED	Wirtschaftsbetrieb Mainz, TU-Kaiserslautern	Oxygen, hydrogen as a by-product	Water electrolysis and extension of the 4th purification step for the elimination of trace substances from ozonation and a filter stage with granulated activated carbon	ca. 1,25 MW	Oxygen for ozonation, waste heat, hydrogen for blending into the natural gas grid	Electrolysis is an out-of-budget tender	(Environmental Innovation Program et al., 2024)
SeWAGE PLANT H	Stadtentwässerung Hannover, Siedlungswasserwirtschaft und Abfalltechnik (ISAH), Institut für Elektrische Energiesysteme (IfES)	Hydrogen, oxygen as a by-product	Water electrolysis	1st. Stage: 2,5 MW; 2nd. Stage: 17 MW	Oxygen for ozonation, waste heat for the district heating network, hydrogen for the natural gas grid	In implementation	(Leibniz Universität Hannover et al., 2024)
WaStraK	Emschergenossenschaft, Forschungsinstitut für Wasserwirtschaft und Klimazukunft an der RWTH Aachen e. V (FIW), TUTTAHS & MEYER Ingenieurgesellschaft mbH, Ingenieurbüro Redlich und	Methanoal, synthesis gas, hydrogen as a necessary substance for the process	Steam reforming, water electrolysis, methanol synthesis reactor	This is not clear from the literature	Waste heat	Pilotphase finished	(EGLV et al., 2024)

	Partner GmbH						

Table 1: Overview of different projects - own illustration

Projects in this direction are also being driven forward in other countries such as Japan, the UK and the USA.

As an example, Thames Water, the UK's largest water treatment company, is working to design a pilot plant that produces hydrogen from wastewater. This plant uses electrolysis to use excess renewable energy from solar panels and produce hydrogen.

In the USA, the Mazzei Injector Company, in collaboration with a wastewater treatment plant in California, has launched a project to produce hydrogen from biogas using high-performance nozzles. This hydrogen can then be used as a fuel or to generate electricity.

4. Funding systems

Subsidies play a crucial role in hydrogen projects for several reasons.

Research and development are to be promoted. Hydrogen technologies are still at a relatively early stage of development, and funding can help drive innovation and improve the efficiency and economics of hydrogen projects. This includes research into new production and storage technologies as well as the development of applications for hydrogen in various sectors such as transport, industry and energy.

The market launch can and must also be supported. Hydrogen is not yet economically competitive on a large scale with conventional energy sources such as natural gas or gasoline. Subsidies can help accelerate the market introduction of hydrogen technologies by supporting investments in infrastructure projects such as hydrogen refueling stations, electrolysis plants and fuel cell vehicles. Subsidies can also be used to incentivize to increase demand for clean hydrogen solutions in various industries.

Subsidies can also lead to cost reductions and economies of scale. Subsidies can reduce the initial costs of building hydrogen infrastructure and producing hydrogen. This can help to achieve economies of scale and reduce the cost of hydrogen technologies in the long term by increasing production and realizing efficiency gains.

Of course, support programs also have a positive impact on environmental and climate protection. Hydrogen is considered a promising clean energy carrier that can help reduce greenhouse gas emissions, especially when produced from renewable energy sources. Funding can help accelerate the transition to a low-carbon hydrogen economy and achieve climate and environmental goals.

Overall, grants play an important role in supporting hydrogen projects by promoting the development, market uptake and scaling of hydrogen technologies and accelerating the transition to a sustainable and low-carbon energy future. Table 2 briefly summarizes some funding opportunities.

Funding Institute	Institute	Amount	Recipient	Reference
Germany for inland and for international cooperation	BMWK, KfW	project budgets range from several thousand euros to several of millions of euros per project	Municipality, company, association, university, research institution, etc.	(BMWK et al., 2024)
Germany for inland and for international cooperation	BMWK, KfW	project budgets range from several thousand euros to several of millions of euros per project	Municipality, company, association, university, research institution, etc.	(DIHK et al., 2022)
European Union	European Commission, Connecting Europe Facility for Energy (CEF-E),	project budgets range from several million euros to several	Municipality, company, association, university, research institution, etc.	(Hydrogen Public Funding Compass et al., 2024)

	Connecting Europe Facility for Transport (CEF-T), European Regional Development Fund (ERDF) and the Cohesion Fund (CF), etc.	hundreds of millions of euros per project		
European Union	European Commission, Horizon Europe 2021-2027	project budgets range from several million euros to several hundreds of millions of euros per project	Municipality, company, association, university, research institution, etc.	(HORIZONT EUROPA et al., 2024)
European Union	European Commission	project budgets range from several million euros to several hundreds of millions of euros per project	Municipality, company, association, university, research institution, etc.	(IPCEI Hydrogen et al., 2024)

Table 2: Overview of different fundings - own illustration

5. Overview of the Urban Wastewater Directive, Regulations and Legislation

a. Urban Wastewater Directive

The Urban Wastewater Directive (Kommunale Abwasserrichtlinie - KARL), also known as Council Directive 91/271/EEC from 21st of May 1991 on urban wastewater treatment, is a legal instrument of the European Union that deals with the treatment and protection of urban wastewater. It lays down minimum requirements for the collection, transport and treatment of wastewater in the Member States in order to protect the environment and ensure human health.

The main objectives of the Municipal Wastewater Directive are:

- To ensure the protection of waters from pollution by wastewater, in particular by reducing the discharge of pollutants such as nitrogen, phosphorus and organic matter.
- To promote sustainable wastewater treatment by setting minimum treatment quality requirements and compliance with emission limits for WWTPs.
- Ensuring adequate collection and treatment of wastewater in urban areas in order to minimise the burden on the environment and reduce the risk to human health.

The Directive requires Member States to draw up wastewater management plans to ensure that the objectives are met and specifies that WWTPs should be operated in accordance with the best available techniques. It also establishes monitoring and reporting obligations to verify implementation and ensure that requirements are met.

The Urban Wastewater Directive has made a significant contribution to the protection of European waters and has driven the development of modern wastewater infrastructure in the Member States. It is an important tool in the EU's water policy and helps to improve the quality of the environment and ensure citizens' right to clean water.

At the beginning of April 2024, the revision of this directive was approved by the EU. Important innovations are listed here:

- Polluter pays principle: The Directive implements the polluter pays principle by imposing requirements on Member States to better protect the environment and human health.
- Fourth purification stage: The European Commission wants to make the fourth purification stage mandatory for all sewage treatment plants with a size of 100.000 population equivalents (PE) or more by 31.12.2035. For settlement areas between 10.000 and 100.000 inhabitants, this level is to be introduced by 31.12.2040 if higher concentrations of micropollutants pose a risk to human health or the environment.
- Extended producer responsibility: To finance these measures, the Commission proposal provides for the implementation of the polluter-pays principle through the introduction of

extended producer responsibility. Manufacturers are to be obliged to make individual contributions based on the quantity and toxicity of the substances they put into circulation.

- Energy neutrality: The draft provides for energy audits for WWTPs with a population of 100.000 or more by the end of 2025 and for WWTPs with a population of 10.000 or more by the end of 2030. In addition, the total amount of energy produced annually from renewable energies generated by WWTPs (≥ 10,000 PE) is to cover 50% of the energy demand of these WWTPs by the end of 2030. By the end of 2040, this share is expected to increase to 100% (Wasser 3.0 gGmbH et al., 2024).

b. Regulations and Legislation

Laws and regulations are important for the hydrogen economy for several reasons. They are intended to ensure safety and health protection. Hydrogen is a highly flammable gas and therefore requires strict safety standards for production, transport, storage and use. Laws and regulations set these standards to prevent accidents and ensure the safety of employees, the public, and the environment.

Quality standards are also required for the various applications of hydrogen to ensure that the hydrogen meets the respective requirements. For example, hydrogen fuels must have certain levels of purity to ensure efficient combustion and proper operation of fuel cells. Laws and regulations can set these standards and monitor their compliance.

The development of a hydrogen economy requires appropriate infrastructure, including production facilities, transport networks, refueling stations and storage. Conditionality can support the development of this infrastructure, for example by incentivising investment, providing access to public land and facilitating planning and permitting procedures to promote the production and use of green hydrogen and accelerate the transition to a low-carbon economy.

Clear and uniform rules prevent a patchwork quilt, which can become more complicated and even less transparent depending on the federal state.

Legal certainty can strengthen economic development and create a positive investment climate for the hydrogen economy. Facilitating market access and ensuring a level playing field can help to increase private and public investment and enable job creation and economic growth.

Overall, laws and regulations are crucial for the development and successful operation of a hydrogen economy by ensuring safety, quality, infrastructure, environmental protection and economic development. Otherwise, there is a risk of a patchwork quilt (DIHK et al., 2023).

6. Discussion, Challenges and Outlook

For water management, there are a variety of technologies that open up the possibility of contributing to the coverage of hydrogen demand. These are not universally applicable. There is a need for an evaluation of the potential of the technology on the ground.

In addition to the production of hydrogen, electrolysis also offers the strong synergy that the oxygen produced can be used for biological processes in the wastewater treatment plant or for the ozone production of the 4th purification stage. However, green electrolysis hydrogen is characterized above all by the fact that the operation of these plants is intermittent. This also means that there is no continuous supply of pure oxygen. As a result, a high level of control for wastewater treatment must be expected. In the worst case, the biological processes in wastewater treatment can be negatively influenced. Electrolysis would therefore only be an option for WWTPs that generate green surplus electricity. This is the case for very few WWTPs in Germany.

The treatment of nitrogen-rich fractions, for example by plasmalysis, is more promising. The higher the nitrogen content of the material flow, as is the case with co-fermentation, for example, the more economically this process can be operated.

Plasmalysis of biogas offers the possibility of producing blue hydrogen, but reduces the degree of self-generation of WWTPs and therefore only makes sense for surplus plants.

In central sewage sludge utilization plants, there is great potential for the production of hydrogen by means of gasification, but the process needs to be further developed and implementation by 2029 or 2032 is rather critical.

The production of hydrogen from wastewater streams, which have a high organic content, is exciting and independent of WWTPs. Here, hydrogen can be produced by degrading the organic matter and at the same time pre-purification of the wastewater can be achieved. In this way, the energy demand of wastewater treatment can be reduced and there is a double contribution to achieving climate targets.

Challenges are, depending on the federal state and the responsible licensing authority, requirements and regulations. It is important to involve the public, associations, nature conservation organizations or the surrounding residents in the process at an early stage in order to minimize fears, resistance, misinformation or lawsuits. Of course, the process must be cost-effective and be able to compete with established, mostly fossil technologies. Industry partners or suitable (IPCEI) funding opportunities are also of great importance.

The transport and marketing of hydrogen must also be organized and ensured. Network operators or suppliers must work hand in hand with WWTPs, authorities and other key stakeholders and define solutions on an equal footing. Therefore, local production and consumption is very important.

In order for all this to succeed, funding opportunities must be expanded, awareness raised and any hurdles for the application process lowered.

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