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Biofuel supply chain planning and circular business model innovation at wastewater treatment plants: The case of biomethane production

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ABSTRACT

Advanced biofuels, such as biomethane, could contribute to environmental sustainability in increasingly interrelated sectors, such as energy and waste management. Accordingly, innovative biomethane production technologies are argued to be the enablers of circular and waste-to-energy concepts, for example, at wastewater treatment plants (WWTPs). Nevertheless, their integration into biofuel supply chain (BSC) research is overlooked from a circular business model innovation (BMI) perspective. This study aims to address this research gap by focusing on an innovative biomethane production approach (power-to-gas, P2G) and related circular business model innovation opportunities in the context of WWTPs. We carried out lab-scale research and a case study at a mid-sized European WWTP to establish an empirical basis for large-scale techno-economic calculations. Despite the explored technological opportunity to increase advanced biofuel supply and decrease carbon dioxide emissions at WWTPs, current market risk levels challenge the economic prospects of the system concept. These empirical results demonstrate the necessity of policy interventions in different combinations (e.g., investment support, favourable taxation, feed-in tariffs). This study is one of the first to combine technological and business modelling aspects to support BSC planning, and supplement optimization-focused BSC research with explorative techno-economic analyses based on empirical data.

1. Introduction

Biofuels, such as bioethanol, biodiesel, biogas, or biomethane, can be generated from waste and they can contribute to reducing greenhouse gas emissions (Singh et al., 2010). While first-generation biofuels from corn or sugar beets have got, however, concerns because of threatening food security, second-generation biofuels are based on non-food biomass, and are well-known in the agricultural and wastewater treatment sector. Even though third- and fourth-generation biofuels based on algal biomass and engineered microorganisms are also promising, they are not mature enough for commercial-scale deployment (Abbasi et al., 2021). Accordingly, as sustainability is becoming a key strategic planning area of supply chain management (Mohammed et al., 2023), sustainable supply chain planning should still focus on transforming cheaply accessible waste (biomass) to biofuels, i.e., a biofuel supply chain (BSC) which “consists of a network of producers of the raw material (biomass), biorefineries, storage facilities, blending stations and end users” (Awudu and Zhang, 2012, p. 1360).

BSC research was heavily focused on optimization in the last decade (Yue et al., 2014), involving different focus points and approaches (Albashabsheh and Stamm, 2021; Moretti et al., 2021; Ge et al., 2021; Kumar Jana et al., 2022). Yet, the produced volume of advanced biofuels, including biomethane is still not sufficient in Europe, and further innovations are needed to address the strategic aims of the REPowerEU plan, and to contribute this way to increasing resilience and sustainability in the energy sector (European Union, 2023). This induces explorative research on BSC, i.e., supplementing optimization research with empirical research about new technologies and systems which can be later also optimized. Based on Ranjbari et al. (2022), new BSC research directions should also support circular economy (CE) development, however, bridging topics of engineers and top management has been also increasingly emphasized (Govindan, 2023). Consequently,

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Abbreviations: BMC, business model canvas; BMI, business model innovation; BSC, biofuel supply chain; CCU, carbon capture & utilization; CE, circular economy; CHP, combined heat and power; LNG, liquefied natural gas; O&M, operations and maintenance; P2G, power-to-gas; PE, population equivalent; PEM, polymer electrolyte membrane; PV, photovoltaics; VVD, volume of gas/volume of liquid/day; WWTP, wastewater treatment plant.

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BSC studies should integrate CE perspectives based on (1) new technological and (2) new economic opportunities.

(1) Among new technological opportunities, those CE solutions can be relevant which are associated with reducing, reusing, and recycling certain input and output materials, and involving the reconfiguration of current systems (Kirchherr et al., 2017). For example, a waste-to-energy network development was highlighted with biogas production and upgrading, e.g., at wastewater treatment plants (WWTPs) (Hwangbo et al., 2020). Another promising option is power-to-gas (P2G) for biofuel production, an innovative energy conversion technology. P2G could be linked to photovoltaics (PV) to the uptake of (excess) renewable electricity (Yuan et al., 2023), reuse the carbon dioxide content of the biogas to produce biomethane (unlike traditional biogas upgrading) (Angelidaki et al., 2018), enable the sector coupling of electricity and gas grids, provide seasonal energy storage and additional flexibility for the energy system (Varone and Ferrari, 2015), or even connect to the transportation sector by biomethane-liquefication (bio-LNG) (Gianone and Imre, 2022). These P2G processes could also be integrated with the current technologies of WWTPs (Michailos et al., 2021). Following the definition of Awudu and Zhang (2012), P2G could be a contributing technology in the BSC by enabling the operation of a novel biorefinery system (Andersen et al., 2018), where biogas purification (traditional upgrading) is replaced by P2G for lower carbon emissions and enhanced circularity (i.e., using the carbon dioxide content of the biogas, instead of releasing).

(2) In terms of the economic context, CE development can serve as an approach for business model innovation (BMI) (i.e., creating biofuel from waste), which comes with the opportunity to increase environmental performance by reconfiguring the value proposition, creation, delivery, and capture (Bocken et al., 2014). This opportunity is highly relevant at WWTPs, as well, since WWTPs are fundamentally important for sustainable water management, and further technological and BMI opportunities also emerge to support the circular management of WWTPs (Shanmugam et al., 2022). Prior research presented that P2G could also mean a business opportunity for WWTP operators, i.e., becoming a part of a BSC, involving, e.g., heating, electricity generation, transportation, or industry (Breyer et al., 2015). Accordingly, business modelling seems to be an emerging perspective in this area, especially “considering that CO_2 is a waste, the implementation of CCU [Carbon Capture & utilization] requires research on business models and policy required to sustain its implementation” (Cordova et al., 2022, p. 9).

Despite these theoretical opportunities, the empirical research on P2G-based circular BMI at WWTPs is lacking. Several biofuel studies tend to focus on topics which are connected to only one part of business models, e.g., feed-in tariffs for biomethane (Hoo et al., 2020), the contribution of P2G to (green) hydrogen and methane supply chain development (Carrera and Azzaro-Pantel, 2021) and green business models which can drive biofuel system development (Nair and Paulose, 2014). Although there are integrative business model approaches in the literature, e.g., between solar and biogas energy (Agyenim et al., 2020), biofuel production and waste management (Donner et al., 2020), or biogas and P2G (Bedoić et al., 2021; Leonzio, 2017), to the best of our knowledge, researching an integrated biofuel system based on empirical assessment (e.g., with solar energy, WWTP, and P2G) is overlooked. Among the very few examples of P2G business model-related findings, which are not based on theoretical but real industrial research and development, only the scientific papers of the STORE&GO project could be mentioned (Böhm et al., 2020; Goree et al., 2019). Nevertheless, these are rather focused on costs than technological alignment and BMI.

Thus, the objective of the study is to answer *what opportunities P2G and circular BMI could generate for BSC planning at WWTPs*. Despite the significance of this topic one can hardly find any answers to this question in the literature. The main contribution of this study is that it combines a technological and business modelling approach with empirical results, so it can inform decision-makers and policymakers about the opportunities and challenges of the circular BMI at WWTPs for BSC planning.

The study is structured as follows. Materials and methods are described in Section 2, focusing on the empirical research of the focal technological system. Section 3 presents and discusses the results from multiple aspects, such as upscaling potential, economic viability, and macro-environmental potential in the research context (Europe). Finally, Section 4 summarizes the conclusions and limitations, and highlights the directions of future research.

2. Materials and methods

2.1. Overview of the methodological choices

Answering the research question was driven by the motivation to interconnect scientific and socio-environmental (practical) aspects, in line with the transdisciplinary principles in sustainability science (Lang et al., 2012). The relevance of this approach is that empirical data and studying concrete industrial conditions can contribute to solving complex sustainability problems (Belcher et al., 2019). In this case, it can result in in-depth and concrete findings about P2G-based BSC opportunities, but such advantages also indicate that the interpretation of the results is limited to the scope of the analysis, as detailed below.

During the empirical research, first, we conducted lab-scale experiments with an ex-situ biomethanation technology, which allowed us to assess the technical feasibility of raw biogas from the focal WWTP. These experiments also led to commercial-scale assumptions based on real industrial research and development results, instead of only prior literature data.

Second, the research focuses on a mid-sized WWTP as the potential site of the commercial-scale P2G deployment, as mid-sized WWTPs could be important for technological diffusion and decentralized biofuel production. The single-case study approach comes with the opportunity to gain an in-depth understanding of BMI potential and reveal real-world problems and solutions, as suggested by the transdisciplinary framework for sustainability-oriented change (Belcher et al., 2019).

Third, the study applies the business model canvas (BMC), following Osterwalder and Pigneur (2010). While the importance of BMC components (e.g., value propositions) has been already mentioned in the P2G research (Leonzio, 2017), the relevance of BMC comes also from its comprehensibility for WWTP managers during data collection and validation. Accordingly, qualitative BMC choices were primarily built on the context-specific infrastructural conditions and managerial insights of the focal WWTP. First, we aimed to explore the relevant opportunities for value creation, delivery, and capture to enhance generalizability, and after that, build the economic calculations on our experiments, prior literature data, and public data to increase reliability.

2.2. Technological concept and prototype structure

The P2G process is realized by the two-step Sabatier reaction, which is the following:

$$\text{electrolysis}: \quad 4\,H_2O + e^- \rightarrow 4H_2 + 2\,O_2 + heat \tag{1}$$

$$\text{methanation}: \quad 4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O + heat \tag{2}$$

According to the methanation Eq. (2), the stoichiometric ratio of hydrogen to carbon dioxide is 4:1, which in practice is higher and a more hydrogen-rich mixture is fed into the reactor (Martin et al., 2013).

For the experiments, a lab-scale prototype was used with the following equipment: polymer electrolyte membrane (PEM) electrolyser for hydrogen production (Proton Onsite G600), carbon dioxide/mixed gas flow controllers (Alicat MC-1SLPM-D), water jacketed, 2 l mixed reactor (Eppendorf), including the pure archaea culture (Methanothermobacter thermautotrophicus), control unit (Eppendorf BioFlo 120), and industrial gas analyser (Awite Awiflex Cool +), which can analyse CH_4, CO_2, CO, O_2, H_2S, and H_2. Fig. 1 shows the structure of the prototype.

Based on the production of the focal WWTP, the following gas sample was used (% $_{m/m}$): 61 % CH_4; 38,9 % CO_2, 0,1 O_2 %. The small amount of oxygen component was important in the gas sample because, theoretically, the archaea culture needs anaerobic environment for the bioprocess, but experiences of the WWTP have shown that biogas mixtures can contain oxygen in minimal concentrations. In the prototype, flow controllers were used to adjust the mass flow and concentration of the H_2:CO_2 or experimental gas sample. The control unit regulates the dosages of the nutrients, the speed of the stirrer and the reactor temperature required for the biocatalyst to work properly, while the gas analyser measures the concentration of methane, hydrogen, and carbon dioxide in the product gas at pre-programmed intervals.

To explore the technical feasibility of the raw biogas when contextual factors change and find practical guidance for a future large-scale operation, different operational methods were followed during the tests, detailed in the Appendix.

The carbon dioxide conversion value was calculated from the measurement results using this formula:

$$conv_{CO_2} = \frac{C_{CH_4}}{\left(C_{CH_4} + C_{CO_2}\right)} \tag{3}$$

where C_{CH_4} is the percentage value of the measured methane concentration, and C_{CO_2} is the percentage value of the measured methane carbon dioxide concentration. In addition to the carbon dioxide conversion, the specific daily gas production of the reactor VVD (Volume of Gas/Volume of Liquid/Day) was also determined. The VVD value shows the volume of gas produced by 1 L of biocatalyst in a day:

$$VVD = conv_{CO_2} \bullet \varphi \bullet \dot{V}_{CO_2} \bullet \frac{60 \bullet 24}{2} \tag{4}$$

In the formula, $\dot{V}_{CO_2}$ refers to the volumetric flow rate of carbon dioxide in l/min. The value 2 in the denominator represents the average volume of 2 L of biocatalyst in the reactor. φ is the carbon dioxide content of the gas to be tested, φ = 1 for pure carbon dioxide and φ = 0,389 for mixed gas.

2.3. Industrial case study selection

The research focused on a potential case of a mid-sized WWTP which could be promising to realize the technological concept. The sampling considered that large WWTPs are above the capacity of 500.000 population equivalent (PE) (Mininni et al., 2004), 20.000 PE was also considered as "mid-sized" (Dürrenmatt and Gujer, 2011), and existing biogas production, i.e., urban WWTP of "big cities" above or around 150.000 PE (EEA, 2021) could be preferred. The case study preparation involved qualitative and quantitative technical data collection from expert-level employees of the WWTP through on-site discussions. Moreover, after the techno-economic calculations, we conducted additional interviews (2 x 2 h) with the top management to explore their thoughts about existing and potential future business model characteristics. The description of the WWTP is presented in Table 1.

Table 1
Details of the focal WWTP.

Location	- Central Europe
Activities	- Water utility services - Drinking water supply, Sewage disposal and treatment - Municipal liquid waste disposal, Operation of a testing laboratory - Biogas production at the wastewater treatment plant
Infrastructure and operation	- Approx. 100.000 PE - Approx. one month of downtime in January-February - A 250 kWth boiler is used for auxiliary heating of the plant - Drying (evaporation increases dry matter content by about 50 %)
Current biogas utilization	- Production of electricity for own use - 250 kWel CHP - Covers 50–60 % of own energy needs
Availability of P2G inputs	- Electricity and demineralised water purified from wastewater and drinking water can be used to ensure the continuous operation of the electrolyser - Biogas production: average 100 Nm^3/h - Availability of free area on site

Fig. 1. P2G prototype structure for the empirical research.

2.4. *Conditions and formulas for the techno-economic analysis of a large-scale plant*

From a technical perspective, certain conditions are fundamental for the focal technology and other conditions are site- and input-specific (Table 2), while annual production data has been generated based on the specific system configuration (Table 3). The system configuration is focusing on biomethane production (because of the existing biogas production, and solely green hydrogen production would not require WWTP-based deployment).

To explore the economic potential of the reconfigured business model of the WWTP, two scenarios have been developed. Table 4 presents related economic assumptions.

3. Results and discussion

In the following, results of the technological analysis will be presented, based on which, business modelling was built.

3.1. *Technological analysis*

To validate the case study selection from a technological perspective, first, we conducted experiments based on the raw biogas production of the focal WWTP, so the following gas sample was used (% $_{m/m}$): 61 % CH_4; 38,9 % CO_2, 0,1 O_2 %. The small amount of oxygen component was important in the gas sample because, theoretically, the archaea culture needs an anaerobic environment for the bioprocess, but experiences of the WWTP have shown that biogas mixtures can contain oxygen in minimal concentrations.

Table 2
Main processes, data, and formulas of the focal technology.

Processes	Conditions	Data/Formula
Electrolysis	Electrolyser capacity	It can be determined based on the availability of CO_2 (the volume and composition of the biogas)
	Water consumption	0,27 m^3/MWh
	Electricity consumption	4,7 kWh/Nm^3 H_2
	H_2 output/input for methanation	= Electrolyser capacity/Electricity consumption
Methanation	Needed CO_2 input	= H_2 input (Nm^3)/4 – 4,2 (in line with the methanation equation)
	CH_4 production with CO_2 conversion	= CO_2 input (Nm^3) • CO_2 conversion efficiency (%) (usually > 95 %)
	CH_4 content in the product gas	= CH_4 production with CO_2 conversion (Nm^3) (usually 96–98 % of the CO_2) + Organic CH_4 (Nm^3) (inherent content of biogas)
Purification, if necessary	H_2 content in the product gas	It depends on the input factors and system control – it is a focal issue of the empirical research
	CO_2 content in the product gas	It depends on the CO_2 conversion efficiency (usually > 95 %) – it is a focal issue of the empirical research
Byproduct utilization, if possible	O_2	H_2 input (Nm^3)/2 (in line with the electrolysis equation)
	Waste-heat	0,12–0,13*Electrolyser capacity (kWh) (based on manufacturer data and experiences)

Table 3
System configuration and formulas for calculating the annual data.

System	Description
System components	Solar panels, Electrolyser, Bioreactor, Hydrogen storage, Biogas storage, Gas grid injection
Annual operation time	4.000 h (local renewable electricity + grid sourcing), from which 75 % of annual operations is with electricity from the grid, as grid balancing
Production and commercial focus	Biomethane with H_2 blend (Full volume of produced H_2 is used for biomethanation, H_2 is only produced when local renewable electricity or surplus electricity grid, and biogas is available)
Calculation of annual green gas production data	- H_2 production: H_2 output (Nm^3) • Annual operation time (h) - CH_4 production: CH_4 content in the product gas (Nm^3) • Annual operation time (h) - Remained H_2 production: H_2 content in the product gas (Nm^3) • Annual operation time (h)
Calculation of annual energy consumption data	- Annual electricity consumption: 4,7 kWh • Annual H_2 production (Nm^3) - Annual water consumption: 0,27 m^3 • Annual electricity consumption (MWh)

Table 4
Economic assumptions.

	Optimist	Pessimist	Based on:
Electricity price	40 EUR/MW	130 EUR/MW	Optimist: following 2015 prices (Breyer et al., 2015), but based on discounts for grid balancing (discounts replace grid services fees in this model) Pessimist: 2021 average (Statista, 2022)
Water	2,5 EUR/m^3		Focal WWTP
O&M	3 % of CAPEX (equipment)		On average (van Leeuwen and Zauner, 2018)
Biomethane price/feed-in tariff	100 EUR/MW	50 EUR/MW	75 EUR was calculated by (Breyer et al., 2015)
Hydrogen price	6 EUR/kg	3 EUR/kg	European data (The Hydrogen Valley Platform, 2022)
Saved costs from waste heat utilization	50 EUR/MW		(Zauner et al., 2019)

To find guidance for the techno-economic analyses of a commercial-scale plant, different operational methods were followed during the tests (see the Appendix). The experiments validated that the biocatalyst used is suitable for a high degree of biomethanation of carbon dioxide content in the raw biogas. The maximum methane concentration in the product gas was 93.8 % and the calculated value for CO_2 conversion was 100 % (which means that no CO_2 remains in the product gas, as CO_2 is converted into CH_4 and a minimal amount of CO_2 is absorbed by the microorganisms) – both measured using a 4.5:1 H_2:CO_2 mixing ratio and elevated temperatures (64 °C and 68 °C). The average result with the preferred setting is the following: 86,33 % CH_4; 2,46 % CO_2; 10,46 % H_2.

The results have shown that biogas can be introduced into the reactor without the need to capture carbon dioxide. This means that methanation can take place in the presence of low oxygen content, even though microorganisms can catalyse the reaction in a basically anaerobic environment. The CO_2 conversion is slightly impaired by the oxygen content of the raw biogas, and CO_2 in the product gas remains around 1–2 %, the conversion rate can be increased in several ways, e.g., by changing the H_2:CO_2 ratio. As limitations for hydrogen injection into the natural gas grid change, e.g., in Austria, up to 10 % hydrogen is allowed since June 2021 (CMS Legal, 2021), at the end of this decade, this limit could be between 15–20 % in the EU gas systems (EU Science Hub, 2022), which will be proper for this technology.

Fig. 2 presents the results of the lab experiments. The dotted vertical line in the Figure shows the boundaries of each scenario. The results of the reference measurement are shown on a yellow background and the results of the tests for the experimental gas mixture are shown in red. During the measurement, blockages were observed in some sections of the piping and the measurement series had to be interrupted and, after

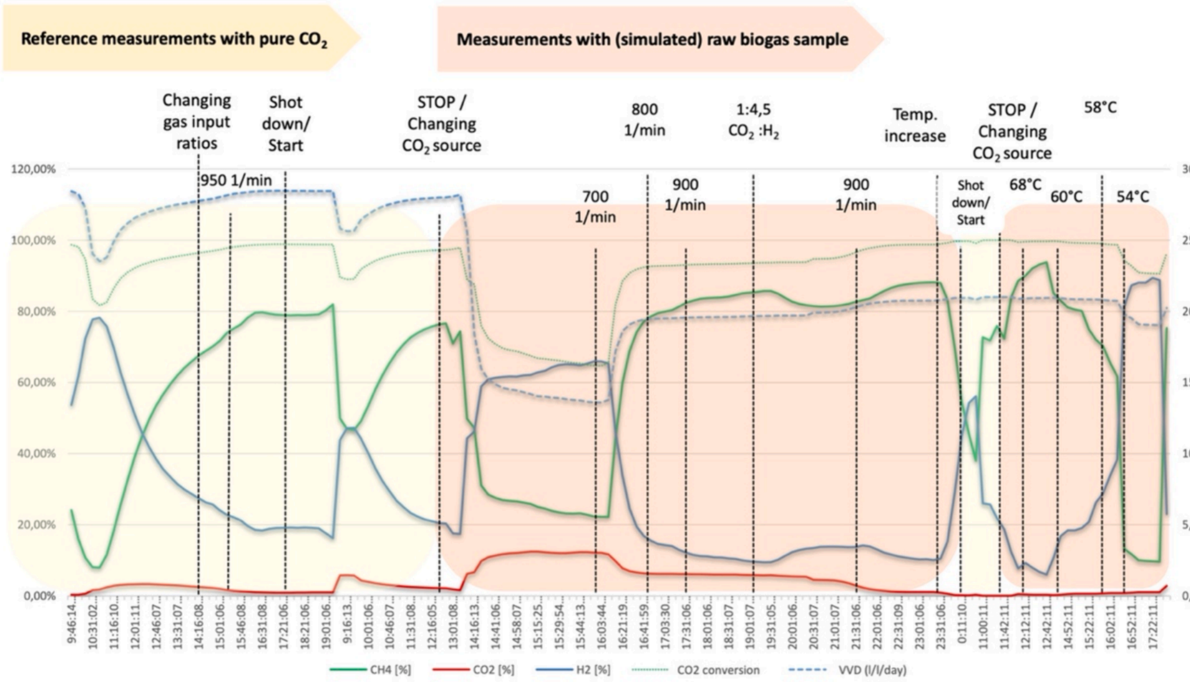

Fig. 2. Results of the experiments.

cleaning the instruments, regeneration was performed using pure carbon dioxide, which explains the yellow area on the right side of Fig. 2.

The main results of the experiments are summarized in Table 5, from the perspective of upscaling.

The size of P2G plants is defined in international practice based on the nominal capacity of the electrolyser. The electrolyser capacity is determined by the need for hydrogen production, and the need for hydrogen production is determined by the available carbon dioxide source (39 Nm^3/h) and the H_2:CO_2 ratio. For the latter, the theoretical ratio of 4:1 is modified in practice to at least 4.2:1 (the excess is justified by the inferior water solubility of hydrogen compared to carbon dioxide), but the results of experiments with mixed gas predict the best carbon dioxide conversion to be between 4.25 and 4.5. Consequently, a H_2:CO_2 ratio of 4.3:1 was used in the calculations. With a source of about 40 Nm^3 CO_2 per hour in the biogas and the above experimental results, the theoretical nominal electrical capacity of the deployable P2G plant is 788 kW_{el}. The details of the theoretical plant are shown in Table 6. Based on the calculations, 98 Nm^3/h of biomethane could be produced from 100 Nm^3/h of biogas. It means that CO_2 conversion efficiency of the technology is demonstrably high, which enables to increase the initial ca. 60 % CH_4 content (biogas) over 95 % CH_4 content (biomethane). Due to the high methane content of the product gas, it can meet the quality standards for natural gas mixtures of high calorific value, group “H”, which are the technical conditions for its injection into the gas grid.

Table 5
Main results of the technical experiments for upscaling.

Actions	Changing stirring speed/ normal operation	Modifying input gas rations, changing stirring speed	Changing operating temperature	Average results
Main parameters for the best CO_2 conversion	900 min^{-1} CO_2:H_2 – 1:4,25	900 min^{-1} CO_2:H_2 – 1:4,5	68 °C 700 min^{-1} CO_2:H_2 – 1:4,5	Preferred setting: 68 °C 900 min^{-1} CO_2:H_2 – 1:4,3
Average CH_4 values	84,7%	86,9%	87,4%	**86,33 %**
Average CO_2 values	5,9%	1,2%	0,3%	**2,46 %**
Average H_2 values	10,2%	11,3%	9,9%	**10,46 %**

Table 6
Main input and output data for the theoretically largest P2G plant that could be deployed at the focal WWTP.

	Value	Unit
Electrolyser	788	kW_{el}
Electricity consumption	4,7	kWh/Nm^3 H_2
Average H_2 input	167,6	Nm^3/h
Average CO_2 input	41,9	Nm^3/h
Average CH_4 input	61	Nm^3/h
CH_4 production with CO_2 conversion	37	Nm^3/h
CH_4 content in the product gas	98	Nm^3/h
H_2 content in the product gas	11,3	Nm^3/h
CO_2 content in the product gas	2,6	Nm^3/h
O_2 production	83,8	Nm^3/h
Waste heat production	268	kWh/h

3.2. *Business modelling*

3.2.1. *BMI opportunities*

Based on the case of the focal WWTP, the BMI could mean a multi-energy system which integrates internal and external flows of electricity, biogas, hydrogen and biomethane (Fig. 3). The concept also shows the key revenue streams and customer segments of a transformed WWTP.

The elements of a BMC could be outlined which orients further economic analyses. Table 7 presents the elements of the reconfigured business model based on prior P2G literature (Breyer et al., 2015), and differentiates three energy sub-systems and certain elements within the sub-systems according to the different value propositions. The Table shows the BMI basically means an extension in the operations, which means additional complexity but also many new revenue streams. Moreover, wastewater treatment, local renewable electricity and biogas

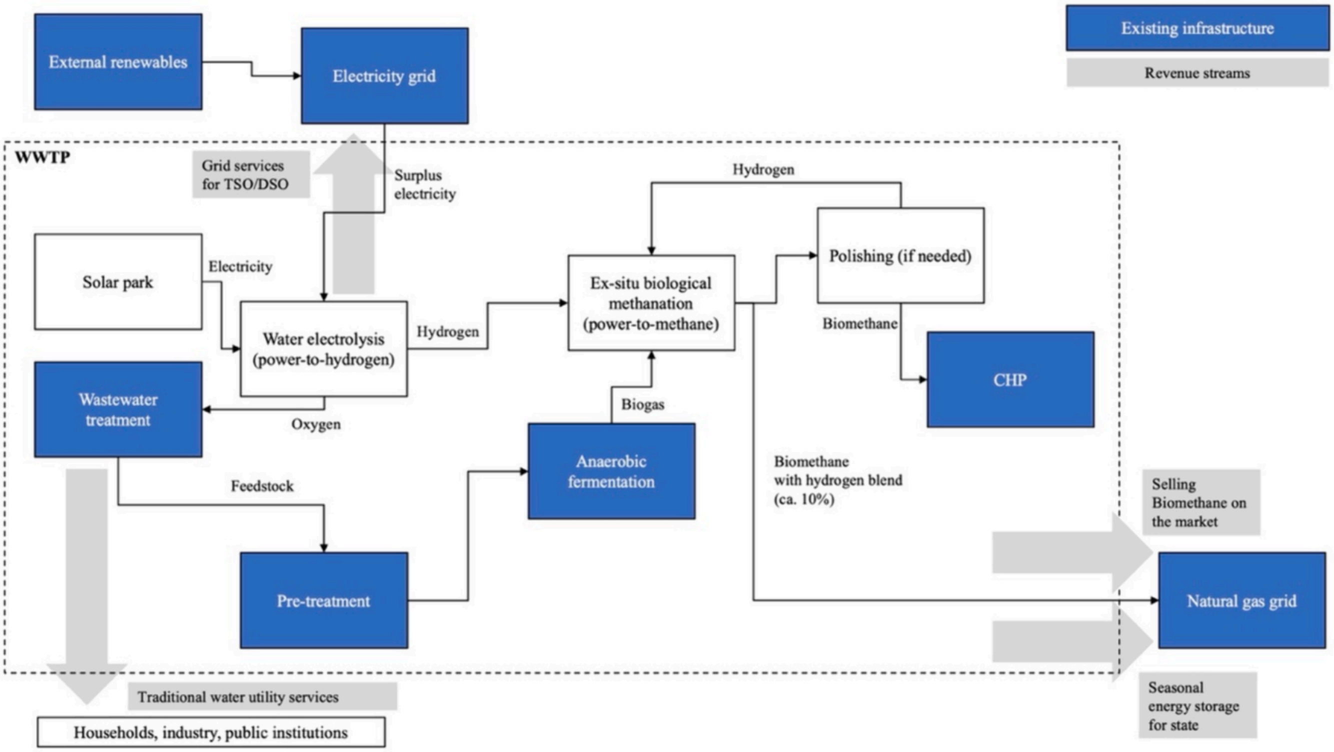

Fig. 3. A possible biomethane-focused business model at a WWTP.

Table 7
Circular BMI opportunities for increased biofuel production at WWTPs.

Dimension	BMC blocks	Wastewater	Green Hydrogen	Biomethane
Market	Value proposition	Removing contaminants, water protection, proper water infrastructure	(A) Renewable fuel (secondary option) (B) Grid balancing	(A) Biofuel (primary option) (B) Seasonal energy storage
	Customer segments	Households, companies, and public institutions	(A) Industrial hydrogen consumers, who are environmentally responsible (B) Transmission/Distribution System Operators	(A) Industrial natural gas consumers, who are environmentally responsible (B) State/State-owned natural gas storage company
	Distribution channels	Sewage system	(A) Hydrogen truck or pipeline/Natural gas grid in case of hydrogen blending (B) Electricity grid	(A, B) Natural gas grid
	Customer relationships	Traditional/online customer service	(A) Providing guarantees of origin for hydrogen (B) Personal sales and techno-economic reporting after sales	(A) Providing guarantees of origin for biomethane (B) Personal sales and techno-economic reporting after sales
	Revenue streams	Automated monthly billing, based on customer type	(A) Selling hydrogen on the market (B) Fees from grid services/discounted electricity sourcing in peak times	(A) Selling biomethane on the market (B) Feed-in tariff or cost-savings from local use
Configuration	Key activities	Sewage disposal and treatment, safety and health control, O&M, using oxygen from electrolysis	Local electricity production: Forecast and monitoring Electrolysis, O&M	Local biogas production: Feedstock pre-treatment, fermentation, biomass handling; Wastewater treatment and green hydrogen production; Bioprocess monitoring and control; O&M, Combined Heat & Power system for local use
	Key resources	Physical infrastructure, Operational know-how	Renewable electricity: Solar panels, inverter, meters, monitoring system, battery energy storage (if needed); Cheap electricity from grid, Electrolysers, Hydrogen storage	Biogas, Biomass, Biogas plant, Biogas storage; Bioreactor and control system, Technological know-how Wastewater and hydrogen infrastructure
	Key partners	Municipalities	Electricity utilities; Hydrogen transporters/infrastructure developers; State administration/Government	Natural gas utilities; State administration/Government; Technological suppliers
	Cost structure	Wages, Biological and chemical materials, O&M resources	(Surplus) electricity sourcing from the grid, water, O&M (e.g., stack replacement)	O&M (e.g., nutrients for biocatalyst), handling of wastewater from the bioprocess

production would serve as input phases for electrolysis and biomethanation. Nevertheless, state administration or government seems to be a key partner regarding the financial aspects of new activities, e.g., feed-in tariff for biomethane, fees for grid balancing or discounted electricity sourcing costs.

3.2.2. *Techno-economic potential of the circular BMI*

Based on the business modelling and the empirical results, there are several uncertain elements in the business model, regarding the potential market price of electricity, the fees for grid balancing, the market price of biomethane and hydrogen, or the feed-in tariff for biomethane, for which there is a scheme in certain European countries, e.g., in Italy (61 EUR/MWh) (Baena-Moreno et al., 2020). The existing infrastructure and biogas production, and the local renewable electricity generation with solar panels, however, could make the business model more attractive, especially if electricity sourcing costs from the grid could be discounted or compensated by fees for grid services, and the market prices or the feed-in tariffs will be high for biomethane.

Based on the results of the technological assessment, the system size could be 750 kW_{el}. Its estimated CAPEX could be ca. 5.500.000 EUR, based on averaging prior calculations, i.e., 2,41 mEUR for 1 MW_{el} by van Leeuwen and Zauner (2018) and ca. 7–8 mEUR for the 1 MW_{el} Biocat Project (Biocat Project, 2017), and concerning additional PV capacities (Statista, 2020).

Regarding the annual green gas production data, this 750 kW_{el} system with 4.000 h operation per year would enable to produce ca. 60 tH_2 by the electrolysis process step. By combining this volume of H_2 with the biogas (containing CO_2), it could mean ca. 8.200 MWh CH_4. Furthermore, following the results of lab-scale experiments, the product gas would also contain a significant amount of H_2, ca. 4 tons per year. The combination of CH_4 and H_2 in this proportion would be still promising for seasonal energy storage by the natural gas grid, as mentioned above.

This configuration would mean that most important revenue stream in the business model would be sales of or the feed-in tariffs for the biomethane, while hydrogen sales and costs savings by waste-heat utilization would be peripheric. In case of costs factors, water sourcing seems to be marginal. While continuous costs of operation and maintenance are considerable in the business model, supplementary grid-electricity sourcing is a significant expenditure even in this PV-based (limited time of annual operation) and optimist scenario, while inhibits promising financial prospects in the pessimist scenario.

Fig. 4 shows the results of the business model analysis. Even in case of easily imaginable scenarios, there can be huge differences between the economic outcomes, e.g., the return on the investment could be between 7 and 47 years. Consequently, this risk level could be larger than the risk appetite of private investors, thus, reconfiguring mid-sized WWTPs based on this system must be financially supported by the state administration.

3.3. *Comparison of results*

There are only a few similar studies which have similar approach to this research. Leonzio (2017) designed and analysed techno-economically a 1000 kW_{el} P2G plant which uses 100 % renewable electricity from an eolic park, with 7.920 operation hours/year. The author concluded that the payback period could be four years, which significantly differs from our results, even in the optimistic scenario. The main reason for this difference is that solar energy is not available

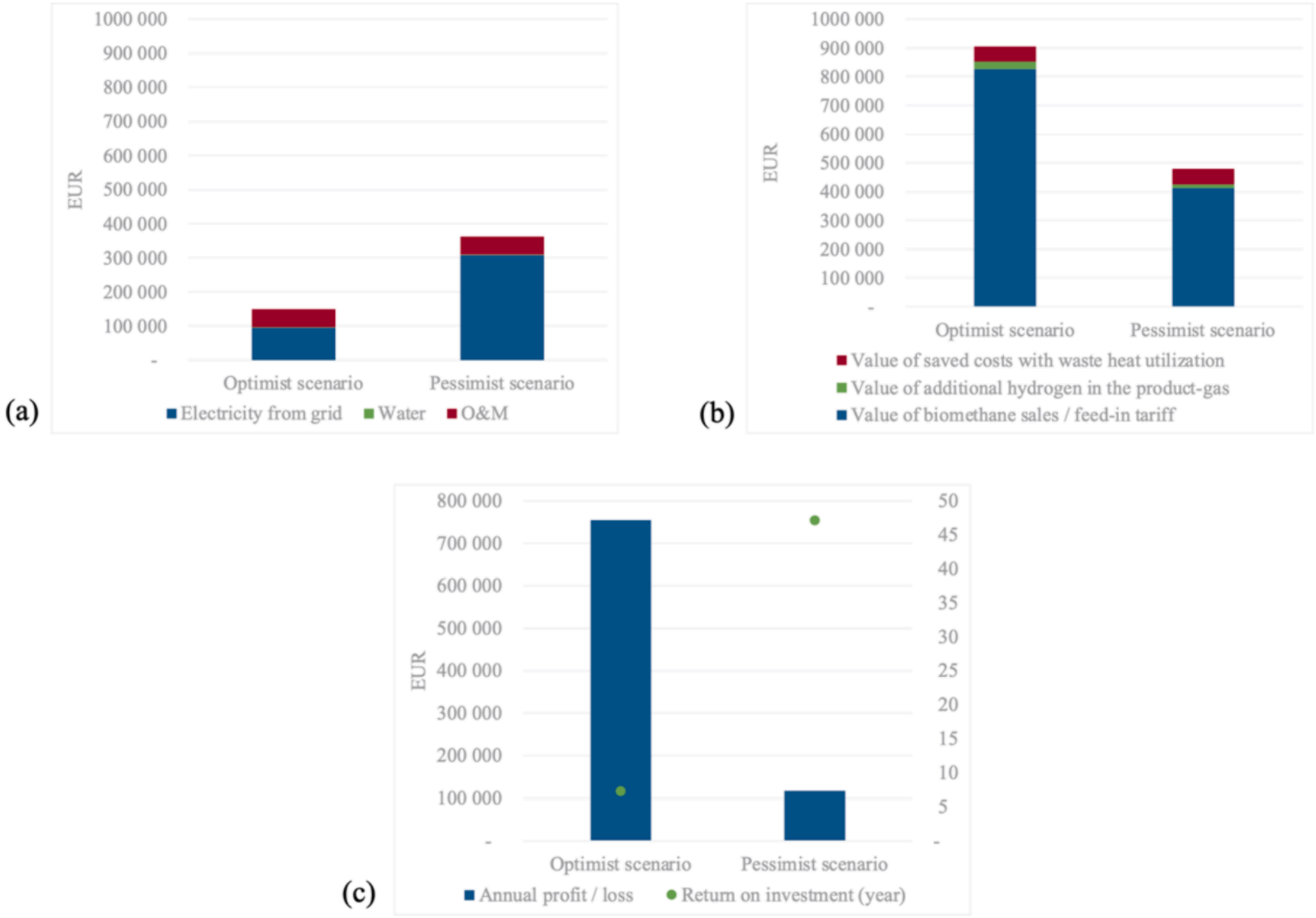

Fig. 4. Results of the business model analysis. (a) Operating expenses/year, (b) Operating revenues/year, (c) Profits/year and return on investment.

continuously in the focal region, thus, the plant must be operated for fewer hours in total, or more hours with grid electricity, the high market price of which decreases the attractivity of the business model. The consequent statement, however, is in line with the identified success factors and risks (Leonzio, 2017), i.e., regulatory environment and economic incentives could be crucial to obtain funding to plant construction.

More recently, Bedoić et al. (2021) assessed the integration of P2G into a food waste-based biogas plant to produce biomethane, similarly with 1.000 kW_{el} installed capacity and wind and solar installation. They argue that "direct methanation of biogas has proven to be an economically attractive option for the integration of power-to-gas concept driven by the PV and wind plant" (Bedoić et al., 2021, p. 21). According to their study, however, only 60 % of the total electricity demand could be covered by variable electricity, unlike in Leonzio's study. The authors found that the feedstock gate fee was a significant factor in cost-efficient biomethane production, moreover, changes in the natural gas market and reduction and investment costs of PV and wind plants would make biomethane economically competitive with natural gas. Although the price of the natural gas has been extremely volatile last years (Trading Economics, 2023) which might also justify higher market prices for biomethane, our results suggest that the focal P2G business model still requires significant support from state administration. It can be either regarding the input side (i.e., fees for grid services) and/or the output side (i.e., feed-in tariffs for biomethane) to ensure the reliability of long-term financial planning and exploit the environmental potential of the P2G at WWTPs.

3.4. *Discussion on European outlook*

P2G-based BMI at WWTPs could have practical significance in Europe from multiple aspects. First, P2G and biomethane seem to be increasingly important for meeting biofuel supply needs, from the European policy perspective. This is because, the European Union aims to become climate neutral by 2050, with a particular focus on developing a hydrogen economy (European Commission, 2020) and decarbonisation (European Commission, 2019). Nevertheless, prior research showed that energy storage is needed for PV power plants for a sustainable and decarbonized sector (Zsiborács et al., 2022), which suggest the applicability of P2G technologies, as well. Accordingly, the REPowerEU Plan aims to implement more solar and wind energy projects combined with green hydrogen deployment to save around 50 bcm of gas imports, and also produce 35 bcm of biomethane per year by 2030 (European Commission, 2022a,b). Second, in line with these goals, one of the main trends of the European biogas sector in the next decades is to increase biomethane production (Brémond et al., 2021), for which P2G is a more environmental-friendly solution than traditional biogas upgrading. Reducing production costs, however, is also a key challenge (Brémond et al., 2021).

Even though there are more than 17.000 biogas plants in Europe, which could be useful for biomethane production by P2G technology, many of them are built on agricultural feedstock, while biogas from landfill gas also represents a significant share, and there are only ca. 2.400 biogas plants (Scarlat et al., 2018). As "most of the biogas plants are in the size range 100–500 kW (electrical output)" (Scarlat et al., 2018, p. 462), our case study at the focal WWTP could be also considered "average" (250 kW). Based on the explored ca. 750 kW_{el} P2G deployment potential at this average WWTP, it could allow 1.800 MW_{el} P2G deployment at European WWTPs, with the potential to produce 940.800.000 Nm^3 biomethane/year, based on only 4.000-hour operation/year. As biogas production from sewage sludge represents a small share in the European biogas production, of course, this volume would mean currently only a few percent of the goal to save gas imports with biomethane production. Nevertheless, it indicates that not only increasing the volume of biomethanation but increasing the volume of biogas production capacities at European WWTPs might be necessary to meet the ambitions of energy sovereignty, partly by advanced biofuels. Using grid-electricity, from other low-carbon sources could also accelerate biomethane production.

4. Conclusions and limitations

This study aimed to explore opportunities of circular BMI and P2G in BSC planning, by synthesising concrete technological advancements and economic analysis of a mid-sized WWTP in Europe. While these results validate the technological viability, the financial prospects of the circular BMI, however, are uncertain. It means that increased biofuel supply by P2G at mid-sized WWTPs might be feasible technologically, and might also be beneficial for environmental sustainability but current market risk levels challenge its economic sustainability. Consequently, engagement in such renewable energy projects needs high risk-appetite from strategic investors which could slow down the diffusion of similar innovative technologies at mid-sized WWTPs until state administration provides additional certainty for financial planning by a supportive regulatory environment. Results reinforced prior considerations that even though PV-based P2G deployment would be feasible for BSC planning, the local renewable capacities might not be sufficient to cover the economic need for cheap electricity input and quick payback. Thus, sourcing grid electricity and grid-balancing, especially from other low-carbon sources must be considered by operators and incited by the state administration, preferably to reach 40 EUR/MWh electricity cost on average. On the other side, 100 EUR/MWh feed-in tariff for biomethane could be attractive enough for potential investors.

The theoretical contribution of the study is threefold. From a supply chain management perspective, this research demonstrated that explorative strategies towards supply chain optimization could include new technologies, and circular BMI could enable their integration. From an economic perspective, the study presents a promising direction for circular BMI of WWTPs based on a validated technological case but also identifies financial uncertainties and risk levels of the investment. From a policy perspective, the study highlights that innovative technologies for BSC might be ready for up-scaling, however, the turbulent economic context could necessitate regulatory changes to engage risk-averse market actors in projects which could generate environmental and economic benefits parallelly.

Given the applied transdisciplinary approach, limitations of the methodological choices must be also mentioned. In general, because of the infrastructural nature of P2G and the empirical case study method, context-specificity was necessary also regarding the economic modelling and BMI, limiting the validity of the conclusions to cases with similar conditions. For example, it means that other technological configurations (e.g., with different reactor structures) might lead to slightly diverging technological performance, which could impact economic performance as well. Furthermore, smaller or larger WWTPs could have different financial results based on the (lack of) economies of scale. Finally, BMC by nature is a qualitative tool, i.e., its application can lead to subjective choices. This case study concentrated on the decentralized PV-based P2G integration due to the context-specific conditions, but available or missing infrastructure might induce other BMI choices (e.g., an opportunity to exploit regional surplus wind energy or focusing on bio-LNG production).

As only one empirical case was analysed, further research might explore more sites based on existing data and calculate the techno-economic potential at the level of certain countries. Moreover, optimization of production and commercialization of different end-products in a multi-energy hub system (hydrogen, biomethane, bio-LNG) could be in the scope of future studies.

CRediT authorship contribution statement

Zoltán Csedő: Writing – review & editing, Supervision, Formal analysis, Conceptualization. **József Magyari:** Writing – review &

editing, Validation, Project administration, Investigation. **Máté Zavarkó:** Writing – original draft, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared the data in the manuscript (Appendix) and the Supplementary material.

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Appendix A

Description of the operational modes during the lab-scale research.

(1) Start of the tests: the tank containing 4,5-grade carbon dioxide, previously used for regeneration activities, was decommissioned, and the contents of the gas bag were emptied. For previous reference tests, a H_2:CO_2 ratio of 4,5:1 was previously set (carbon dioxide flow rate: 40 ml/min, hydrogen flow rate: 180 ml/min). The lower hydrogen solubility in water explains the higher hydrogen enrichment than the theoretical 1:4 ratio. Since this setting is applicable to pure carbon dioxide, it had to be converted for the mixed gas case, since its composition was 61 % methane and 38.9 % carbon dioxide.

(2) Warm start: the warm start simulates a situation where the right amount of feedstock is temporarily unavailable, but the shortage can be overcome at any time (e.g., there is not enough renewable electricity in the grid to power the electrolysis). The warm start was also used to see whether methane conversion would occur if the mixing was omitted, and if so, to what extent mixing would contribute to carbon conversion. The warm start was carried out both without stirring and, later, at 700 min^{-1} rpm. Before the warm start, the reactor temperature was maintained at 62 °C.

(3) Normal operation: Operation with a given mixture composition and the corresponding feed pump settings and a mixing shaft speed of 700 min^{-1} was tested.

(4) Changing the stirring speed: increasing the speed improves the gas–liquid transition, so a higher carbon dioxide conversion value is likely. The mixer speed was increased from 700 min^{-1} to 800 min^{-1} and then to 900 min^{-1}. The gas flow and temperature values were not changed.

(5) Changing the H_2:CO_2 ratio: prior experiences confirm that a hydrogen-rich mixing ratio of at least 1:4.2 should be used compared to the theoretical 1:4 CO_2:H_2 input gas ratio. One common cause of residual carbon dioxide in the product gas is a lack of hydrogen, which is a consequence of poorer hydrogen solubility in water and can be remedied by increasing the hydrogen mass flow rate of the input gases, i.e., hydrogen enrichment. The settings were changed from an initial (1:4,25) mixing ratio of the input gases to a more hydrogen-enriched ratio of 1:4,5.

(6) Changing the temperature: the effect of temperature increase and decrease on the biocatalyst is investigated. Although the gas–liquid phase transition improves with temperature decrease, the biocatalyst activity is lower at low temperatures and the metabolism of the microbes is impaired. First, we analysed the changes caused by increasing the temperature: the temperature was first increased to 64 °C, then to 68 °C, and the biocatalyst temperature stabilised within 10 min. We then investigated the effect of temperature reduction – reactor temperature was first reduced to 60 °C, then to 58 °C and 54 °C. When testing the effect of temperature reduction, sufficient time was allowed for the biocatalyst to cool down and measurements were only started afterwards.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clscn.2024.100158.

References

Abbasi, M., Pishvaee, M.S., Mohseni, S., 2021. Third-generation biofuel supply chain: a comprehensive review and future research directions. J. Clean. Prod. 323, 129100 https://doi.org/10.1016/j.jclepro.2021.129100.

Agyenim, F.B., et al., 2020. Powering communities using hybrid solar–biogas in Ghana, a feasibility study. Environ. Technol. Innov. 19, 100837 https://doi.org/10.1016/j.eti.2020.100837.

Albashabsheh, N.T., Stamm, J.L.H., 2021. Optimization of lignocellulosic biomass-to-biofuel supply chains with densification: literature review. Biomass Bioenergy 144, 105888. https://doi.org/10.1016/j.biombioe.2020.105888.

Andersen, L., et al., 2018. Biogas plants as key units of biorefinery concepts: options and their assessment. J. Biotechnol. 283, 130–139. https://doi.org/10.1016/j.jbiotec.2018.07.041.

Angelidaki, I., et al., 2018. Biogas upgrading and utilization: current status and perspectives. Biotechnol. Adv. 36 (2), 452–466. https://doi.org/10.1016/j.biotechadv.2018.01.011.

Awudu, I., Zhang, J., 2012. Uncertainties and sustainability concepts in biofuel supply chain management: a review. Renew. Sustain. Energy Rev. 16 (2), 1359–1368. https://doi.org/10.1016/j.rser.2011.10.016.

Baena-Moreno, M.F., Sebastia-Saez, D., Wang, Q., Reina, T.R., 2020. Is the production of biofuels and bio-chemicals always profitable? Co-production of biomethane and urea from biogas as case study. Energ. Conver. Manage. 220, 113058 https://doi.org/10.1016/j.enconman.2020.113058.

Bedoić, R., et al., 2021. Synergy between feedstock gate fee and power-to-gas: an energy and economic analysis of renewable methane production in a biogas plant. Renew. Energy 173, 12–23. https://doi.org/10.1016/j.renene.2021.03.124.

Belcher, B.M., Claus, R., Davel, R., Ramirez, L.F., 2019. Linking transdisciplinary research characteristics and quality to effectiveness: a comparative analysis of five research-for-development projects. Environ. Sci. Policy 101, 192–203. https://doi.org/10.1016/j.envsci.2019.08.013.

Biocat Project, 2017. Final Report. [Online] https://energiforskning.dk/sites/energiforskning.dk/files/slutrapporter/12164_final_report_p2g_biocat.pdf [28 12 2022].

Bocken, N.M.P., Short, S.W., Rana, P., Evans, S., 2014. A literature and practice review to develop sustainable business model archetypes. J. Clean. Prod. 65, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039.

Böhm, H., Zauner, A., Rosenfeld, D.C., Tichler, R., 2020. Projecting cost development for future large-scale power-to-gas implementations by scaling effects. Appl. Energy 264, 114780. https://doi.org/10.1016/j.apenergy.2020.114780.

Brémond, U., et al., 2021. A vision of European biogas sector development towards 2030: Trends and challenges. J. Clean. Prod. 287, 125065 https://doi.org/10.1016/j.jclepro.2020.125065.

Breyer, C., Tsupari, E., Tikka, V., Vainikka, P., 2015. Power-to-gas as an emerging profitable business through creating an integrated value chain. Energy Proc. 73, 182–189. https://doi.org/10.1016/j.egypro.2015.07.668.

Carrera, E., Azzaro-Pantel, C., 2021. A methodological design framework for hydrogen and methane supply chain with special focus on Power-to-Gas systems: application to Occitanie region, France. Comput. Chem. Eng. 153, 107386 https://doi.org/10.1016/j.compchemeng.2021.107386.

CMS Legal, 2021. Hydrogen Law, Regulations & Strategy in Austria. [Online] https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/austria [28 12 2022].

Cordova, S.S., Gustafsson, M., Eklund, M., Svensson, N., 2022. Potential for the valorization of carbon dioxide from biogas production in Sweden. J. Clean. Prod. 370, 133498 https://doi.org/10.1016/j.jclepro.2022.133498.

Donner, M., Gohier, R., de Vries, H., 2020. A new circular business model typology for creating value from agro-waste. Sci. Total Environ. 716, 137065 https://doi.org/10.1016/j.scitotenv.2020.137065.

Dürrenmatt, D.J., Gujer, W., 2011. Identification of industrial wastewater by clustering wastewater treatment plant influent ultraviolet visible spectra. Water Sci. Technol. 63 (6), 1153–1159. https://doi.org/10.2166/wst.2011.354.

EEA, 2021. Urban waste water treatment in Europe. [Online] https://www.eea.europa.eu/data-and-maps/indicators/urban-waste-water-treatment/urban-waste-water-treatment-assessment-5 [28 12 2022].

EU Science Hub, 2022. Blending hydrogen into the EU gas system [Online]. https://joint-research-centre.ec.europa.eu/jrc-news/blending-hydrogen-eu-gas-system-2022-01-19_en [28 12 2022].

European Commission, 2019. The European Green Deal – Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions, Brussels: 11.12.2019.

European Commission, 2020. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020.

European Commission, 2022a. REPowerEU Plan. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483.

European Commission, 2022b. Biomethane. [Online] https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biomethane_en [28 12 2022].

Ge, Y., Li, L., Yun, L., 2021. Modeling and economic optimization of cellulosic biofuel supply chain considering multiple conversion pathways. Appl. Energy 281, 116059. https://doi.org/10.1016/j.apenergy.2020.116059.

Gianone, J., Imre, A.R., 2022. LNG as a key to sustainability and the rise of connected green technologies. 2022 IEEE Industry Applications Society Annual Meeting, Detroit, MI, USA, pp. 1–10. https://doi.org/10.1109/IAS54023.2022.9940091.

Goree, J., Ortloff, F., van Leeuwen, C., 2019. Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. Appl. Energy 253, 113594. https://doi.org/10.1016/j.apenergy.2019.113594.

Govindan, K., 2023. Pathways to low carbon energy transition through multi criteria assessment of offshore wind energy barriers. Technol. Forecast. Soc. Chang. 187, 122131 https://doi.org/10.1016/j.techfore.2022.122131.

Hoo, P.Y., Hashim, H., Ho, W.S., 2020. Towards circular economy: economic feasibility of waste to biomethane injection through proposed feed-in tariff. J. Clean. Prod. 270, 122160 https://doi.org/10.1016/j.jclepro.2020.122160.

Hwangbo, S., Sin, G., Rhee, G., Yoo, C., 2020. Development of an integrated network for waste-to-energy and central utility systems considering air pollutant emissions pinch analysis. J. Clean. Prod. 252, 119746 https://doi.org/10.1016/j.jclepro.2019.119746.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kumar Jana, D., et al., 2022. Bi-criteria optimization of cleaner biofuel supply chain model by novel fuzzy goal programming technique. Clean. Logist. Supply Chain 4, 100044. https://doi.org/10.1016/j.clscn.2022.100044.

Lang, D.J., et al., 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustain. Sci. 7, 25–43. https://doi.org/10.1007/s11625-011-0149-x.

Leonzio, G., 2017. Design and feasibility analysis of a Power-to-Gas plant in Germany. J. Clean. Prod. 162, 609–623. https://doi.org/10.1016/j.jclepro.2017.05.168.

Martin, M.R., et al., 2013. A single-culture bioprocess of methanothermobacter thermautotrophicus to upgrade digester biogas by CO2-to-CH4 conversion with H2. Archaea.

Michailos, S., et al., 2021. A techno-economic assessment of implementing power-to-gas systems based on biomethanation in an operating waste water treatment plant. J. Environ. Chem. Eng. 9 (1), 104735 https://doi.org/10.1016/j.jece.2020.104735.

Mininni, G., Braguglia, C.M., Ramadori, R., Tomei, M., 2004. An innovative sludge management system based on separation of primary and secondary sludge treatment. Water Sci. Technol. 50 (9), 145–153. https://doi.org/10.2166/wst.2004.0557.

Mohammed, A., et al., 2023. Multi-tier supply chain network design: a key towards sustainability and resilience. Comput. Ind. Eng., 109396 https://doi.org/10.1016/j.cie.2023.109396.

Moretti, L., Milani, M., Lozza, G.G., Manzolini, G., 2021. A detailed MILP formulation for the optimal design of advanced biofuel supply chains. Renew. Energy 171, 159–175. https://doi.org/10.1016/j.renene.2021.02.043.

Nair, S., Paulose, H., 2014. Emergence of green business models: The case of algae biofuel for aviation. Energy Policy 65, 175–184. https://doi.org/10.1016/j.enpol.2013.10.034.

Osterwalder, A., Pigneur, Y., 2010. Business Model Generation. John Wiley & Sons:, Hoboken.

Ranjbari, M., et al., 2022. Biofuel supply chain management in the circular economy transition: An inclusive knowledge map of the field. Chemosphere 296, 133968. https://doi.org/10.1016/j.chemosphere.2022.133968.

Scarlat, N., Dallemand, J.-F., Fahl, F., 2018. Biogas: developments and perspectives in Europe. Renew. Energy 129 Part A, 457–472. https://doi.org/10.1016/j.renene.2018.03.006.

Shanmugam, K., et al., 2022. A sustainable performance assessment framework for circular management of municipal wastewater treatment plants. J. Clean. Prod. 339, 130657 https://doi.org/10.1016/j.jclepro.2022.130657.

Singh, A., Smyth, B.M., Murphy, J.D., 2010. A biofuel strategy for Ireland with an emphasis on production of biomethane and minimization of land-take. Renew. Sustain. Energy Rev. 14 (1), 277–288. https://doi.org/10.1016/j.rser.2009.07.004.

Statista, 2020. Benchmark capital expenditure for utility-scale solar photovoltaics worldwide from 2010 to 2020. [Online] https://www.statista.com/statistics/971982/solar-pv-capex-worldwide-utility-scale/ [28 12 2022].

Statista, 2022. Prices of electricity for industries with a consumption of 500 to 2,000 megawatt hour in the European Union from 2008 to 2021. [Online] https://www.statista.com/statistics/1046630/electricity-prices-for-industries-european-union/ [28 12 2022].

The Hydrogen Valley Platform, 2022. Hydrogen cost and sales prices. [Online] https://h2v.eu/analysis/statistics/financing/hydrogen-cost-and-sales-prices [28 12 2022].

Trading Economics, 2023. EU Natural Gas. [Online] https://tradingeconomics.com/commodity/eu-natural-gas [24 01 2023].

Union, E., 2023. Innovative Biomethane for REPowerEU. Publications Office of the European Union, Luxemburg.

van Leeuwen, C., Zauner, A., 2018. Report on the costs involved with PtG technologies and their potentials across the EU, STORE&GO.

Varone, A., Ferrari, M., 2015. Power to liquid and power to gas: an option for the German Energiewende. Renew. Sustain. Energy Rev. 45, 207–218. https://doi.org/10.1016/j.rser.2015.01.049.

Yuan, Z., Wang, W., Li, J., 2023. Carbon dioxide recycling in hydrogen-based energy systems using power-to-gas facility and stochastic multi-objective optimization. J. Clean. Prod. 387, 135892 https://doi.org/10.1016/j.jclepro.2023.135892.

Yue, D., You, F., Snyder, S.W., 2014. Biomass-to-bioenergy and biofuel supply chain optimization: overview, key issues and challenges. Comput. Chem. Eng. 66, 36–56. https://doi.org/10.1016/j.compchemeng.2013.11.016.

Zauner, A., Böhm, H., Rosenfeld, D.C., Tichler, R., 2019. Analysis on future technology options and on techno-economic optimization, STORE&GO.

Zsiborács, H., et al., 2022. The reliability of photovoltaic power generation scheduling in seventeen European countries. Energ. Conver. Manage. 260, 115641 https://doi.org/10.1016/j.enconman.2022.115641.