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Economic and Operational Feasibility of Biological Methanation in Power-to-Gas Systems: Enhancing Renewable Energy Integration

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Abstract

The urgent need for sustainable and stable energy systems has propelled the exploration of innovative solutions like Power-to-Gas (PtG) technology, which offers a promising pathway to integrate renewable energy sources (RES) into existing energy infrastructures. This study delves into the economic viability and operational efficiency of employing biological methanation processes within PtG systems, with a particular focus on the trickle bed methanation technique. By converting excess renewable electricity into hydrogen and subsequently methane, PtG technology represents a strategic approach to mitigate the intermittency of renewable sources such as wind and solar power. This research assesses the operational parameters and economic implications of utilizing proton exchange membrane (PEM) electrolyzers and biological methanation in the context of fluctuating electricity prices and regulatory environments. Furthermore, it examines the potential of retrofitting existing biogas plants for methane production through biological methanation, thus leveraging existing infrastructure for enhanced energy storage and grid stability. The findings highlight the critical factors influencing the economic feasibility of PtG technology, including investment and operational costs, and propose strategic recommendations to enhance its market penetration and viability. This comprehensive analysis underscores the significance of PtG technology, particularly biological methanation, as a cornerstone for achieving a sustainable and resilient energy future.

Keywords: Power-to-Gas Technology, Biological Methanation, Renewable Energy, Economic Feasibility, Energy Storage Solutions

1. Introduction

The global energy landscape is undergoing a significant transformation, driven by the urgent need to address climate change and the increasing demand for sustainable energy solutions. At the heart of this transformation is the integration of renewable energy sources (RES) such as wind and solar power, which are pivotal for reducing greenhouse gas emissions and fostering energy independence. However, the intermittent nature of these energy sources presents a considerable challenge for energy systems, necessitating innovative solutions for storage and grid stability (Sensfuss and Pfluger, 2014; Elegbede *et al*., 2023) [19, 10]. Power-to-gas (PtG) technology has emerged as a promising approach to address the intermittency of RES by converting surplus electricity into hydrogen or methane, which can then be stored or utilized within the existing gas network (Dominik *et al*., 2010) [13]. This technology not only provides a versatile solution for energy storage but also plays a crucial role in sector coupling, bridging the gap between the electricity, heating, and transportation sectors (Ess *et al*., 2012; Amos *et al*., 2024a) [11, 2].

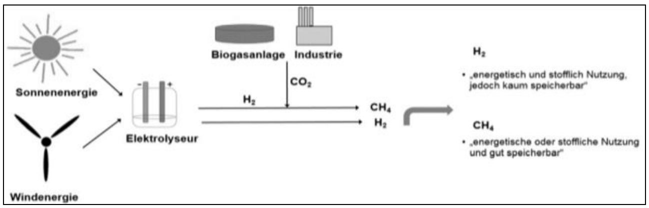
Among the various PtG processes, biological methanation holds particular promise due to its potential for high conversion efficiency and compatibility with existing biogas infrastructure. By leveraging the process of microbial conversion of hydrogen and carbon dioxide into methane, biological methanation offers a sustainable and efficient method for synthesizing renewable methane, which can be readily integrated into the natural gas grid or used as a renewable fuel (Anne and Georg, 2008) [18]. This study focuses on the economic and operational feasibility of integrating biological methanation within PtG systems, with a particular emphasis on the trickle bed methanation technique. Trickle bed reactors, known for their operational stability and efficiency in bio-catalytic processes, present an innovative approach to enhancing methane production from renewable sources (Manuel *et al*., 2017) [6]. The economic viability of PtG technologies, and biological methanation in particular, is influenced by a myriad of factors, including the cost of electricity, technological advancements in electrolysis and methanation processes, and the regulatory and policy landscape. As such, understanding the economic parameters and operational dynamics of these systems is crucial for their successful implementation and integration into the energy market (Timo *et al*., 2018) [22]. Furthermore, the retrofitting of existing biogas plants for biological methanation represents a strategic opportunity to utilize existing infrastructures for renewable methane production, potentially reducing initial capital expenditures and accelerating the deployment of PtG technologies (Bernhard *et al*., 2017) [14].

In light of these considerations, this study aims to provide a comprehensive analysis of the economic feasibility and operational considerations of biological methanation in PtG systems. By examining the potential for integrating this technology into existing energy infrastructures and assessing its impact on the renewable energy landscape, this research contributes valuable insights into the role of PtG technologies in achieving a sustainable and resilient energy future (Stephen and Pierluigi, 2015) [8]. Despite the technological advancements in PtG technologies, their economic viability remains a critical challenge, especially in contexts with fluctuating energy prices and varying regulatory frameworks. Furthermore, the integration of biological methanation processes into existing energy systems, including biogas plants, necessitates a comprehensive understanding of the operational, economic, and environmental implications. Addressing these challenges is essential for developing efficient and economically viable PtG solutions that can support the large-scale adoption of renewable energy. This review paper will specifically assess the operational efficiency and economic viability of integrating biological methanation processes into PtG systems; evaluate the potential of existing biogas plants for the implementation of trickle bed methanation technology; analyze the impact of electricity prices and regulatory policies on the economic feasibility of PtG technologies; and develop recommendations for enhancing the economic attractiveness and market penetration of PtG solutions, particularly through the utilization of biological methanation.

Also, the integration of PtG technology, specifically through biological methanation, into the energy system presents a strategic opportunity to address the intermittent nature of RES and improve energy system flexibility. By examining the economic feasibility of these technologies, this study contributes to the body of knowledge necessary for policymakers, energy producers, and stakeholders to make informed decisions regarding the adoption and support of PtG solutions. Furthermore, the research outcomes will provide insights into optimizing PtG systems for enhanced efficiency and economic viability, thus paving the way for a more sustainable and resilient energy infrastructure.

2. Power - to - Gas process and Economic Feasibility Possibilities

The core component of a PtG system is the electrolyser, which utilizes electrical power to electro chemically split water to H_2 and O_2 and prevents gas remixing by a selective membrane and electrolyte. Two key indicators parameters responsible for this are, operating voltage and current density, and they help in the evaluation of cell performances (Fig 1). The operating voltage defines the electrolysis (electrical) efficiency, while the current density determines hydrogen production per cell area and the source of CO_2 for methanation. Thus, low operating voltage and high current density are the focus targeted by research. The development of proton exchange membrane-based electrolyser (PEM) offers high flexibility, fast dynamic response, and higher efficiency with a cell operating voltage of 1.7 – 2.0 V and compact design with a current density over 1.0 Acm−2. The operating current density can even reach over 10 A cm^2 by employing novel catalysts (Bundesverband *et al*., 2013). However, due to the employment of an expensive proton exchange membrane and noble materials as the catalysts, acidic electrolysers are more expensive and suffer from a faster degradation thus a shorter lifetime of around 5 years (Bundesverband *et al*., 2013).



Source: Burkhardt (2012) [7]

Fig 1: Energy conversion and storage strategy for the proposed PtG process chain

2.1 PEM Electrolyser model description

The core elemental part of PtG is the electrolyser, whose behavioural dynamism must be well-investigated in order to assess the optimum performances of the whole system when fed with intermittent power sources as well evaluate its performances under different conditions. Electrolyser uses electrical current (wind and solar RES) to decompose water into hydrogen and oxygen. It consists of many several electrolysers cells, connected in series or parallel. The current when compare to voltage feature of an electrolyser depends on its working temperature according to Faraday's law, the production rate of hydrogen in an electrolyser cell is directly proportional to the rate of transfer of electrons at the electrodes, which is equivalent to the electrical current in the circuit expressed according to the following equation,

$$n_{H_2} = \frac{n_F . n_x . i_e}{2F} \qquad (1)$$

n_{H_2} = Hydrogen production rate, $mols^{-1}$
n_F = Faraday's efficiency
n_c = the number of electrolyser cells in series
i_e = electrolyser current A
F = Faraday constant [C kmol−1].

The ratio between actual and maximum theoretical amount of produced hydrogen in the electrolyser is Faraday efficiency. Electrolyser is an apparatus that separates hydrogen and oxygen from water. It converts DC electrical energy into chemical energy stored in hydrogen, in terms of an electro-chemical reaction happening in the fuel cell to generate DC electricity. The circuit of an electrolyser is represented as a voltage sensitive nonlinear DC load, so when the applied voltage is increased the load current increases, which in turn increases the hydrogen, produced. PEM cells are reversible devices for hydrogen production having advantages like lower operating temperatures, lower power consumption, smaller dimension and mass, etc. A PEM electrolyser modelled in MATLAB/Simulink in order to run the simulation. The modelling is based on mathematical equations shown below, the V-I characteristics and amount of hydrogen produced is also obtained from these steady state equations. The electrolysis process is modelled using Eq. (a).

$$V = IR_i + e_{rev} \qquad \text{(a)}$$

Where R_i is the initial resistance and e_{rev} is the reverse potential. The ideal potential V_i is calculated using Eq. (b)

$$V_i = \frac{\Delta G}{2F} \qquad \text{(b)}$$

Where, ΔG is Gibbs free energy change (J/mol) of hydrogen gas and F is Faraday constant (96,487 C/mol). ΔG for any given temperature T °C can be calculated by Eq. (c):

$$\Delta G = 285840 - 163.2*(273+T) \qquad \text{(c)}$$

The value of V_i is calculated under nominal operating conditions at 1 atm pressure and room temperature of 20 °C. The molar volume V_m is obtained from the ideal gas expression in Eq. (d):

$$V_m = \frac{R(273+T)}{P} \qquad \text{(d)}$$

Where, R and P are the ideal gas constant (0.0821 atm k^{-1} mol^{-1}) and pressure, respectively. The hydrogen production rate which is V_H (l/year) with respect to the input current I is determined using Eq. (e)

$$V_H = V_M\, 10^3 * 60 * \frac{I}{2F} \qquad \text{(e)}$$

The electro chemical hydrogen energy per second P_{H2} is obtained by Eq. (f)

$$P_{H2} = V_i * I \qquad \text{(f)}$$

The useful power delivered from the electrolyser depends on the electrolyser input current I and ideal voltage V_i. The input electrical power P of PEM electrolyser cell, which is the function of the V_H, is obtained using Eq. (g)

$$P = VI = I^2R_i + Ie_{rev} \qquad \text{(g)}$$

The resistance (Ri) of PEM subsystem is assumed to be 10 Ω at temperature 20 °C and 1 atm. The input of V-I model of the PEM electrolyser cell as function of temperature and pressure is modelled using Eq. (h). The model is as shown in Fig 2.

$$V(T,P) = IR_i + e_{rev}\,(T,P) \qquad \text{(h)}$$

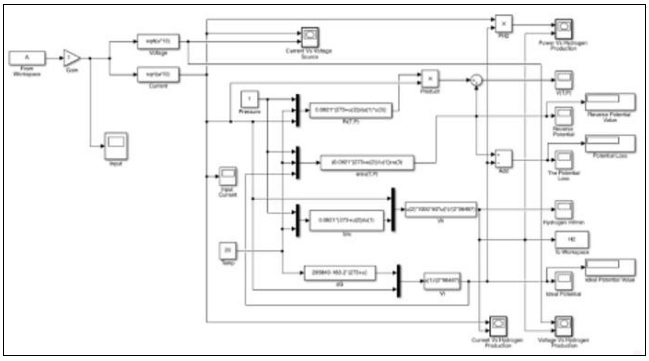


Fig 2: A typical Simulink diagram of electrolyser model

2.2 Hydrogen Storage Model

The hydrogen storage techniques are a physical hydrogen storage, which includes tanks to store either compressed hydrogen gas or liquid hydrogen. The produced hydrogen storage can be stored in a tank whose system dynamics is expressed as follows:

P_b = Pressure of tank (pascal)
P_{bi} = Initial pressure of the storage tank (pascal)
R = universal (rydberg) gas constant (J/kmol K)
T_b = Operating temperature K
V_b = Volume of tank M^3
Z = Compressibility factor as a function of the pressure

$Z = \frac{PV_m}{RT}$, P = pressure, V_m = Molar volume, t = temperature

Compressed hydrogen gas is stored in tanks by using different techniques. A dynamic model of tank is created in Simulink using Eq. (2) to store the hydrogen gas that is produced by the electrolyser

$$P_b - P_{bi} = z * \frac{N_{H2}RT_b}{M_H V_b} \qquad \text{(2)}$$

Where, T is the temperature, R is the universal gas constant (J/kmol·K), P_{bi} is the initial pressure of the storage tank, P_b is the pressure of the tank in Pascal, T_b is the operating temperature in Kelvin, V_b is the volume of the tank in m^3 and Z is the compressibility factor as a function of the pressure as shown in Equation (a):

$$Z = \frac{PV_m}{RT} \qquad \text{(a)}$$

Where, V_m and P are the molar volume and pressure, respectively. The hydrogen storage model is implemented in Simulink using Eq. (2) and the system is as shown in Fig 3.

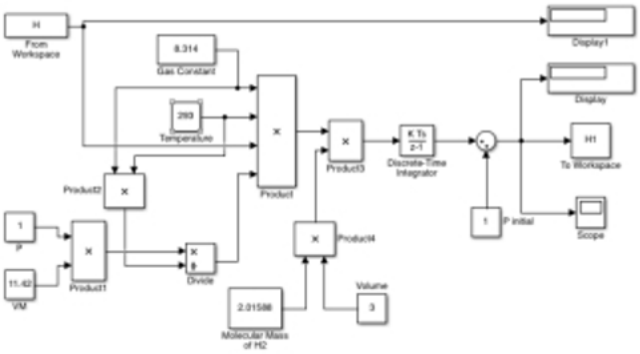


Fig 3: Hydrogen Storage system

2.3 Biological Methanation Model

The hydrogenotrophic trickle bed methanation converts hydrogen and carbon dioxide through biological methanation according to the reaction $CO_2 + 4H_2 = CH_4 + 2H_2O$. Excess or residual power from RES Fig. 41 for year 2010 0,1 TWh and 2020 1 TWh are used for the dissociation of water, that is, electrolysis process to produce hydrogen, the quantity of the produced hydrogen are 25.000.000 and 250.000.000 Nm^3 for 2010 and 2020 respectively. The synthesis of hydrogen and carbon dioxide for the year 2010 6.250.000 and 2020 62.500.000 Nm^3 in the trickle bed biogas reactor produces for 2010 28,5 and 43,2 GW_{el} respectively, while the quantity of electrical power produced for 2020 after reconversion are 0,28 and 0,43 TW_{el} accordingly. The performance of biologically catalysed system by dosing pure hydrogen gases and carbon dioxide according to Fig 4. The load limits and the operating behaviour of the entire technical was observed properly. The biological methanation process showed a very good behavior with regard to long-term stability (because the catalyst renews itself) and good properties for load changes system. The methane content in the biogas reactor is enhanced because the system is designed in a way that the substrates flows, interacts, and mixes easily naturally. In this way, conversion process is done with need for little energy, no need for agitators, compressors and pressure vessels and no special addition of cultures. However, when comparing its performance with other approaches, attention is currently paid to performance parameters such as room load or methane yield (Adegoroye *et al*., 2024; Mope *et al*., 2024; Amos *et al*., 2024b) [5, 17, 3]. There are so many factors to bear in mind when modelling or designing biological methanation with the synthesis of hydrogen and carbon dioxide to produce methane. Some of these parameters or factors are very significant to designing a unit system that will be optimal and flexible for application. Such factors are:

Type of reactor but this research, trickle – bed reactor is considered

Mode of operation (e.g., batch/fed-batch/continuous/semi-continuous) and

Required plant components, according to the ‘CO_2-Methanation process’ boundary definition,

Potential specific characteristics of the plant/process concepte.g.,co-current/counter-currentmode, flow chart, etc.

One major limitation to biological methanation process is slow hydrogen gas – to - liquid mass transfer, which leads to low space - time yields.

Table 1: Performance data of biological, hydrogenotrophic trickle bed methanation

Reaktor-typ	T in °C	p in bar	pH	H_2:CO_2	B_R,H_2 in $m^3/(m^3\ d)$	X_{H_2} in %	X_{CH4} in %	Y_{CH_4} in $m^3/(m^3\ d)$
RB	37	1	7,3	3,76:1	6	100	>98	1,49
RB	40	5	6,6	3,75:1	20	97	80	4,28
RB	55	1	7,0	4:1	62	99	98	15,4
CSTR	65	1	6,8	4:1	-	-	96	288
RB	65	1	8,0	4,2:1	17	99	95	4,2

Source: GICON

Reactor-, Gas-, Reaction- and Liquid Volume, h/d-Ratio, Packing Volume.

The apparent meaning of the actual ‘reactor volume’ (VR in m^3) is the sum of the volume of all sections within the reactor, including e.g., head and space, sump, liquid and internal components. The volume in pipes is usually negligible and not considered in the calculation of the reactor volume. For a cylindrical vessel, V_R is defined by ‘reactor height’ (h_R in m) and ‘reactor diameter’ (d_R in m) from which the ‘h/d-ratio’ can be calculated. The ‘liquid volume’ (VL in m^3) consists of just the liquid present within the reactor during operation with the volume of suspended biomass and solids. For the specific application of trickle-bed reactors, in addition, the suspended biomass and ‘packing volume’ (V_P in m^3) are known. It is the volume of the packing zone and, if cylindrical, can be calculated by the ‘packing height’ (hP in m) and ‘packing diameter’ (d_P in m). The ‘gas volume’ (V_G in m^3) contains the total volume of the gaseous phase within the reactor volume V_R. The ‘reaction volume’ (V Reaction in m^3) is the volume in which the reaction takes place (Martin *et al*., 2019; Amos *et al*., 2024c) [15, 4].

Plant Capacity, Size and Footprint,

Plant Operating States,

Reactant and Product Gas Specification,

Gas Hourly Space Velocity,

Gas Retention Time,

Hydraulic Retention Time and Liquid Recirculation,

Gas Conversion Rat,

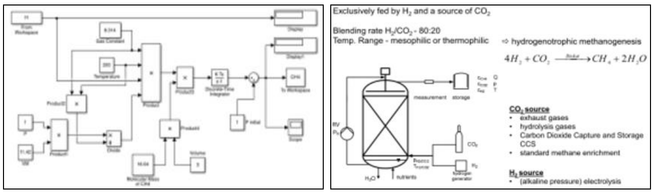
Methane Yield,

Methane Production Rate,

Methane Production Dynamics or Load Change Rates,

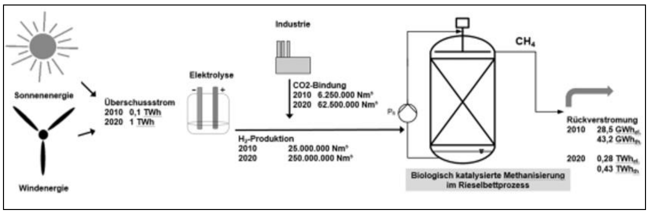
Methanation Efficiency and System Availability.

Compressed methane gas is stored in tanks by using the same technique as that used to model the Hydrogen tank and all the equations are the same. The only change is that the Molecular weight of methane gas is 16.04 and that of hydrogen is 2.01588. The model is as shown in Fig 5



Source: GICON

Fig 5: Model of Methane Storage system Figure: 40 Plant set up for $10m^3$ test for Trickle bed reactor

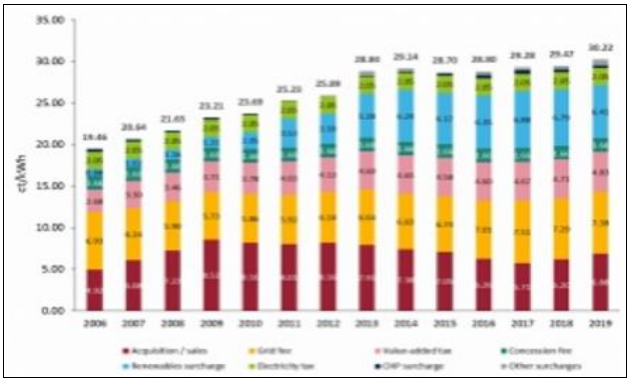


Source: Burkhardt (2012) [7]

Fig 6: Energy balance to harness residual electricity via BM in the Trickle bed reactor for PtG process

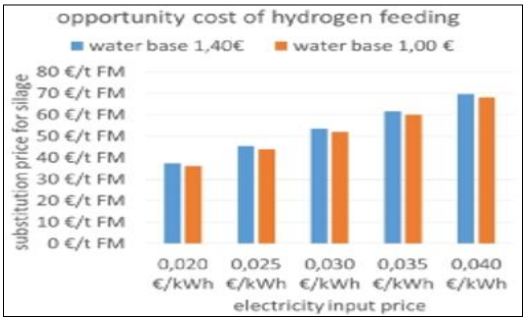
3. Economic Feasibility Possibilities

With the slim system structure, this study aims at a low investment hurdle when integrating trickle bed systems into existing biogas plants. In the context of the energy transition already in existence, there are currently few incentives to avoid carbon dioxide, the necessary energy storage or sector coupling are only being cautiously or not at all funded with monetary benefits. The scenario in Fig 6 is part of the case studies considered for the presentation of possible economic concepts considered for future price developments. The greatest financial dependency with Power-to-Gas technology is the conversion of the available electricity into chemical energy (hydrogen). The investment and operating costs represent the largest share of the storage technology investment. The different cost parameters for biological methanation systems is the capital expenditures (CAPEX) and should be provided as cost per power contained per normal cubic meter product gas at the nominal point with respect to lower heating value LHV in €/kW. Operational expenditures (OPEX) on the other hand should be given in €/kWh as related to nominal point of operation and LHV. The cost parameters of the methanation system, which comprises of different components within the system boundaries of the methanation process unit, are important.



Source: Clean Energy Wire (2018) [9]

Fig 6: Average price of electricity in Germany



Source: Clean Energy Wire (2018) [9]

Fig 7: BM to substitute agricultural substrates GICON

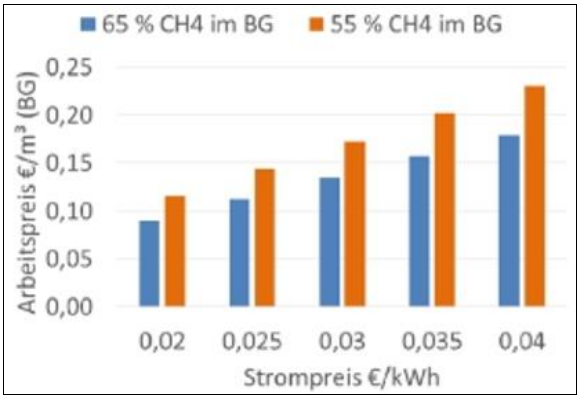


Fig 8: Costs preparation for biological Methanation, GICON

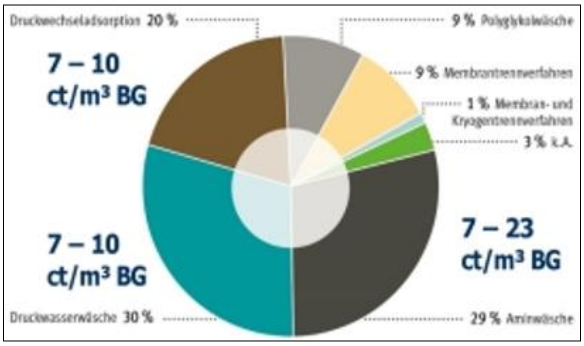


Fig 9: Biogas upgrading process distribution (Finanzen.net, 2019) [12]

Electricity cost is 100 times higher than the cost of water used for the production of hydrogen and the single largest variable cost of hydrogen production by electrolysis is electricity. The price of electricity is divided into three parts; about 40 % of the price of electricity belongs to the electricity supplier and are most times compensation to the electricity producers. About 20 % does go to the electric grid operator, is referred to as cost for electricity distribution. The rest 40 % is for taxes and fees clearance. Carbon dioxide and sulphur taxes, the price of electricity to produce hydrogen and methane primarily is an integral part of electricity grid cost, certificates and energy cost.

4. Conclusion and Recommendations

This study critically examined the integration of biological methanation within Power-to-Gas (PtG) technology as a means to enhance the utilization and storage of renewable energy sources in Germany. Focusing on the economic feasibility and operational efficiency of this integration, particularly through the use of proton exchange membrane (PEM) electrolyzers and trickle bed methanation processes, it was found that PtG technology presents a viable solution to the intermittency challenges of renewable energy sources. The analysis revealed that biological methanation, when integrated into existing biogas plants, could significantly improve the economic viability and scalability of PtG systems. This approach not only leverages existing infrastructure but also contributes to the sustainability and resilience of the energy system by facilitating a higher penetration of renewable energies into the grid. However, the economic viability of such systems is heavily influenced by current energy market dynamics, regulatory policies, and the technological costs associated with electrolysis and methanation processes. It is therefore recommended that continued investment in R&D is crucial for improving the efficiency and reducing the costs of PEM electrolyzers and biological methanation processes. Innovations in catalyst development and membrane technology could lead to lower operational costs and extended system lifespans. Governmental policies should encourage the adoption of PtG technologies through incentives, such as subsidies for renewable energy storage, tax benefits for research, and streamlined regulatory approvals for new PtG projects. Additionally, establishing clear regulatory frameworks for the operation and integration of PtG systems into the energy grid will be vital. Investing in the necessary infrastructure, including hydrogen storage facilities and pipelines for hydrogen and synthetic methane distribution, is essential to support the widespread deployment of PtG technology. Develop economic incentives that reflect the true value of energy storage and grid stabilization provided by PtG systems. This could include mechanisms for energy market participation that allow PtG operators to benefit from energy price fluctuations. Initiatives to increase public awareness of the benefits of PtG technology and its role in a sustainable energy future are needed. Educational campaigns can help garner public support and potentially stimulate investment in renewable energy technologies. Finally, encourage collaboration between government bodies, research institutions, and industry stakeholders to share knowledge, co-fund research projects, and pilot test new technologies to accelerate the development and commercialization of PtG systems.

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