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Seasonal Energy Storage Potential Assessment of WWTPs with Power-to-Methane Technology

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Received: 29 August 2020; Accepted: 18 September 2020; Published: 22 September 2020



Abstract: Power-to-methane technology (P2M) deployment at wastewater treatment plants (WWTPs) for seasonal energy storage might land on the agenda of decision-makers across EU countries, since large WWTPs produce a notable volume of biogas that could be injected into the natural gas grid with remarkable storage capacities. Because of the recent rapid increase of local photovoltaics (PV), it is essential to explore the role of WWTPs in energy storage and the conditions under which this potential can be realized. This study integrates a techno-economic assessment of P2M technology with commercial/investment attractiveness of seasonal energy storage at large WWTPs. Findings show that a standardized 1 MW_{el} P2M technology would fit with most potential sites. This is in line with the current technology readiness level of P2M, but increasing electricity prices and limited financial resources of WWTPs would decrease the commercial attractiveness of P2M technology deployment. Based on a Hungarian case study, public funding, biomethane feed-in tariff and minimized or compensated surplus electricity sourcing costs are essential to realize the energy storage potential at WWTPs.

Keywords: seasonal energy storage; power-to-methane; wastewater treatment plants; techno-economic assessment

1. Introduction

There is broad consensus within the power-to-gas (P2G) literature, especially in the power-to-methane (P2M) literature, as well as among industry actors that wastewater treatment plants (WWTPs) could play a significant role in scaling up P2G technology by ensuring key input factors, mainly efficiently useable carbon-dioxide sources in the produced biogas [1]. Meanwhile, a notable volume of previous research has shown several technical, and techno-economic challenges of the P2M technology [2], and recent research has also pointed out that a supportive regulatory environment is essential to further develop and scale up the P2M technology [3]. As the EU must significantly increase the PV installation rate to reach a carbon-neutral electricity supply by 2050 [4], and considering the integration challenges of the renewable energy to the grid [5], it is becoming a key priority for decision-makers to also focus on concrete opportunities and limitations of seasonal energy storage that could be realized with P2M technology deployment at WWTPs.

While the promising role of the P2G technology in the energy sector has been argued comprehensively in recent years (e.g., from the aspect of long-term energy storage [2], system analysis [6] or technological and economic factors [7]), researchers have also started to focus on the role of WWTPs with respect to different aspects of renewable energy transition and power-to-X technologies. Schäfer et al. [8] pointed out that WWTPs have notable synergy potential in sector coupling, for example, hydrogen and methane can be produced at WWTPs (with P2G technologies), and the oxygen (as the byproduct of the electrolysis) can be used to enhance purification processes. Gretzschel et al. [9]

focused on power-to-hydrogen (P2H) technology and the elimination of organic micropollutants at WWTPs, considering the possibility of offering system service, as well: automatic frequency restoration reserve (aFRR), which can provide short-term flexibility for network operators. Ceballos-Escalera et al. [10] examined the energy storage attributes of a prototype with a bioelectrochemical system for electromethanogenesis (EMG-BES) at a WWTP, which is an emerging technology in the P2M segment besides chemical and biological methanation. They also showed the future potential of the interconnectedness of renewable energy overproduction, biomethane production, and wastewater treatment. WWTP functions regarding sustainability are, however, researched in terms of other aspects, as well, considering that they also play a significant role in nutrient recovery, where new practices have been suggested [11], and have also been designed [12] for environmentally and economically more viable clarification and treatment technologies.

In this paper, the authors make a step forward on the route outlined by these previous researchers, using Hungary as a case study and focusing on biological methanation technology. Its technology readiness level makes it possible to plan grid-scale implementations, even in the short term [13]. These opportunities are paved by the theoretical synergies between biological methanation and WWTPs mentioned above, as well as empirical data of:

(1) the innovative lab-scale P2G prototype with biological methanation developed by Power-to-Gas Hungary Kft. in cooperation with Electrochaea GmbH (the developer of the 1 MW_{el} P2G facility with biomethanation, located in Avedøre, Denmark).

(2) large Hungarian WWTPs, from which the authors collected technical data to evaluate the implementation opportunities and limitations. The senior executives of these WWTPs provided valuable insights regarding the economic and technology incentives of commitment for grid-scale technology implementation projects.

Techno-economic assessments have already been conducted regarding P2G technologies with different methods and scopes in recent years. In terms of the return of the investment, for example, Ameli et al. [14] analyzed the role of different capacities of battery storage and P2G systems in Great Britain with the Combined Gas and Electricity Networks (CGEN) model. Addressing electricity balancing challenges, they concluded that the capital costs must reach £0.5 m/MW for P2G to justify the investment. As a comparative approach, Collet et al. [15] analyzed five different scenarios of biogas upgrading and P2G, pointing out that P2G technologies “are competitive with upgrading ones for an average electricity price equal to 38 EUR MW h⁻¹ for direct methanation and separation by membranes” [p. 293]. In the case of production costs, Peters et al. [16] can be mentioned among others, who evaluated eight scenarios based on different combinations of H₂ and CO₂ sources and found methane costs in the range of 3.51–3.88 EUR/kg for P2G. Collet et al. and Peters et al. complemented their techno-economic analyses with ecological and environmental aspects, focusing on greenhouse gas (GHG) emissions, as well. P2M is important, but is not the only means of decarbonization in the case of waste management; for example, the latest techno-economic analyses show increasing economic and ecological viability regarding biochar farming [17], agricultural waste management [18] and solid biofuels [19], as well.

As detailed above, there are several approaches to perform a techno-economic assessment of the P2G and waste management technology [20]. Inspired by these studies, the authors also emphasize the economic aspects besides the technical parameters, based on which the seasonal energy storage potential can be calculated at large Hungarian WWTPs. The novelty of this paper is that it aims to open up new perspectives in the techno-economic assessment of P2M technology by:

(1) narrowing its focus to individual WWTPs in the first step and carrying out in-depth analysis regarding not only techno-economic, but also commercial/investment questions as complementary viewpoints (in addition to the important and frequently assessed environmental impacts). Economic and commercial aspects are differentiated, as the former considers general interrelations of technical data, costs, revenues, return on investment; while the latter incorporates WWTP-specific infrastructure, strategic management and investment related viewpoints of WWTPs as organizations, as well.

(2) extending the focus to a national-level assessment, based on specific empirical data, as well as evaluating the seasonal energy storage and practical implementation opportunities and limitations of the P2M technology with integrated commercial/investment expectations of stakeholders.

Consequently, the research questions are the following:

- (1) What is total seasonal energy storage potential with P2M at large WWTPs in Hungary?
- (2) What are the economic conditions under which WWTPs are financially incited to participate in a grid-scale implementation of the biological methanation?

The research questions indicate that the authors aim to connect theory and practice, to explore the seasonal energy storage potential and also the practical key success factors under which this potential can be realized. The focus of this paper makes meaningful contributions to P2M research and industry that are beyond the specific geographical area:

(1) First, while numerous studies have drawn important conclusions about the “hard” factors of P2G technology development and implementation (such as levelized cost of energy, process design, cost optimization, life-cycle assessment) based on quantitative data [2], the authors combine quantitative and qualitative data collection to contribute to an overall understanding of P2M technology deployment opportunities and limitations at concrete future operators of P2M.

(2) Second, the techno-economic assessment with the complementary commercial/investment viewpoint (based on interviews and financial modeling) shows how WWTPs senior executives could be incited by changes of the regulatory environment to take the innovation-related and upscaling risks, as well. Figure 1 summarizes the research framework.

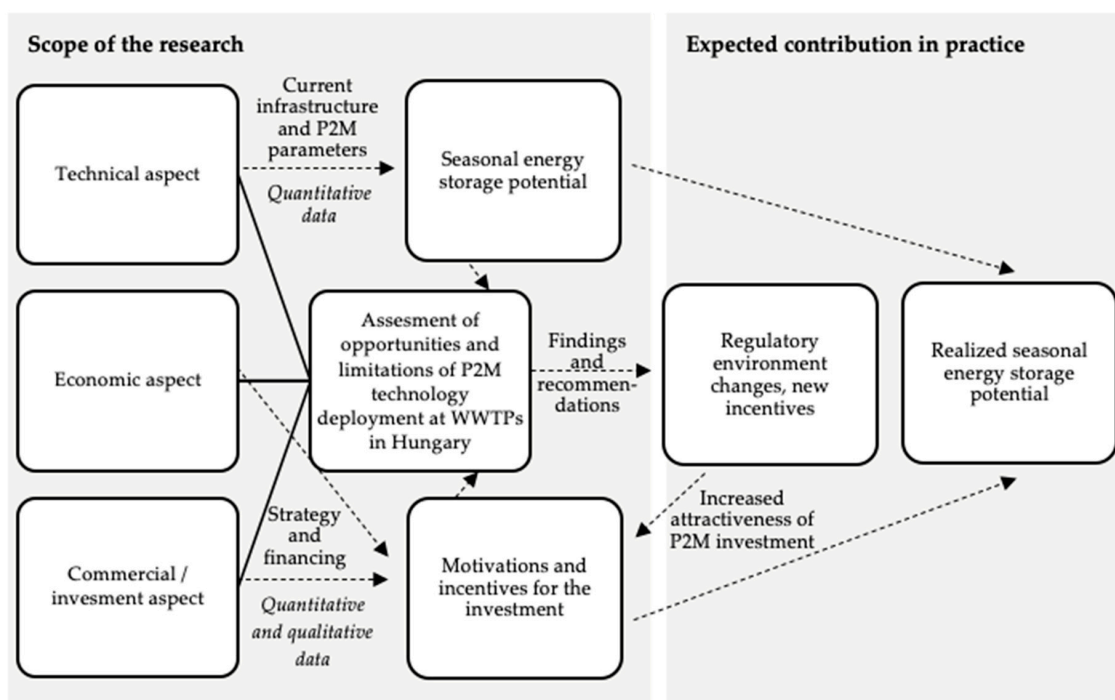


Figure 1. Research framework. The scope of the research incorporates the assessment of opportunities and limitations of P2M technology deployment at WWTPs in Hungary in terms of technical, economic, and commercial/investment aspects. The current WWTP infrastructure and P2M technology parameters determine the seasonal energy storage potential. Commercial and investment challenges of WWTPs and P2M business models determine motivations and incentives for such projects. Based on these findings, recommendations can be outlined for changes of the regulatory environment. The expected contribution of these recommendations is that new incentives could increase the attractiveness of P2M investments for WWTPs and allow them to realize the energy storage potential.

As the research framework suggests, based on a previous Hungarian P2G study [3], the specific research hypothesis is the following:

Economic, commercial, and investment aspects of P2M seasonal energy storage do not motivate WWTPs to act as future P2M operators, consequently, there is a need for change in the regulatory environment to incite them to realize their seasonal energy storage potential with P2M deployment.

There is a rapidly growing need for seasonal energy storage in the EU, especially in Hungary (where the national energy strategy also forecasts rapid growth of national PV capacities [21]), for which P2M would be a promising technology, but its grid-scale implementation has not happened yet. The objective of the research is to examine the P2M deployment opportunities and limitations at large WWTPs in Hungary and explore possible ways of realizing the seasonal energy storage potential of P2M technology. The main contribution of this techno-economic assessment is that it incorporates complementary commercial and investment attractiveness of seasonal energy storage by collecting and analyzing both quantitative and qualitative data as well. It shows the challenges of P2M technology deployment also from the aspect of future operators highlighting their motivation and strategic interests.

2. Materials and Methods

2.1. Technology Description

P2G is often called a “disruptive” technology, since it brings a new techno-socio-economic approach into the energy sector and redefines the scope of duties of each stakeholder (Ferrero, 2016). This disruptive process started in Hungary with the foundation of Power-to-Gas Hungary Kft., in 2016. The startup developed a lab-scale P2M prototype and has been operating it since April 2018. The prototype is a scaled-down operational unit with mass and energy flows in proportion to the commercial process of P2G, and also contains the complete basic unit operations to carry out research and development (R&D) in the field of P2G.

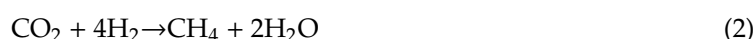
The planned P2M plants can produce a gas mixture that meets the requirements of natural gas standards. The applied process consists of three main steps.

(1) In the power-to-hydrogen (electrolysis) step, the plant would use surplus electricity from the electric grid [22] and produce hydrogen (with oxygen as a byproduct), in line with the chemical reaction below:



In this research, polymer electrolyte membranes (PEMEC) electrolysis is applied, which is preferred for seasonal energy storage (as it is applied also by Power-to-Gas Hungary Kft), mainly because of its high flexibility, fit to volatile renewable energy generation, and high technology-readiness level [23]. While hydrogen is going to be used in the next P2G step (methanation), oxygen generation can also be exploited at WWTPs; the efficiency of the aeration system can be increased by injection of oxygen into it [8].

(2) In the methanation step, the CO₂ content of the biogas (typically 30–50%) is converted to methane, carried out by basic reactions and mediated by the biocatalyst employing a unique set of enzymes [24]:



In this research, a flexible biomethanation process is applied that is provided by an optimized strain of Archaea (*Methanothermobacter thermautotrophicus*), a proprietary biocatalyst, a robust, highly selective and efficient strain [25]. Unlike biogas upgrading [26], methane and carbon dioxide gas components are not separated in this process, and the biogas is injected to the continuous stirred-tank reactor along with hydrogen. Mass-flow rates are set to maintain the stoichiometric ratio of hydrogen and carbon dioxide (increased, 4.1:1 in practice because of the 23 times lower dissolution of hydrogen than carbon dioxide in water).

(3) In the injection step, the product gas in which the guaranteed purity of methane is more than 97% is injected into the natural gas grid after a polishing process (segregation of hydrogen gas compound, removal of water vapor, cooling).

The evaluated total efficiency of the P2M plant (η_{P2G}) is calculated as follows:

$$\eta_{P2G} = \eta_{el} \cdot \eta_{meth} = \left(\frac{\dot{V}_{H_2} \cdot HHV_{H_2}}{3.6 \cdot P_{el}} \cdot \frac{\dot{V}_{wpg} \cdot HHV_{wpg}}{\dot{V}_{H_2} \cdot HHV_{H_2}} \right) \cdot 100 = 27.7 \cdot \frac{\dot{V}_{wpg} \cdot HHV_{wpg}}{P_{el}} [\%] \quad (3)$$

where:

\dot{V}_{H_2} – Hydrogen gas volumetric flow ($\frac{Nm^3}{h}$)

HHV_{H_2} – Hydrogen gas higher heating value ($\frac{MJ}{Nm^3}$)

P_{el} – power output of electrolyzer units [kW_{el}]

\dot{V}_{wpg} – wet product (effluent) gas volumetric flow ($\frac{Nm^3}{h}$)

HHV_{wpg} – wet product (effluent) gas higher heating value ($\frac{MJ}{Nm^3}$)

After substituting the correspondent values into the equation, the total P2M plant efficiency is in the range of 55–60%.

2.2. WWTPs in Hungary

WWTPs in Hungary are units of regional or municipal waterworks, typically owned by municipals responsible for water supply, wastewater drainage, and treatment. There were 826 WWTPs in Hungary in 2016, ca. 96% of which were under 100,000 PE (Population Equivalent). Considering the goal of grid-scale P2M technology implementation and its complex infrastructural and input conditions [3], the 28 WWTPs above 100,000 PE could be relevant for this research. Not every WWTP with large PE produces biogas, however (for example, the authors found that only 13 WWTPs have biogas plants from the 19 WWTPs of Hungary's county seats), but there are other WWTPs at non-county seats which also have biogas. In sum, there are around 20 WWTPs with favorable infrastructure that produce biogas in Hungary. In 2016, the calorific value of biogas was 897,066,000 MJ/year on the national level [27].

2.3. Data Collection

The authors analyzed the implementation potential of the innovative and efficient biomethanation technology of Power-to-Gas Hungary Kft. At different sites, technical data was collected from large Hungarian WWTPs, and several interviews were carried out at the level of experts and senior executives, as well. The authors were able to collect data from seven WWTPs from four different regions of Hungary, which is in line with the decentralization trends of the energy sector [28]. As all of the analyzed WWTPs were above 100,000 PE, this research represents the biggest cities of Hungary.

The data collection process contained at least four steps in every case:

(1) Pre-evaluation of the P2M technology relevancy with the Chief Technology Officer or the Technical Director (semi-structured interviews);

(2) In-depth presentation of the technology and exploration of the commercial opportunities with the Chief Executive Officer or the executive team (semi-structured interviews or focus group interviews);

(3) Collection of existing techno-economic data and documentation;

(4) On-site techno-economic data collection and consultation.

Table 1 shows the structure of the data collection. Because of confidentiality, specific financial data were provided only in terms of trends, or highlighting opportunities and challenges.

Table 1. Structure of data collection.

Data	Technical, Technological, Infrastructural	Economic, Commercial, Investment Related
General (Senior executive and director level)	<ul style="list-style-type: none"> Power supply from grid, current or planned PV capacity Water supply CO₂ input: % in the biogas, produced volume per h The geographical area for the P2M plant and its local infrastructural connections (for example to the biogas plant or the WWTP) Connection to the natural gas grid Byproduct use potential (waste heat, oxygen) 	<ul style="list-style-type: none"> Openness for technological innovations and collaborations Financial situation Current biogas use Current or planned infrastructural developments, potential synergies with P2M
Specific (Director and expert level)	<ul style="list-style-type: none"> Fermentation (e.g., temperature) Raw biogas composition (e.g., sulfur) Gas characteristics (e.g., gas flow, pressure) Gas engines (e.g., type, electric and thermal power) Power grid connection (e.g., voltage) Natural gas grid connection (e.g., distance from the plant) Water and wastewater (e.g., treatment technology) Technological and infrastructural connections (e.g., current or possible use of waste heat) Expansion potential (e.g., transport connections, geographical area). 	<ul style="list-style-type: none"> Mobilizable capital for the investment Current contracts defining energy costs Current revenues produced or costs saved on biogas use

Moreover, the authors conducted interviews with technology suppliers, researchers, strategic and financial investors, and other stakeholders in the P2G inter-organizational innovation networks [3] as well, which helped to contextualize the former techno-economic analyses and the new data from WWTPs in Hungary.

2.4. Data Analyses

2.4.1. Applied Model for the Calculation of Seasonal Energy Storage Potential

The seasonal energy storage potential can be calculated on the basis of *HHV* of the total generated injected gas. The parameters of the injected gas mixture must meet the gas requirements set in Hungarian Standards [29] and Annex 13 of Implementing Regulation of Natural Gas Supply [30]. The most significant specifications to meet are

- Wobbe index: 45.66–54.76 MJ/m³
- *HHV*: 31.00–45.28 MJ/m³ (8.61–12.58 kWh/m³)
- Hydrogen sulfide content: max. 20 mg/m³
- Water vapor content: 0.17 g/m³

Since the polished wet gas carbon dioxide concentration exceeds 97%, the higher heating value of the injected gas (*HHV*_{P2G}) is calculated as follows:

$$HHV_{P2G} = 0.97 \cdot HHV_{CH_4} = 0.97 \cdot 36.3 \frac{MJ}{Nm^3} = 35.21 \frac{MJ}{Nm^3} = 9.78 \frac{kWh}{Nm^3} \quad (4)$$

2.4.2. Applied Model for the Economic Analysis

The economic analysis is based on a single “average” WWTP case in the first step and extends the scope to the national level in the second. The authors built their financial calculations largely on the data and the analyses of the EU-funded STORE&GO project. This project was focused on three variations of P2G implementation since 2016, one of them with biological methanation [31].

The background driver of this economic analysis was the National Energy Strategy 2030 of Hungary, which aims towards the rapid growth of electricity generating units from photovoltaic sources (the planned installed capacity will exceed 6000 MW by 2030) [21]. This is indeed a favorable trend for the renewable transition. The literature has also pointed out, though, the challenges of surplus energy generation and the need for energy storage [32]. In this respect, the Hungarian natural gas grid would be appropriate for seasonal energy storage, with its 6,330,000,000 m³ storage capacity [21].

The fundamental assumption of this economic analysis is that during the rapid growth of PV capacities in Hungary, the Hungarian feed-in tariff (FiT) system and its green premium [33], which provides higher electricity prices for renewable energy producers to incite more PV investments, negatively affects the P2M business model and its attractiveness for investors. As P2M technologies are key in energy storage [34], further regulatory changes and incentives are needed to avoid energy loss and network imbalance. There is a clear need for a system in which seasonal energy storage can be incited and realized but without impeding the further growth of PV capacity in the country. Figure 2 illustrates the background and the focus of the economic analysis of the study.

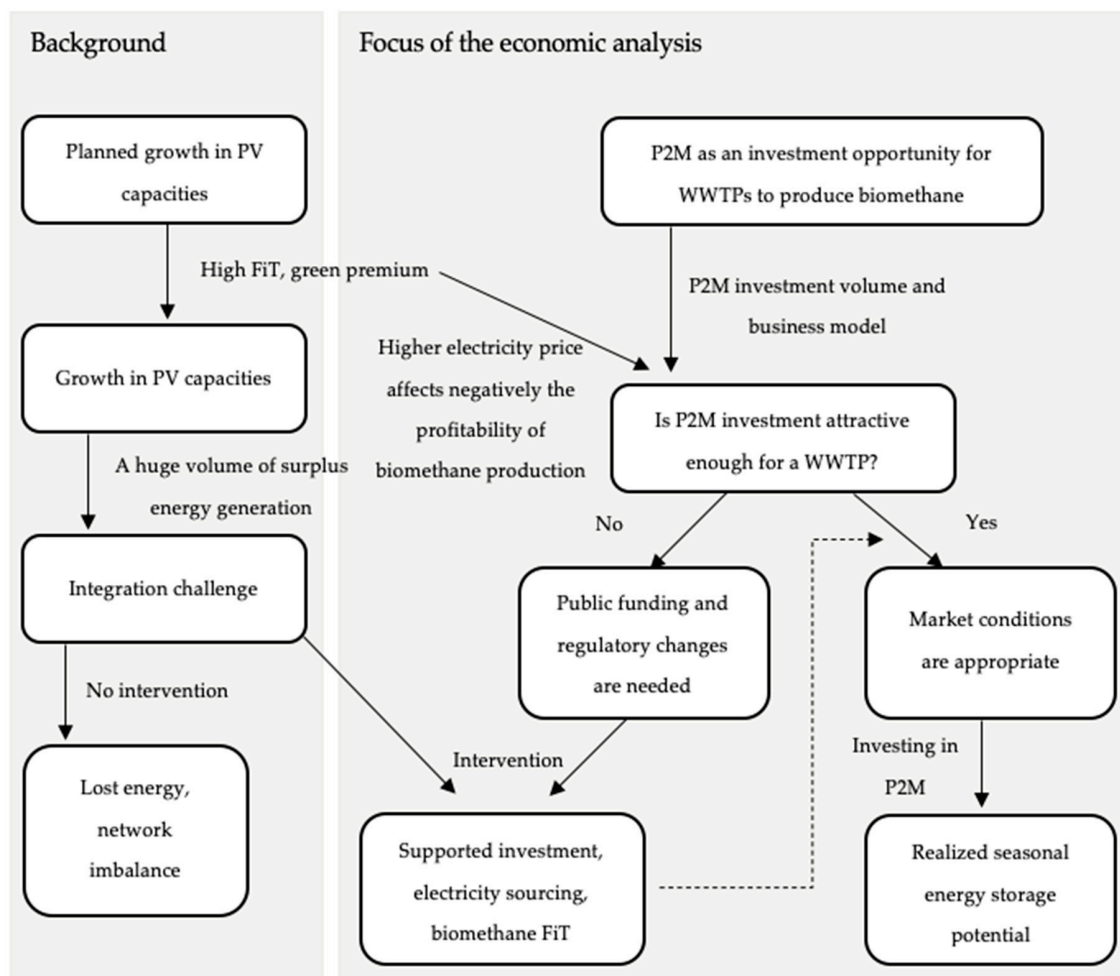


Figure 2. Model of economic analysis.

As previous studies have shown that electricity sourcing is the most determining factor of operating expenditures (OPEX) and the most economic benefit can be realized when the P2X plant is directly connected with PVs or wind turbines [35], one possible way to incite P2M investments could be to provide a framework in which P2G plants can use this surplus energy at well below market price, or if this sourcing were compensated as an acknowledged system service for flexibility or energy storage. This optimization of the price difference between the input (electricity) and the output (biomethane) on the cost side is relevant practically in ca. 1200 h per year [36] with respect to seasonal energy storage. Seasonal energy storage can be supported further on the revenue side, as biomethane FiT has been implemented in a few countries in Europe [37].

On the capital expenditures (CAPEX) side, EU-funded and state-funded projects can foster P2M investment, mostly with dominant research, development and innovation (R&D&I) focus, like in the case of the STORE&GO project [31]. These concepts are not far away from the approach of the National Energy Strategy 2030 of Hungary, because it plans to build a pilot, then a grid-scale P2G plant, a regulatory sandbox model, and a mandatory national purchasing system for biomethane [21].

Based on the technical parameters, the economic and business analysis explores whether current market conditions are attractive for WWTPs to invest in P2M technology or not. If not, the analysis identifies scenarios combining the incentive opportunities of the cost, the revenue, and the investment dimensions to meet the criteria of WWTP executives (identified during the interviews).

2.4.3. Qualitative Data Analysis

As mentioned before, the techno-economic assessment has a complementary commercial/investment viewpoint. Consequently, 21 interviews were conducted with senior executives and directors and analyzed using the coding technique of the grounded theory [38]. The approach of this data analysis method fits the functionalist research, as it provides a structured process (open coding, axial coding, selective coding) to build or fine-tune a theory (a general conclusion) [39] opposed to other (mostly interpretative) qualitative methods (e.g., qualitative content analysis [40]).

(a) To improve the validity, the authors continued the research even after the fourth and fifth cases, even though they did not obtain significantly new information compared to the previous ones (reached theoretical saturation [38]).

(b) To improve the reliability, validation of the pre-conclusions was asked about during the on-site consultations.

(c) To improve the generalizability, the interview questions were modified according to the conclusions of the previous case, testing whether these conclusions were valid in other contexts or not.

3. Results

3.1. Seasonal Energy Storage Potential

In this section, the authors present the theoretical seasonal energy storage potential at large Hungarian WWTPs; then they point out the difference between this theoretical potential and the practical potential, which is calculated based on their empirical data collection.

3.1.1. Storage Potential of an “Average” WWTP Case

As previously described, storage potential is evaluated by taking WWTPs exceeding 100,000 PE into consideration. Based on previous research, the biogas yield of an average sewage anaerobic digestion (AD) facility in Hungary reaches $0.04 \text{ m}^3/\text{day}/\text{PE}$ [41]. The 20 WWTPs which are relevant in this study and exceeding 100,000 PE, have a combined PE value of 5,901,866. Based on the data above, the average size of Hungarian WWTPs that are relevant for P2G technology (C_{P2G}):

$$C_{P2G} = \frac{5,901,866 \text{ PE}}{20} = 295,093 \text{ PE}$$

The average biogas yield of an average WWTP:

$$P_{P2G} = 0.04 \frac{\text{Nm}^3}{\text{day} \cdot \text{PE}} \cdot C_{P2G} = 0.04 \frac{\text{Nm}^3}{\text{day} \cdot \text{PE}} \cdot 295,093 \text{ PE} = 11,804 \frac{\text{Nm}^3}{\text{day}} \quad (5)$$

Presuming the methane ratio of the biogas yield is 0.55, the hourly volumetric carbon dioxide flow of an average WWTP is calculated by the equation below:

$$\dot{V}_{\text{CO}_2} = (1 - 0.55) \cdot \frac{P_{P2G}}{24} = 0.45 \cdot \frac{11,804}{24} = 221.2 \frac{\text{Nm}^3}{\text{h}} \quad (6)$$

The electrolyzer capacity of a P2G facility using biogas of an average WWTP is calculated with the presumption of the 4.7 kWh electrical energy demand for the yield of 1 Nm³ of biomethane is 4.7 kWh/Nm³:

$$P_{P2G} = \dot{V}_{H_2} \cdot 4.7 \frac{\text{kWh}}{\text{Nm}^3} = \dot{V}_{\text{CO}_2} \cdot 4.1 \cdot 4.7 \frac{\text{kWh}}{\text{Nm}^3} = 221.2 \frac{\text{Nm}^3}{\text{h}} \cdot 4.1 \cdot 4.7 \frac{\text{kWh}}{\text{Nm}^3} = 4263 \text{ kW} = 4.26 \text{ MW}_{\text{el}} \quad (7)$$

The other way of calculating P2G capacity for an average WWTP is by using the biogas volumetric flow rates burned in combined heat and power (CHP) units at WWTP sites. Kisari [42] defined regional WWTPs' onsite CHP capacity by analyzing 10 relevant biogas plants using biogas generated from anaerobic degradation of sewage slurry. In accordance with his research, the average built-in CHP capacity was 730 kW_{el} (P_{CHP}). Sinoros [43] calculated the theoretical P2G potential with the focus on available regional bioethanol and biogas yield in Hungary. That research carried out conclusions on total biogas annual yield and considered no difference in the sources, particularly on WWTP biogas streams.

The calculation of P2G plant capacity on the basis of built-in CHP capacity of WWTPs:

$$P'_{P2G} = (\dot{V}_{\text{CO}_2}) \cdot 4.1 \cdot 4.7 \frac{\text{kWh}}{\text{Nm}^3} = \left(\frac{P_{\text{CHP}} \cdot (1-0.55)}{\frac{\eta_{\text{CHP}}}{100} \cdot \left(\frac{100-r_s}{100}\right) \cdot \text{HHV}_{\text{CH}_4}} \right) \cdot 4.1 \cdot 4.7 \frac{\text{kWh}}{\text{Nm}^3} = , \text{ where} \quad (8)$$

r_s-AD plant electric self-consumption percentage—15%

η_{CHP}-CHP electric efficiency—35%

HHV_{CH₄}-Higher heating value of methane—10.3 kWh/Nm³

After executing the substitution, the calculated capacity is:

$$P'_{P2G} = \left(\frac{730 \text{ kW} \cdot (1 - 0.55)}{\frac{35}{100} \cdot \left(\frac{100-15}{100}\right) \cdot 10.3} \right) \cdot 4.1 \cdot 4.7 \frac{\text{kWh}}{\text{Nm}^3} = 107.2 \frac{\text{Nm}^3}{\text{h}} \cdot 4.1 \cdot 4.7 \frac{\text{kWh}}{\text{Nm}^3} = 2065 \text{ kW}_{\text{el}} = 2065 \text{ MW}_{\text{el}} \quad (9)$$

Although P_{P2G} is more than two times higher than P'_{P2G}, due to the constraints of site conditions the authors justified P2G potential at a lower value than P'_{P2G}. In accordance with the information collected onsite and all the datasets provided by WWTP site managers, a P2G plant with 1 MW_{el} electrolyzer capacity could be fit to the WWTPs with the load exceeding 100,000 PE in general, because

(1) the methane content is usually higher (around 60–65%) than expected based on the literature, which is beneficial for biogas production but not for P2M, because there is less CO₂ (around 35–40%) to convert to biomethane;

(2) the raw biogas flow is around 130 Nm³/h on average at the empirically examined WWTPs, which slightly exceed 100,000 PE, but there are 9 WWTPs that are above even 250,000 PE (obviously they are still within the necessary scope for P2M deployment);

(3) there is some seasonality in the case of several WWTPs (e.g., at Lake Balaton) that affects biogas production, but the higher values are typically in the summer, which fits the seasonal energy storage concept.

3.1.2. Energy Storage Potential

According to Section 2.4.1, total seasonal energy storage potential can be calculated on the basis of the higher heating value of the injected gas. Based on the stoichiometry, the values of E and E' are calculated as follows:

$$E = \dot{V}_{CO_2} \cdot 9.78 \frac{\text{kWh}}{\text{Nm}^3} \cdot t_{OP} = 221.2 \frac{\text{Nm}^3}{\text{h}} \cdot 9.78 \frac{\text{kWh}}{\text{Nm}^3} \cdot 1200 \frac{\text{h}}{\text{year}} = 2,596,004 \text{ kWh} \approx 2596 \text{ MWh} \quad (10)$$

$$E' = \dot{V}'_{CO_2} \cdot 9.78 \frac{\text{kWh}}{\text{Nm}^3} \cdot t_{OP} = 107.2 \frac{\text{Nm}^3}{\text{h}} \cdot 9.78 \frac{\text{kWh}}{\text{Nm}^3} \cdot 1200 \frac{\text{h}}{\text{year}} = 1,258,099 \text{ kWh} \approx 1258 \text{ MWh} \quad (11)$$

Total theoretical seasonal energy storage potential of 20 WWTPs exceeding 100,000 PE is

$$E_{\text{total}} = E \cdot 20 = 2596 \text{ MWh} \cdot 20 = 51,920 \text{ MWh} \approx 51.9 \text{ GWh} \quad (12)$$

$$E'_{\text{total}} = E' \cdot 20 = 1258 \text{ MWh} \cdot 20 = 25,160 \text{ MWh} \approx 25.2 \text{ GWh} \quad (13)$$

Considering all the information collected in site visits, the practical seasonal energy storage potential of an average WWTP is

$$E_p = \dot{V}_{pCO_2} \cdot 9.78 \frac{\text{kWh}}{\text{Nm}^3} \cdot t_{OP} = 50 \frac{\text{Nm}^3}{\text{h}} \cdot 9.78 \frac{\text{kWh}}{\text{Nm}^3} \cdot 1200 \frac{\text{h}}{\text{year}} = 586,800 \text{ kWh} \approx 587 \text{ MWh} \quad (14)$$

Total practical seasonal energy storage potential of 20 WWTPs exceeding 100,000 PE is

$$E_{\text{ptotal}} = 20 \cdot E_p = 20 \cdot 587 \text{ MWh} = 11,740 \text{ MWh} \approx 11.7 \text{ GWh} \quad (15)$$

3.2. Commercial and Investment Perspectives

3.2.1. Investment Volume, Operating Expenses, and Revenues

An important statement of the financial analyses of the STORE&GO project is that a high range of possible investment costs of electrolyzers and methanation systems can be seen in the literature [44]. The economies of scale are a determining factor of CAPEX [44]. The investment costs in this study are based on the calculations of van Leeuwen and Zauner [45] with minor modifications according to the technical infrastructure of the analyzed WWTPs and additional costs of a public-funded technology development projects. Interviewees also pointed out that one must take into account the costs of public grant/public financing-specific R&D and maintenance tasks, and furthermore, the needed software background supporting the P2M technology operations (not only the hardware and the physical infrastructure). Appendix A shows the basis of the CAPEX calculations.

(1) The specific investment cost of the PEM electrolyzer system is 1640 EUR/kW, which is the base case according to van Leeuwen and Zauner.

(2) In the case of the methanation system, a slightly higher CAPEX than the base case, 0.5 EUR/kW_{el} is taken into account because of some high specific investment costs for biomethanation presented by Böhm et al. [44].

(3) There is an integrated “infrastructure” cost item, as well, because different kinds of infrastructure development are needed at the analyzed WWTPs (e.g., there is gas storage at a few WWTPs, or the new infrastructure for the use of the oxygen as a byproduct can be also relevant in this cost item).

(4) An additional 28% investment is needed for project development, planning, expert services, quality management, according to van Leeuwen and Zauner, and an additional 50% for public grant/public financing-specific R&D, software development, and maintenance tasks.

Based on the above, the CAPEX of a 1 MW_{el} P2M plant at an “average” WWTP is 5,696,000 EUR if the investment would be realized this year.

The deployment of even one P2M plant, however, could require even more than a year-long project planning, and 20 P2M plants cannot be deployed in one year. Consequently, the time horizon must be extended for the investment. Previous P2G research has shown that there is a significant cost reduction potential regarding investment costs because of experience curves and learning rates. Böhm et al. [44] calculated that PEMEC CAPEX will decrease from 1200 EUR/kW_{el} (2017) to 530 EUR/kW_{el} (2030), and biological methanation CAPEX will decrease from 600 EUR/kW_{SNG} (2017) to 360 EUR/kW_{SNG}. This means that CAPEX of these components will decrease by 55% and 45% in 13 years. As the authors in this research assume that P2M plants in question will be deployed between 2020 and 2030, in parallel with the planned growth of PV capacities in Hungary, some CAPEX reduction is needed based on the quoted estimation. Assuming even distribution of P2M deployment for the next 10 years, the year 2025 can be taken as the basis of the calculation, so the 1 MW_{el} P2M CAPEX for 2025 with PEMEC CAPEX can be decreased by 25% and the CAPEX of biomethanation system can be decreased by 20%. Consequently, the model calculates on the basis of the reduced, 4,806,000 EUR CAPEX.

In the economic analysis, this CAPEX was considered as a fixed component, while operating expenses and revenues were influenced by the costs of electricity sourcing (power grid fees) or its compensation, and biomethane price was considered as a variable contingent on potential regulatory changes. Appendix B shows the assumptions of the OPEX and revenue calculations. It is worth mention that besides biomethane, waste-heat could generate an important revenue stream at 55 EUR/MWh [46]; however, this low-temperature heat source from electrolysis and methanation (ca. 60–75 °C), which is usually challenging to use with high efficiency [47], could be used to an extent of only 50% in the summer (when P2M operates focusing on energy storage) based on the infrastructure and the expert interviews regarding WWTPs.

3.2.2. Commercial Challenges

Based on the financial analysis results, it can be seen that a 1 MW_{el} P2M plant could operate with minor profitability with an operation time of 1200 h/year at a WWTP, even if it did not pay for the electricity (or it were compensated), and only for system usage. For example, this means only ca. 73,000 EUR profit/year at a biomethane price of 150 EUR/MWh, which is the highest in Europe according to Koonaphapdeelert et al. [37]. Consequently, as the interviews outlined, this business model was not attractive enough for WWTP executives, if they would have to finance the investment costs. According to them, a 7–15 year-long payback period would be favorable. However, even if it were possible, the specific financing questions outlined that WWTPs do not have the financial resources to realize such an investment. For example, the 4,806,000 EUR CAPEX is rather high for a WWTP, if its annual revenue is around 20,000,000 EUR (illustrative data). Moreover, some large rural WWTPs operated unprofitably in previous years, some operated with almost zero balance, and even the profitable ones, which could generate over 500,000 EUR per year, argued that this profit must be handled as retained earnings for unexpected maintenance tasks, not for R&D&I investments.

Even though increasing the number of operating hours could enhance profitability at first glance, other problems would arise:

(1) If a P2M plant—as van Leeuwen and Zauner suggested [45]—were to source electricity from the day-ahead market without any discounts or compensation, one could see that the growing electricity prices in Hungary in recent years do not enhance profitability (the Hungarian Power Exchange Day-Ahead Market Base Average Price was 40 EUR/MWh in 2015 and 5036 EUR/MWh in 2019) [48].

(2) There is some uncertainty as to whether the “bio” prefix, and therefore the premium price, is applicable in the market (outside a national mandatory system) for the output methane gas if only one

input factor comes from renewable sources. There is no consensus in the literature, or in the industry, regarding this question. For example, biomethane is often described as a biogas, the CO₂ content of which is mostly eliminated or separated [49], while green gases are also characterized as a renewable gas [50] that is virtually carbon-neutral [51], made from biomass or with P2G technology [52], but only preferably (and not always) from renewable electricity sources [50]. In one STORE&GO study, “a green gas is defined as a gaseous energy carrier offered to the market without a serious GHG footprint” ([53], p. 12). Even though Jempa et al. [53] pointed out that not only renewable but the nuclear energy can be considered to be carbon-neutral, the concrete business opportunities of such a product gas remain uncertain, mainly because of the currently underdeveloped certificate markets [54] and the missing harmonized and detailed rules on guarantees of origin at the EU level [55].

In sum, neither the characteristics of the seasonal energy storage-focused business model, nor their financial opportunities allow WWTPs to commit to P2M deployment.

3.2.3. Scenarios to Incite WWTPs to Participate in Seasonal Energy Storage

Based on the above, the authors generated scenarios with specific variables including not only electricity sourcing and biomethane price, but public funding for the investment. The goal was to identify the conditions under which the P2M investment could be considered attractive (7–15-year-long payback period) for seasonal energy storage at WWTPs. Specific variables are presented in Table 2. The variables for electricity sourcing are based on the formerly introduced assumption that Transmission System Operators (TSOs) will be forced to avoid energy loss and network imbalance with a framework in which P2M plants can use surplus energy at a favorable or compensated price. The lowest biomethane FiT was generated as a more or less competitive price compared to natural gas, while the highest was based on the highest European FiT (Italy) [37]. The percentage of the public funding of CAPEX was adjusted to the established institutional routines at similar development projects.

Table 2. Specific variables for financially attractive scenario generation for WWTPs.

Financial Factors	Variable 1	Variable 2	Variable 3
Electricity sourcing costs (ESC)	Partly disregarded or compensated: P2M plants do not have to pay for the energy or it is compensated with flexibility/energy storage fees but has to pay the grid power fees for system usage.	Fully disregarded or compensated: P2M plants do not have to pay for the energy, nor for system usage or these are compensated with flexibility/energy storage fees.	
Biomethane FiT (EUR/MWh)	50	100	150
CAPEX support (% of public funding)	50	70	90

Configurations in which the payback period was 7 years and 15 years were explored based on the variable biomethane price. Figure 3 shows that a 7-year-long payback period with 1200 operating hours could be achievable with a reasonable biomethane price (based on international benchmarks [37]) if there were 90% public funding, and even electricity sourcing costs (ESC) were not only partly but fully (including system usage fees) disregarded or compensated (e.g., there was a fee for providing flexibility services or energy storage).

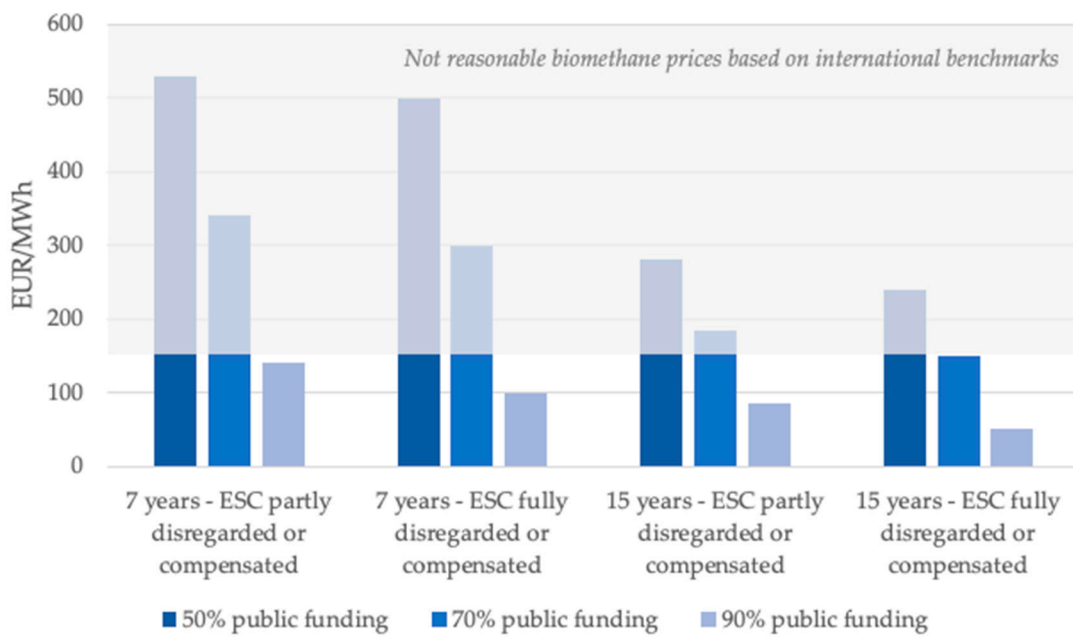


Figure 3. Biomethane prices for 7- and 15-year-long payback periods of a 1 MW_{el} P2M plant focusing only on seasonal energy storage with 1200 operating h/year.

Figure 4 shows that almost 100% public funding is needed to meet the 7-year-long criterion if there is a low biomethane price of 50 EUR/MWh. The lowest public funding percentage is 69% at a biomethane price of 150 EUR/MWh, with fully disregarded or compensated ESC, resulting in a 15-year-long payback period.

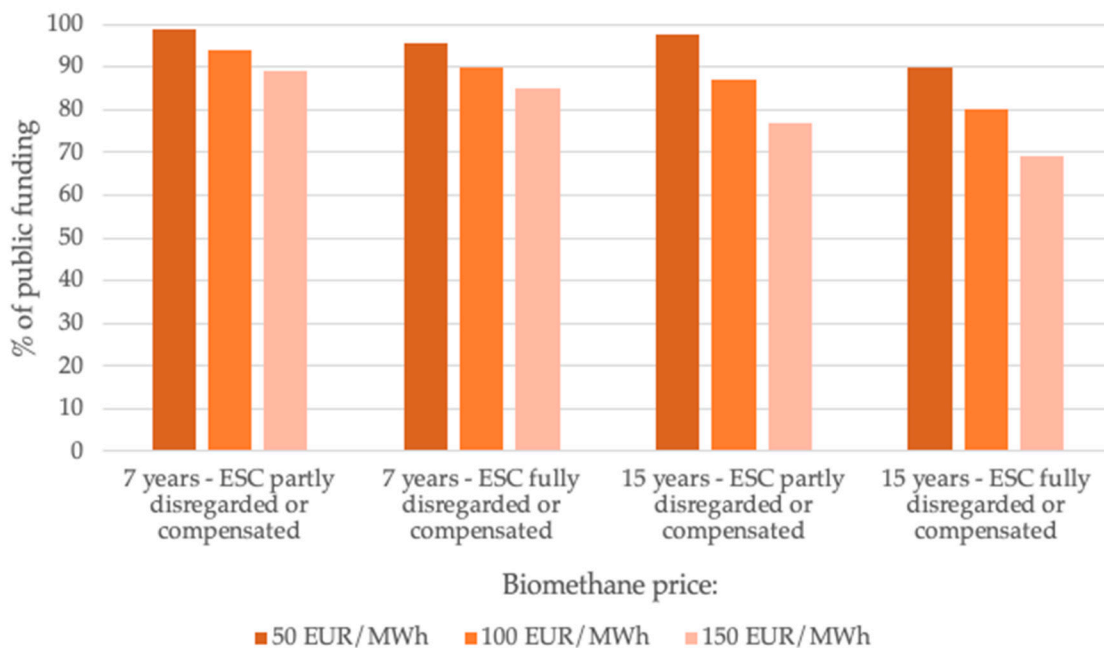


Figure 4. Percentages for public funding of CAPEX for 7- and 15-year-long payback period of a 1 MW_{el} P2M plant focusing only on seasonal energy storage with 1200 operating h/year.

As the executive interviews outlined that Hungarian WWTPs do not have financial resources for a P2M investment, and core activities of WWTPs require stability, prudent risk-management, and efficient operation, they cannot take the innovation-related up-scaling risks and the uncertainties of the business

model (currently as potential “first movers” in Hungary) under the current market and regulatory environment. Consequently, public funding is needed to incite WWTPs towards P2M deployment.

For seasonal energy storage with biomethane production, which could be considered an economically beneficial activity in a country that imports ca. 80% of its natural gas [21], dominant public funding for P2M deployment could be justified. Based on the calculations above, the public funding of the CAPEX for $20 \times 1 \text{ MW}_{\text{el}}$ P2M plant would require 66,000,000–93,000,000 EUR, depending on the biomethane FiT, and a framework is also needed within the costs of surplus electricity consumption are minimized or compensated on the revenue side.

4. Discussion

This study focused on techno-economic assessment of the P2M technology deployment in Hungary with a complementary business viewpoint to highlight the concrete opportunities and limitations of seasonal energy storage at WWTPs with biological methanation. The research aimed to answer the following two questions:

- (1) What is the total seasonal energy storage potential with P2M at large WWTPs in Hungary?
- (2) What are the economic conditions under which WWTPs are financially incited to start the grid-scale implementation of the biological methanation?

Regarding the first research question, the empirical research pointed out that the practical potential of a P2M plant (1 MW_{el}) is half of the theoretical potential because of higher methane content and smaller gas flow than expected based on official data and previous research. The 1 MW_{el} P2M size, however, meets the current state of the technology, demonstrated by Electrochaea in Avedøre, Denmark, where the largest P2G plant with biological methanation has been built. As there are around 20 relevant WWTPs exceeding 100,000 PE with biogas production, the total P2M potential at them is around $20 \text{ MW}_{\text{el}}$, meaning 11.7 GWh seasonal energy storage potential on national level. It could be argued that this volume could be considered part of the decentralized seasonal energy storage system of the country, as the research was focusing on the WWTPs of larger rural cities of Hungary. Considering this potential in a broader context, the national energy strategy plans to reduce the overall natural gas consumption to $8,700,000,000 \text{ m}^3$ (ca. 2550 GWh) to 2030 [21]. With $20 \text{ MW}_{\text{el}}$ P2M deployments for seasonal energy storage at WWTPs, the 11.7 GWh stored energy could mean ca. 0.5% of the reduced natural gas consumption and equal to the annual energy consumption of ca. 5400 households currently (as the average consumption was 2168 kWh/year/household in 2019 [56]) Though it is not much, at first sight, savings on natural gas import and additional positive externalities (higher integration of renewables, carbon reuse, sector coupling, prevented electricity network imbalances, and related maintenance costs) must be also taken into account. Further research could extend the scope of the financial analyses for these externalities as well.

Regarding the second research question, this energy storage potential can be realized if WWTPs are incited by public funding for P2M deployment and operation, because the current market and regulatory conditions do not meet the criteria of WWTPs for the payback period, and the WWTPs do not have financial resources either to realize a P2M deployment, or to take risks with the still uncertain grid-scale operation and business environment of P2M. This operational uncertainty is derived mainly from the skepticism of WWTP executives, as they have not seen such a plant operating anywhere before, especially not in Hungary. As the National Energy Strategy 2030 plans to support a pilot P2G plant within a few years [21], hopefully, this problem will be solved.

Based on the financial calculations of an “average” WWTP case, the planned mandatory national purchasing system for biomethane by the national energy strategy and the public funding of CAPEX seem not to be enough to incite WWTPs to participate in seasonal energy storage. In other words, while P2M energy storage fits the technological infrastructure of WWTPs, it does not meet their business opportunities and requirements. Currently high and growing electricity prices, through which further PV capacity investment is incited, fundamentally limits the viability of the P2M business

model if there are no discounts on the cost side for the consumption of surplus energy or new revenue streams (e.g., aFRR supporting P2G) through which electricity sourcing costs can be compensated.

Nevertheless, one could argue that growing PV capacities (as supply) will suppress electricity market prices, as negative electricity prices have been seen in other European countries (e.g., in Germany) [57]. This could be true in a perfect (in practice: never existing) market and in the long-term, but Hungary's electricity generation from PVs is still low (for example, the annual volume of electricity produced from solar photovoltaic was only 0.02% compared to Germany's production in 2019 [58]). In the short term, with former state intervention to incite PV investment by a FiT system, there is a need for intervention regarding energy storage as well.

Obviously, there is a trade-off between support mechanisms, for example, a larger percentage of public funding of CAPEX can be combined with a lower FiT for biomethane. Based on the generated scenarios and missing financial resources of the WWTPs, there is a clear need for public funding of over 90%. Considering a reasonable FiT for biomethane, other European prices could be referred to in order to contextualize this question: 1.03 EUR/Nm³ in The Netherlands, 129.7 EUR/MWh in France, 70 EUR/MWh in the UK, 150 EUR/MWh in Italy [37]. Based on these prices, around 75 million EUR CAPEX support and 100 EUR/MWh FiT seem to be the preconditions for realizing the energy storage potential at WWTPs if surplus electricity sourcing costs were also minimized or compensated within a new framework.

The presented results show a significant contribution to the latest literature, as well. For example, while Guerra et al. [59] filled the research gap of the overlooked potential grid benefits of seasonal storage (the literature mainly focused on costs, previously) with their new model for pumped hydro, compressed air, and hydrogen seasonal storage and showed that “for more than 2 days of discharge duration, the only cost-effective technology is hydrogen” [p. 23], this paper emphasized the promising role of methane-based seasonal energy storage if a connection to the natural gas grid is given. Moreover, this research extended the scope of the analysis even more by integrating the motivation and strategic interests of future seasonal energy storage operators and building the financial model on the empirical data of individual sites. Other findings of this paper are in line with the conclusions of latest studies related to global carbon mitigation initiatives [60]. To mitigate environmental damage, Doğan et al. [61] suggest that “OECD governments should directly invest in technological innovation to enhance sustainable economic growth” [p. 9] and Shahzad et al. [62] conclude that “the policymakers of the United States should adopt policies to encourage investors to invest in cleaner energy infrastructure and advanced technologies” [p. 12]. These statements are in line with the conclusion that public funding for P2M seasonal energy storage is essential not only because of the missing capital of WWTPs, but for decreasing GHG emissions, as well. According to Doğan et al., these technological innovations include, however, much more than energy technologies: artificial intelligence and ICT developments could also be mentioned here. These technologies could indicate further possible development projects that would affect the overall WWTP efficiency, and thus, the P2M CAPEX or OPEX in the long term. For example, industrial big data analytics and machine learning [63], which could forecast weather conditions for renewable energy generation (and storage) [64], could become a key success factor (or following Osterwalder and Pigneur's terminology [65], a key resource) in the business model for cost-efficient operation. Furthermore, combining this with the trend towards smart energy systems [32] and technology-driven shared economy [66] could subsequently redefine the role of WWTPs within the rising smart energy communities [67]. These future directions could generate further R&D&I projects which could be also valid for public funding.

5. Conclusions

The hypothesis of this study was the following:

Economic, commercial and investment aspects of P2M seasonal energy storage do not motivate WWTPs to act as future P2M operators, consequently, there is a need for change in the regulatory environment to incite them to realize their seasonal energy storage potential with P2M deployment.

The hypothesis can be accepted, as the results showed that the main criterion of WWTPs for P2M technology investment was the 7–15-year-long payback period. This cannot be achieved in the current market and regulatory environment; possible regulatory changes could affect, however, some of their key motivating factors. To address WWTP stakeholders' expectations, a total of ca. 75 million EUR public funding of CAPEX and 100 EUR/MWh biomethane feed-in tariff is needed to realize their energy storage potential in Hungary if surplus electricity sourcing costs are also minimized or compensated under a new national regulatory framework. The research hypothesis indirectly also suggested that technical aspects would not be hampering factors of P2M technology deployment at large Hungarian WWTPs, which was also proven in this study. The findings show that a standardized 1 MW_{el} P2M technology would fit with most potential sites, and this is in line with the current technology readiness level of P2M.

This study opened new perspectives on techno-economic assessments of P2M technology by integrating not only techno-economic, but also complementary commercial/investment attractiveness of seasonal energy storage at large WWTPs, as well. Due to this approach, the authors could reveal three lessons using Hungary as a case study. First, regarding other economies at similar levels, it is important to highlight that former state interventions inciting new renewable energy generation investments induce a need for intervention on the energy storage side, as well, to avoid loss of surplus energy generation and network imbalance. Second, the research highlighted the 7–15-year-long payback period expectations of future P2M technology operators. Without fulfilling their commercial and investment motivations, any seasonal energy storage initiative will fail. Third, it was shown for the first time (by concrete numbers and proportions) that a three-element regulatory configuration (public funding, FiT, ESC) could have an impact on the attractiveness of P2M seasonal energy storage for WWTPs.

Even though WWTPs could be key for sector coupling and seasonal energy storage, this is only one possible segment of P2M deployment. For example, agricultural biogas plants are also promising because of their on-site CO₂, where the impacts of recent advances in nutrient management to accelerate biogas production [68] could be researched with the P2M process, as well. Further development of carbon capture technologies will bring more flexibility for locating P2M plants. Furthermore, even the lack of a nearby natural gas grid could be bypassed with liquid methane (LNG) and re-gasification [69]. Consequently, examining other or all of the possible P2M deployment segments could be the scope of further research to support policymakers with a more comprehensive analysis.

There are possibilities for further research regarding the method of economic analysis, as well. For example, with respect to a single WWTP or another future P2M technology operator, a complex valuation of the business is needed, by analyzing the business opportunity of the public-funded R&D&I project phase with a limited lifespan [70] and the phase after the mandatory maintenance period of the project with operations on own financial risks. Besides the new tangible assets and perhaps a more favorable market environment, evaluating the acquired intangible assets during an R&D&I project (which could generate premium revenues [71]) could also be a determining factor on whether a WWTP would integrate P2M and seasonal energy storage into their core activities. In line with Machová and Vochozka [72], artificial neural networks could be used not only for the analysis of business companies, but business opportunities to handle these technical, market, and asset valuation complexities of the P2M business case, as well. If site-specific technological complexities would arise because of parallel development projects (e.g., P2M deployment, a capacity increase of a biogas plant, new infrastructure to use oxygen by-product), simulation software like ASPEN PLUS [73] could be applied.

As a concluding remark, the authors hope that their WWTP-focused, in-depth analysis was able to illustrate that there are important commercial and investment viewpoints of future P2M technology operators which should be taken into account to make a step forward with seasonal energy storage towards a more carbon-neutral energy sector.

Author Contributions: Conceptualization, Z.C.; Data collection: Z.C., B.S.-S., M.Z.; Technical analyses: B.S.-S.; Economic analyses: M.Z.; writing: Z.C., B.S.-S., M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank Hiventures Zrt./State Fund for Research and Development and Innovation for their investment that enabled this research.

Conflicts of Interest: The authors perform their P2G research at Corvinus University of Budapest, and they have founded the innovative startup company Power-to-Gas Hungary Kft. in order to perform industrial R&D and further develop the technology in pre-commercial and commercial environments.

Appendix A

Table A1. Base case for CAPEX calculation at a single WWTP.

Category	Item	Thousand EUR	Unit	Source
Components, physical infrastructure	Electrolyzer system (PEM)	1.6	/kW _{el}	STORE&GO: D8.3. p. 14, 25, 34, 35 D7.5. p. 48
	Methanation system (biological)	0.5	/kW _{el}	
	Infrastructure, installation, storage for gas puffer (H ₂ , CO ₂), injection	1.1	/kW _{el}	
Other	Project development, planning, expert services, quality management	+28%	on costs of total components	Own estimation based on interviews
	Tender-specific R&D, software and maintenance tasks	+50%		

Appendix B

Table A2. Base case for operative expenses and revenues at a single WWTP.

Category	Item	EUR	Unit	Source
Input materials-unit prices	Electricity price	None	-	Disregard based on the fundamental assumption of the study
	Water	0.6	/kW _{el}	Hungarian waterworks
	Power grid fees/System usage	Variables: None or 1,1	/kW _{el}	Based on Hungarian Energy and Public Utility Regulatory Authority [74]
Operation and maintenance costs	Electrolysis system	4.0%	% of CAPEX at 8000 operating hours	Own estimation based on STORE&GO D8.3. p. 35
	Methanation system	5.0%		
	Infrastructure, installation, storage for gas puffer (H ₂ , CO ₂), injection	3.5%		
Revenues	Biomethane	Variables: 50–150	/MWh	Based on Koonaphapdeelert, et al. [37]
	Waste heat	55	/MWh	STORE&GO D7.7 p. 65
	CO ₂ quota	25	/tons	[75]
	Oxygen	0.07	/Nm ³	STORE&GO D7.7 p. 65
Operation data	Operating hours	1200	/year	-
	Directly connected PV capacity	0%	-	Based on WWTP interviews
	Sold/injected biomethane	100%	/total produced	
	Used or sold waste-heat	50%	/total produced	
	Used or sold oxygen	50%	/total produced	

Abbreviations

AD	Anaerobic digestion
AFFR	Automatic frequency restoration reserve
CAPEX	Capital expenditures
CGEN	Combined Gas and Electricity Networks
CHP unit	Combined heat and power unit
EMG-BES	Bioelectrochemical system for electromethanogenesis
ESC	Electricity sourcing costs
FiT	Feed-in tariff
GHG	Greenhouse gas
HHV	Higher heating value
LNG	Liquefied natural gas
OPEX	Operating expenditures
P2G	Power-to-gas
P2H	Power-to-hydrogen
PM	Power-to-methane
PE	Population Equivalent
PEMEC	Polymer electrolyte membranes electrolysis
PV	Photovoltaics
R&D&I	Research, development, and innovation
SNG	Synthetic Natural Gas
TSO	Transmission System Operator
WWTP	Wastewater treatment plant

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