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Power-to-Transport (P2T)

Energy storage for sustainable regional development: Optimised integration of renewables in smart transport systems



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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Summary

This transnational project intends to define the best option to defossilize a bus fleet by using solar irradiation and biogenic waste as primary energy sources. Specific methods and models have been developed to perform techno-economic evaluations of the solutions, as well as an assessment of greenhouse gas emissions. Although in the framework of this project these methods are applied to a specific case study, they are flexible, generic and could be applied to any geographic location.

To defossilize the bus fleet, two scenarios are suggested and evaluated in the project: increase the number of electric vehicles and increase the amount of carbon-neutral methane used in the gas-fuelled buses. To implement these scenarios, additional units are required in completion to the existing infrastructures. Region Uppsala recently installed a PV plant on the roof of the bus depot, but to cope with the intermittence and seasonality of solar irradiation, part of the case study focuses on defining an optimal storage and operation strategy. Concurrently, more than half of the biomethane used by the bus fleet is produced at the facilities of Uppsala Vatten, a waste-management company that produces raw biogas while treating wastewater and digesting organic waste. The project investigates how the CO₂ emitted into the air by the process could be combined with hydrogen to produce renewable methane (power-to-gas).

With these goals in mind, different modelling tools have been developed. To forecast the grid electricity prices, estimate its emission factors, and optimize the design and operation of a power-to-X plant. The results of the study show that the defossilisation of the bus fleet is technically feasible, however, the economic feasibility is a challenge. It is indeed currently still difficult for renewable gas (hydrogen, renewable methane or biogas) to compete with fossil fuels, especially with highly volatile electricity prices. In addition, politic uncertainties such as the possible ban of all internal combustion engines in the EU makes it difficult for stakeholders to invest in the long-term future.



Zusammenfassung

In diesem transnationalen Projekt soll die beste Option für die Defossilisierung einer Busflotte durch die Nutzung von Sonneneinstrahlung und biogenen Abfällen als Primärenergiequellen ermittelt werden. Es wurden spezifische Methoden und Modelle entwickelt, um eine techno-ökonomische Bewertung der Optionen sowie eine Bewertung der Treibhausgasemissionen durchzuführen. Obwohl diese Methoden im Rahmen dieses Projekts auf eine spezifische Fallstudie angewandt werden, sind sie flexibel und allgemein und könnten auf jeden geografischen Standort angewendet werden.

Um die Busflotte zu defossilisieren werden zwei Szenarien vorgeschlagen: Erhöhung der Anzahl der Elektrofahrzeuge und Erhöhung der Menge an kohlenstoffneutralem Methan, das in den gasbetriebenen Bussen verwendet wird. Um diese Szenarien umzusetzen sind zusätzliche Geräte zur Ergänzung der bestehenden Infrastrukturen erforderlich. Die Region Uppsala hat vor kurzem eine PV-Anlage auf dem Dach des Busdepots installiert, aber um die Schwankungen der Sonneneinstrahlung zu bewältigen, konzentriert sich ein Teil der Fallstudie auf die Festlegung einer optimalen Speicher- und Betriebsstrategie. Gleichzeitig wird mehr als die Hälfte des von der Busflotte verbrauchten Biomethans in den Anlagen von Uppsala Vatten produziert, einem Abfallentsorgungsunternehmen, das bei der Aufbereitung von Abwässern und der Vergärung organischer Abfälle Rohbiogas erzeugt. Das Projekt untersucht, wie das in die Luft abgegebene CO₂ mit Wasserstoff kombiniert werden könnte, um erneuerbares Methan zu erzeugen (Power-to-Gas).

Um die Ziele des Projekts zu erreichen, wurden verschiedene Modellierungsinstrumente entwickelt: Zur Schätzung der Netzstrompreise sowie seiner Emissionsfaktoren und für die optimale Auslegung und den Betrieb einer Power-to-X-Anlage. Die Ergebnisse zeigen, dass die Defossilisierung der Busflotte technisch machbar ist, die wirtschaftliche Machbarkeit jedoch eine Herausforderung darstellt. Tatsächlich ist es für erneuerbare Gase (Wasserstoff, erneuerbares Methan oder Biogas) noch schwierig, mit fossilen Brennstoffen wettbewerbsfähig zu sein, insbesondere aufgrund der stark schwankenden Strompreise. Darüber hinaus erschweren politische Unsicherheiten wie das mögliche Verbot aller Verbrennungsmotoren in der EU eine langfristige Verpflichtung für die Wirtschaftsakteure.



Résumé

Ce projet transnational vise à définir la meilleure option pour défossiliser une flotte de bus en utilisant les ressources primaires disponibles comme l'irradiation solaire et les déchets verts. Des méthodes et des modèles spécifiques ont été développés pour réaliser des évaluations techno-économiques ainsi qu'une évaluation de l'impact sur le climat. Bien que dans le cadre de ce projet, ces outils soient appliqués à un cas spécifique, ils sont flexibles, généraux et pourraient être appliqués à n'importe quelle localisation géographique.

Pour défossiliser la flotte de bus, deux scénarios sont proposés : augmenter le nombre de véhicules électriques et accroître la quantité de méthane neutre en carbone utilisé dans les bus fonctionnant au gaz. Pour mettre en œuvre ces scénarios, des équipements supplémentaires sont nécessaires pour compléter les infrastructures existantes. La région d'Uppsala a récemment installé une centrale photovoltaïque sur le toit du dépôt de bus, mais pour faire face à l'intermittence et au caractère saisonnier du photovoltaïque, une partie de l'étude de cas se concentre sur la définition d'une stratégie optimale de stockage et d'exploitation. Parallèlement, plus de la moitié du biométhane utilisé par la flotte de bus est produit dans les installations d'Uppsala Vatten, une entreprise de gestion des déchets qui produit du biogaz brut en traitant les eaux usées et en digérant les déchets organiques. Le projet étudie comment le CO₂ rejeté dans l'air pourrait être combiné à de l'hydrogène pour produire du méthane renouvelable (power-to-gas).

Pour atteindre les objectifs du projet, différents outils de modélisation ont été développés. Pour estimer les prix de l'électricité du réseau ainsi que ses facteurs d'émission, et pour la conception et l'exploitation optimales d'une centrale power-to-X. Les résultats montrent une bonne faisabilité technique des différentes mesures à prendre pour parvenir à une défossilisation complète de la flotte de bus, mais une faisabilité économique qui représente un défi. En effet, il est encore difficile pour les gaz renouvelables (hydrogène, méthane renouvelable ou biogaz) de concurrencer les combustibles fossiles, notamment en raison de prix de l'électricité très volatiles. En outre, les incertitudes politiques telles que la possible interdiction de tous les moteurs à combustion dans l'UE rendent un engagement à long terme difficile pour les acteurs économiques.



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List of abbreviations

ADP	Anaerobic digestion plant
AEF	Average emission factor
CAPEX	Investment costs
CBG	Compressed biogas (biomethane)
CNG	Compressed natural gas
FLH	Full load hours
HEV	Hydrogen electric vehicles
HHV	Higher heating value
HVO	Hydrogenated vegetable oils (fuel)
KPI	Key performance indicator
LBG	Liquified biogas (biomethane)
LCOH	Levelized cost of hydrogen
LNG	Liquified natural gas
MAPE	Mean absolute percent error
MEF	Marginal emission factor
NPV	Net present Value
OPEX	Operational costs
P2T	Power-to-transport
PtX	Power-to-X
PtG	Power-to-Gas
PV	Photovoltaics
SFOE	Swiss Federal Office of Energy
SNG	Synthetic natural gas. The product of power-to-Gas
WP	Work package
WWTP	Wastewater treatment plant



1 Introduction

1.1 Context, background information and motivation

The project “Energy storage for sustainable regional development: Optimised integration of renewables in smart transport systems” (Power-to-Transport) intends to define the best option to defossilize a bus fleet by using solar irradiation and biogenic waste as available primary energy sources. Specific methods and models are developed to perform techno-economic evaluations as well as a climate impact assessment. Although these tools are applied to a specific case study in the framework of this project, they are flexible, generic and could be applied to any geographic location or any vehicle fleet.

The international consortium is composed of four main partners, namely the Institute for Energy Technology (IET) at OST, the Region of Uppsala, Uppsala Vatten and the Swedish University of Agricultural Sciences (SLU). The team at OST focused on the development of a modelling tool which allows to optimally size the units of a system that includes power-to-gas and energy storage technologies. The team of SLU developed two models, one for the forecasting of load and electricity prices in the spot market and one to quantify the emission factor of the electricity from the grid. Concerning the role of the Swedish partners involved in this project, Region Uppsala manages the public transport sector including both local and regional bus fleets, whereas Uppsala Vatten is a public utility company responsible for biogenic waste digestion and wastewater treatment. Both entities are tightly connected since Uppsala Vatten currently provides biomethane to the bus fleet managed by Region Uppsala.

The evaluated case study is located in the municipality of Uppsala, and it aims at defining which combination of locally available primary energy sources and technologies allows to reduce the overall greenhouse gas emissions of the current bus fleet by at least 25% at the minimum possible cost. The current fleet of buses in Uppsala is composed by 190 city buses and 210 regional buses. From the 190 city buses 71 are operated with biodiesel (produced from HVO), 97 with biomethane and 24 are battery-electric vehicles. From the regional buses 58 are fuelled with biomethane, whereas the rest uses biodiesel. Uppsala Vatten produces ca. 9.3 mio. Nm³ of raw biogas per year which covers about 70% of the current overall gas consumption of the buses.

1.2 Purpose of the project

To reach the aims of the Paris Agreement [1], as well as the Net Zero Emissions target by 2050, both countries Switzerland and Sweden need to drastically reduce their dependence on fossil energy. Furthermore, the recent geopolitical instabilities in the Eastern part of Europe emphasized the importance of increasing domestic energy production and thereby increasing the countries’ level of energy self-sufficiency. The purpose of this project is hence to provide a concrete solution to decrease the GHG emissions of the bus fleet of Uppsala, and to develop tools and methodologies that can be applied to similar realities and push forward the defossilization of the energy system as well as its resilience.

1.3 Project objectives

Figure 1 summarizes the main objectives of this study; on the left are the objectives concerning the case study, whereas the general objectives of the three technical work packages, namely WP2, WP3, and WP4, are on the right.



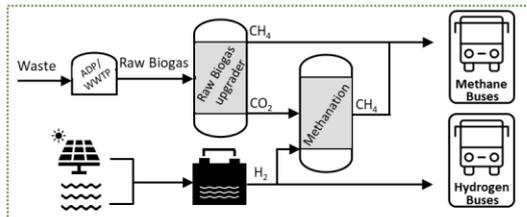
Overall objectives of the case study

The municipality of Uppsala aims at decreasing the overall GHG emissions in the sector of public transportation by at least 25 %.

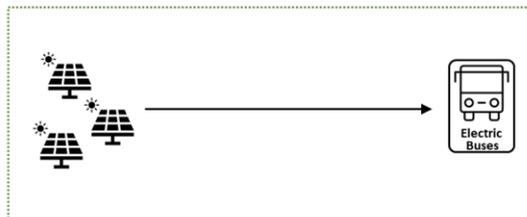
Overall objectives of the WPs

Develop universal methodologies to design and operate cost-optimal and sustainable energy systems

Concrete measures to reach the main objective of the case study:



Increase the production of renewable fuel by converting the biogenic CO₂ with renewable H₂ into synthetic methane and/or directly use H₂



Increase the number of BEV by 30% and assure they can be charged with renewable electricity produced by the PV infrastructure located at the bus depot

Specific objectives of the WPs

WP2

Develop a tool to optimally design and size power-to-X facilities including energy storage technologies

WP3

Develop a methodology to operate power-to-X facility economically

WP4

Develop a methodology to express the emission factors of the grid electricity and perform overall environmental assessments

Figure 1: Overview of the objectives of this study.



2 Description of existing facilities

2.1 Region of Uppsala and its capital the city of Uppsala

Uppsala county is one of the 21 counties of Sweden and has a total population of approximately 400'000 residents. Uppsala Region consists of 8 municipalities, of which Uppsala municipality is the largest with ca 245'000 inhabitants. 180'000 of them live in the urban area (see Figure 2).

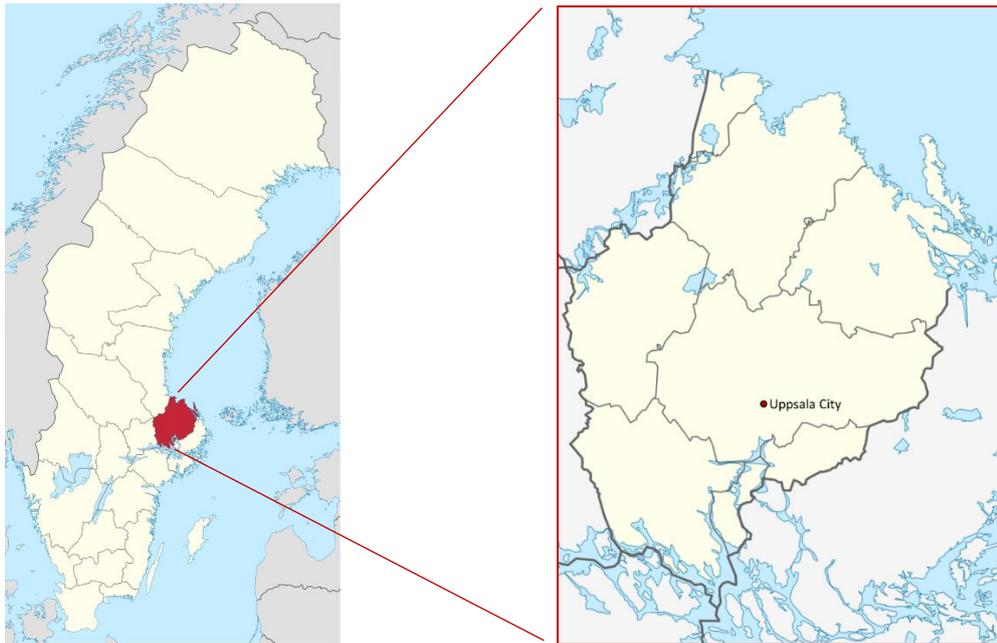


Figure 2: Map representing the Region Uppsala and its capital, Uppsala city.

The facilities of interest for this study are situated in the southeast part of Uppsala (see Figure 3). The anaerobic co-digestion facility is located 800 meters away from the wastewater treatment plant, and the new bus depot about 3 km north of the anaerobic digestion facility. It started its operation in 2021 and replaced the old bus depot which was located closer to the city center.

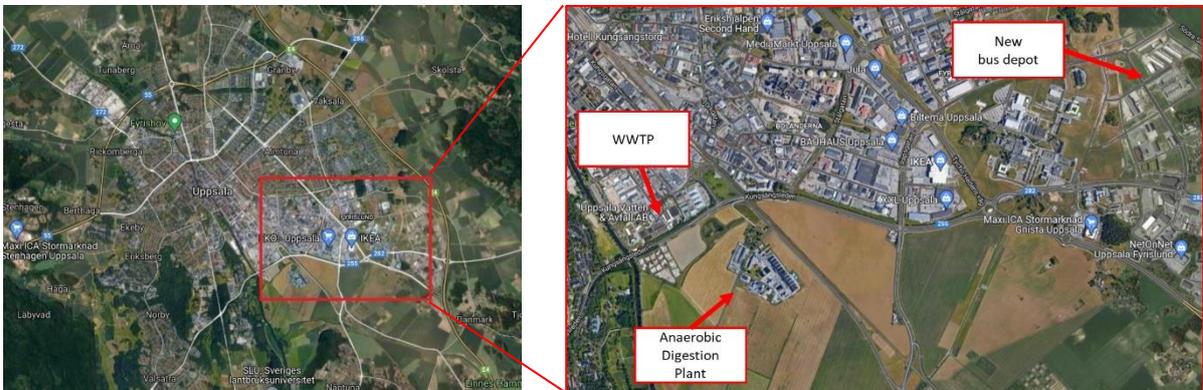


Figure 3: Location of the facilities of interest in the city of Uppsala. In the figure on the right the location of the anaerobic digestion plant, the new bus depot as well as the waste-water treatment plant (WWTP) are indicated.



2.2 Biogas facility and gas grid

Uppsala Vatten manages a wastewater treatment plant (WWTP), where biogas is produced from sewage sludge, as well as an anaerobic co-digestion plant (ADP) that digests sorted household waste and other biodegradable organic waste. The raw biogas, which consists of about 60-65% biomethane and 40-35% carbon dioxide, is upgraded using a water scrubber to separate the CO₂ from the biomethane. The CO₂-rich stream exits the scrubber at atmospheric pressure, and since air is added into the system to perform the separation process, the CO₂-rich stream is not pure but diluted with nitrogen (80 vol%) instead. On the other end, the biomethane produced contains less than 100 ppm H₂S and is at a pressure between 2 and 4 bar gauge at the grid injection point. Table 1 shows the amount of gas delivered by Uppsala Vatten to the bus depots and refuelling stations from 2020 to 2024. As reported in Table 1, the biomethane delivered by the WWTP and the ADP does not cover the consumption of the whole bus fleet, and thus, liquefied natural gas and additional liquified biomethane are imported. Even more so in the last years because the number of buses to supply have increased. It is also important to notice, that the biogas production hardly fluctuates during the year. In April 2023, the biogas plant was extended with a new post-digester to get a better biogas quality, a slightly higher production, and a larger buffer storage capacity for biofertilizer. In 2024, Uppsala Vatten acquired a new environmental permit allowing them to take more feedstock in and therefore increase their biogas production. This would help reducing the gas import even if the number of buses to supply grows. And for the upcoming years, Uppsala Vatten has several projects for the extension and the improvement of the biogas plant, such as a better logistics, a third pre-treatment line, a new gas upgrader or the required equipment for the intake of manure.

Table 1: Biomethane produced by Uppsala Vatten, and imported natural gas delivered to the bus depot from 2020 to 2024. From the produced biomethane, the WWTP delivers ca. 30% whereas the ADP delivers the remaining 70%. *The values for 2024 have been extrapolated from the production and import from January to November 2024.

	2020	2021	2022	2023	2024*
Biomethane produced [GWh]	59.3	57.3	58.5	59.1	67.8
Biomethane imported [GWh]	0	3.7	23.8	35.0	31.5
Natural gas imported [GWh]	2.9	3.2	13.0	6.5	0

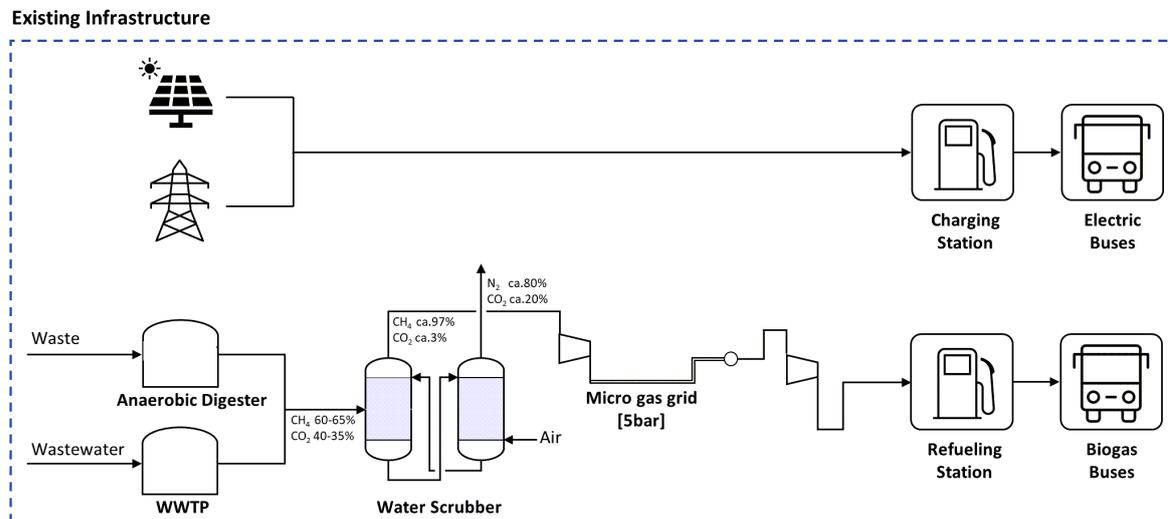


Figure 4: Schematic representation of the existing infrastructure, where electricity for the charging stations can either be provided by the local PV plant or by the grid (top part of the figure). The bottom part of the figure shows the raw biogas production plants with gas purification, which are connected to the gas refuelling station for the biogas bus fleet.

2.3 Electricity infrastructure

As shown in Figure 4, the electricity required to power the existing and/or future electric buses could be provided either by local PV plants or by the grid. The bus depot has four PV plants with a total peak power of around 400 kWp and an average annual production of around 8 MWh [2], and the buses can be recharged directly from these PV. Region Uppsala also has plans for the extension of the PV facility in a much larger scale outside of the bus depot, but since that electricity would need to be transported over the grid, it is found in the second category.

2.4 Bus fleet and depot

The newly built bus depot is located outside the city in an industrial area (see Figure 3 on the upper right side) and shelters two type of buses: the regional buses travel longer distances between cities while the city buses are mainly used in the city of Uppsala directly. From the 190 city buses, 71 are currently operated with biodiesel (from HVO), 97 are CNG/CBG vehicles and 24 are battery-electric vehicles. From the regional buses, 58 are CNG/CBG vehicles, while the remaining 154 use biodiesel. As shown in the graphic below (Figure 5), the number of city buses running on biogas has increased steadily from 1996, when the first biogas plant was put in production. In 2021, the first full-electric buses have been introduced. On the regional buses side, the introduction of biogas was less regular, with the decision taken in 2022 to switch all the 58 existing CNG buses to biogas at once. This was a challenge for Uppsala Vatten who needed to rapidly find additional biogas to supply them. Because the dataset used to produce Figure 5 and Figure 6 was not complete and the total number of buses before 2019 was unknown to the research team, it is assumed that the total number of buses was constant and the remaining buses were powered by diesel if not specified otherwise. In addition, it is interesting to observe that the number of diesel city buses has now remained constant since 2021. This is a prerequisite from the Swedish crisis management unit, which requires to be able to operate the buses even in case of major crises. Since the Swedish strategic energy reserves are mainly made of diesel, a given number of buses need to remain diesel driven.

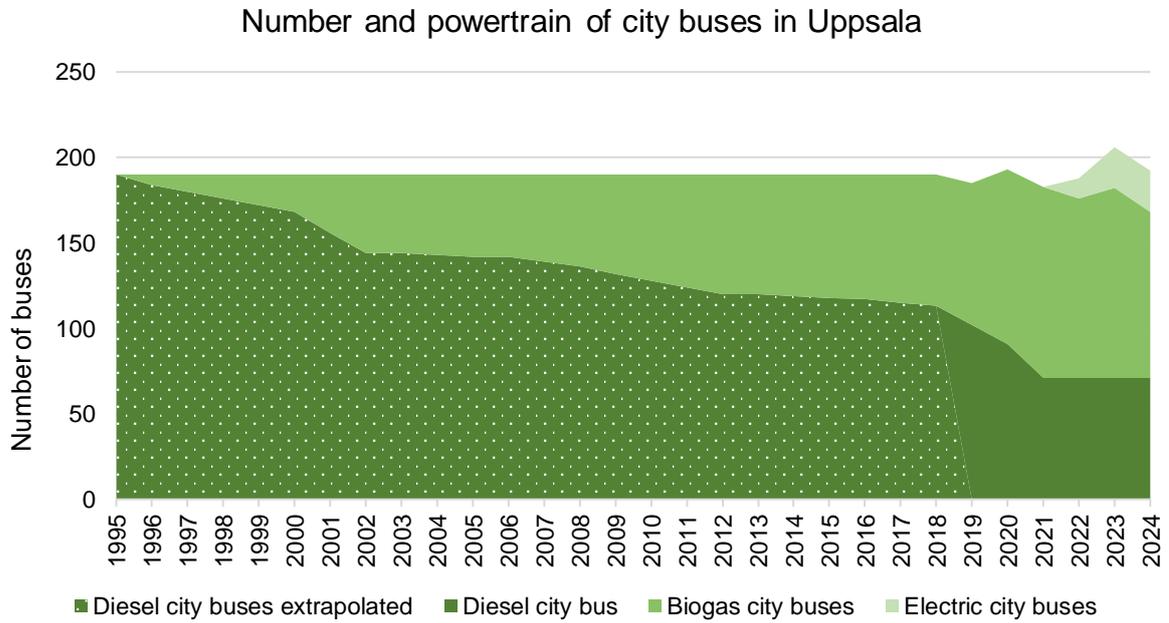


Figure 5: Number and powertrains of Uppsala city buses. Until 2019 the total amount of buses was assumed to be constant with an increasing share of biogas city buses.

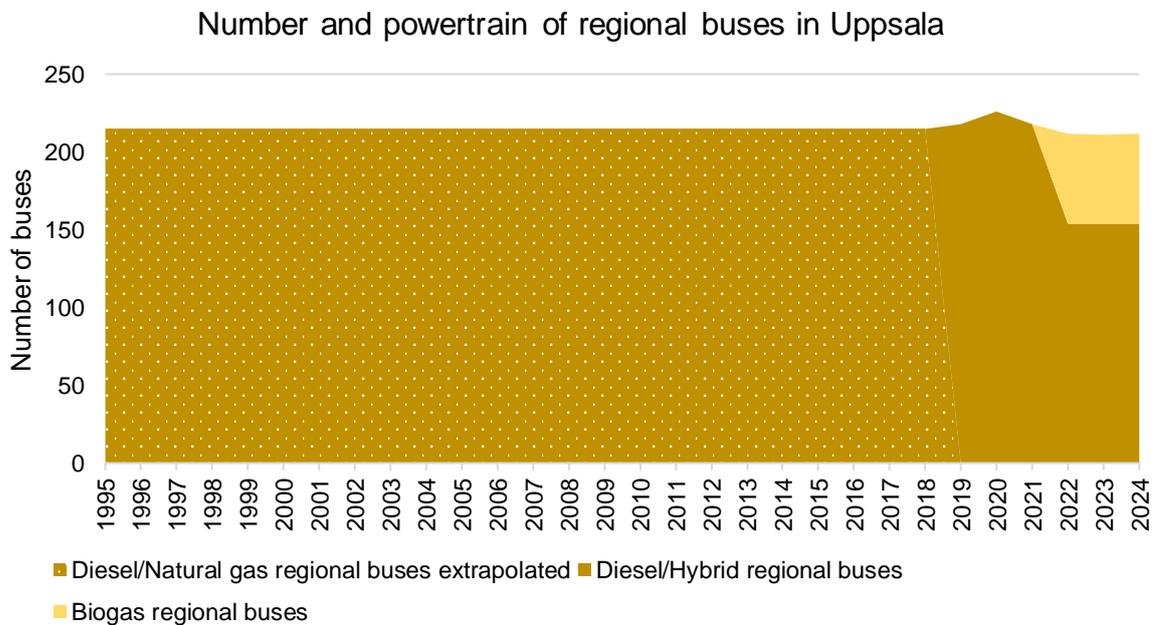


Figure 6: Number and powertrains of Uppsala regional buses. Until 2021 the regional buses exclusively run on diesel. Due to the lack of data, the total number of buses until 2019 was assumed to be constant.



3 General Strategy

This chapter focuses on the strategy adopted to achieve the objectives of the case study schematically represented in Figure 1. Given the existing infrastructure present in the area of interest (see Figure 3 and Figure 4) and the current composition of the bus fleet, the municipality suggests to investigate the following two strategies; The first one consists in implementing a power-to-X solution to increase the share of carbon-neutral methane and hydrogen used by the bus fleet, while the second consists of increasing the number of electric vehicles powered by renewable electricity.

3.1 Objective 1: Implementation of a power-to-X plant

In the framework of this project, only two power-to-X pathways are considered, namely power-to-methane and power-to-hydrogen. The two routes are complementary since hydrogen is required to produce synthetic methane. However, because of the existing infrastructure (i.e., CNG/CBG buses, refuelling station, and transport and storage facilities) and the availability of biogenic CO₂ on site, the efforts during this project mainly focused on the power-to-methane route. Another objective of the power-to-X route is to increase the proportion of locally produced energy carrier and therefore avoid importing.

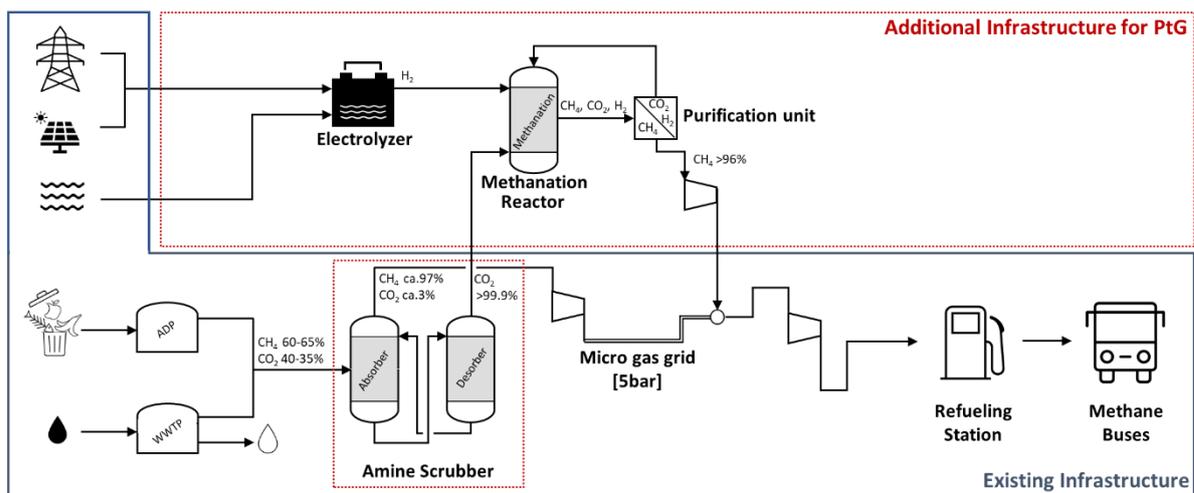


Figure 7: Schematic representation of the additional infrastructure required to produce synthetic methane from the CO₂ coming from the raw biogas. Here the option of replacing the biogas upgrader with an amine scrubber has been selected as representative case.

3.1.1. Implementation of a power-to-methane plant

The integration of a power-to-methane production plant into the existing infrastructure entails a series of challenges (Figure 7). As previously mentioned, the current upgrader produces a CO₂ stream diluted with nitrogen, which make the use of the CO₂ in a reactor impossible. To avoid the dilution of the product (i.e., methane), there are three possibilities: 1) bypass the upgrader and feed the raw biogas directly into the methanation reactor, 2) add a cleaning section after the existing upgrader or 3) substitute the upgrader with a nitrogen-free solution. While the first option would solve the issue of the upgrader without adding new equipment, it would result in higher investment costs of the downstream units (reactor, cooling, ...) because of their increased size. In fact, both reactor and storage technologies would require double capacity because of the 60-65 vol% of CH₄ present in the raw biogas that would not participate to the reaction. This option was examined mainly from a byproducts point-of-view (see chapter 3.4). The second option avoids the substitution of the current upgrader by adding a second separation unit to clean the CO₂-rich stream. This solution comes with the advantage that it can be custom sized, to clean only the desired amount of CO₂ and can be operated in a flexible mode, such as when renewable hydrogen is available. However, it comes with significant technical challenges. The available technologies to perform this separation are for example liquefaction, absorption processes, membrane or adsorption



separation, and regardless of the option chosen, the downstream separation of CO₂ and N₂ is energy intensive, causing a significant drop in efficiency and an increase in costs. A more efficient solution would be to substitute the water scrubber with a nitrogen-free alternative, such as an amine scrubber (third option). This third option, however, requires a significant investment to replace the current upgrading section, as the new upgrader will be sized to treat the entire amount of raw biogas produced. As of end of 2023, Uppsala Vatten took the decision to complete their biogas upgrading system with a model able to provide a high CO₂ purity. When the new upgrader will be installed and what technology it will adopt is not yet clear, but it should be used in redundancy with the old one for a while.

As shown in Figure 7, in addition to a new nitrogen-free separation process, a series of main components need to be provided in order to produce synthetic methane: an electrolyser, a methanation reactor (either biological or catalytic), and a post-methanation purification section (e.g. membrane). To make the system more flexible, several intermediate storages could also be added (see Figure 8). More precisely, a battery could compensate for daily fluctuations in the renewable electricity production, and a hydrogen storage and/or a CO₂ storage could be used to buffer the different availabilities between biogenic CO₂ and renewable electricity (and/or cost-competitive low-carbon grid electricity).

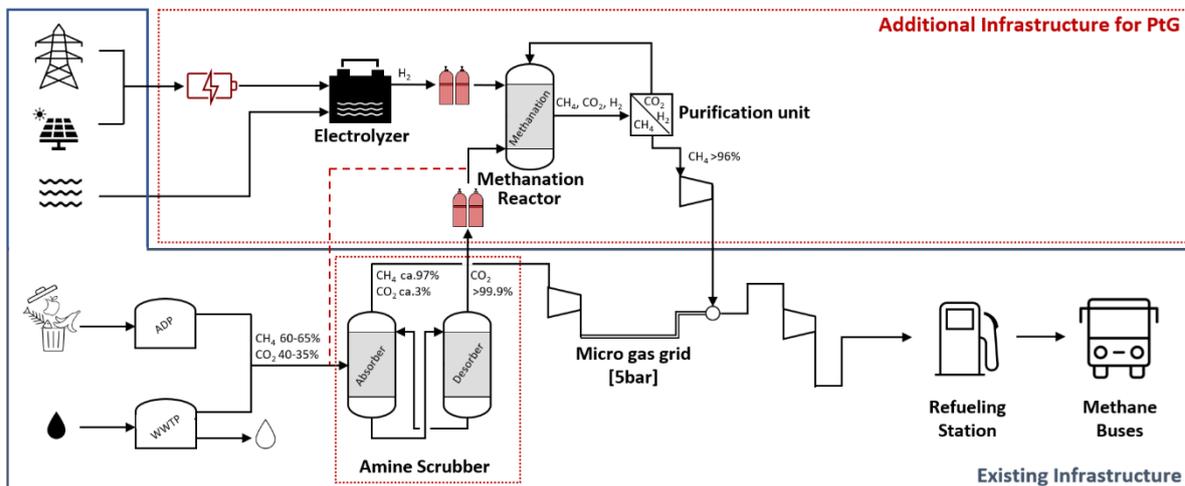


Figure 8: Schematic representation of the additional infrastructure required to produce synthetic methane from the CO₂ coming from the raw biogas with storage technologies available. Here the option the old biogas upgrader has already been replaced by an amine scrubber, as planned by Uppsala vatten. The optional storage units are coloured in red.

The tool and methods developed in the frame of this project will be used to provide a series of sustainable cost-optimal options for the integration of a power-to-methane plant in the city of Uppsala. Beside the sizing of the technologies schematically shown in Figure 7 and Figure 8, the trade-off between the size of the equipment, the overall cost (capital, operational, and maintenance) and the CO₂ intensity of the system is investigated.

3.1.2. Implementation of a power-to-hydrogen pathway

From a technical point of view the power-to-hydrogen pathway is complementary to the power-to-methane route (see Figure 9). In this case as well, the combined use of the tool and models developed will provide an insight on the trade-offs between capital and operational costs, and the overall GHG intensity. The final aim is to provide a series of low-carbon cost-optimal designs and operation modes of a power-to-hydrogen plant.

Besides the technical challenges related to a hydrogen-supply-chain, significant investment costs are required to adapt the existing infrastructure present in Uppsala: hydrogen buses need to be purchased, hydrogen refuelling stations must be installed, and hydrogen transport and storage facilities need to be created. While most of that infrastructure would need to be newly built in Uppsala, some of these



challenges are tackled within another project. In fact, Region Uppsala commissioned the construction of a hydrogen refuelling station that, after some delay, will be finished by the end of 2024.

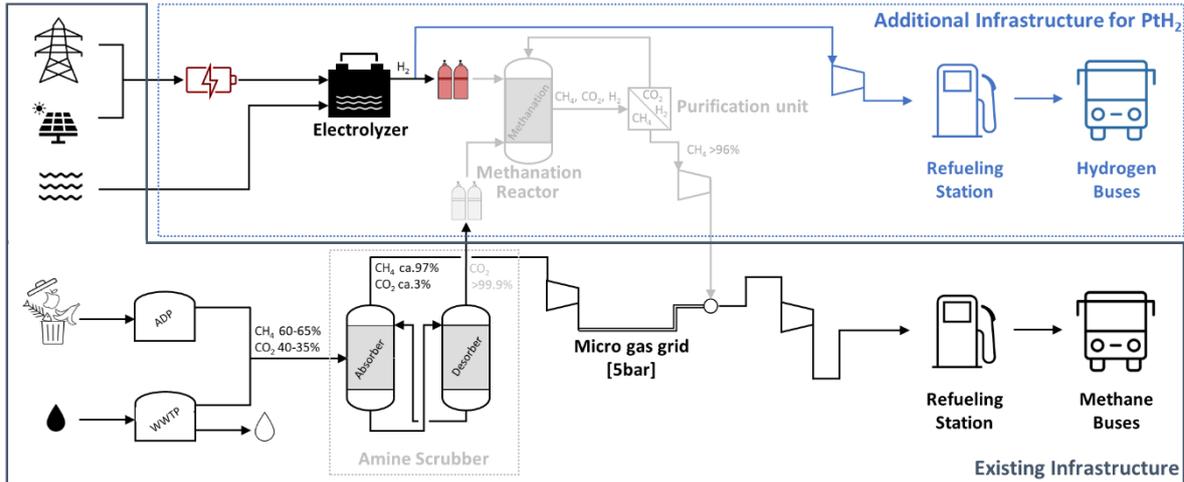


Figure 9: Schematic representation of the additional infrastructure required for renewable hydrogen production from water electrolysis. The optional storage units are coloured in red.

3.2 Objective 2: Increase the number of BEV

To obtain a tangible reduction in GHG emissions, the electricity used to charge the BEVs must be renewable. To this aim, on the roof of the new bus depot the municipality of Uppsala recently installed several PV panels with an average annual production of about 8 MWh. Therefore, to understand how to optimally size and operate the BEVs fleet by reaching an overall decrease of the associated GHG emissions at a reasonable total cost, the three tools developed within WP2, 3 and 4 are applied. More precisely, the tool delivered by WP2 is able to optimally size all components of the methanation plant, including a battery storage. It is taking into consideration the trade-offs between the intermittent availability of renewable electricity produced by the PV plant, the price and carbon intensity of the electricity taken from the grid. It is able to integrate the information provided by the tools of WP3 and WP4 respectively.

3.3 Intersections between objective 1 and 2

The two objectives 1 and 2 can also be analysed as a whole system (see Figure 10). By applying the different tools developed within WP2, 3 and 4, a set of solutions including the whole system have been provided to Region Uppsala and Uppsala Vatten at the end of the study.

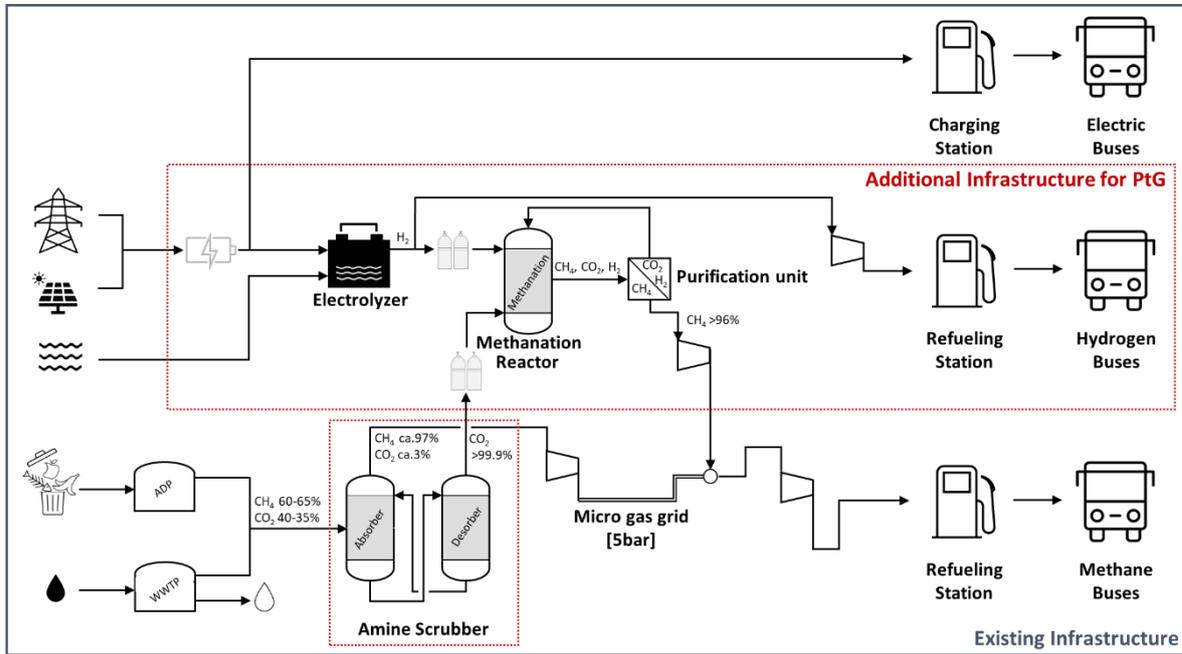


Figure 10: Energy system including electric buses, hydrogen buses and methane buses fuel with renewable fuel.

3.4 Additional objective: by-product utilization

As the development of the forecasting tool for electricity prices became extremely challenging to improve due to fluctuating prices during 2021 and further on (see chapter **Error! Reference source not found.**), discussions with the stakeholders (Uppsala Vatten and Region Uppsala) in the project led to a changed focus and an additional objective related to the utilization of by-products from electrolysis and methanation and its subsequent impact on techno-economic performance. Electrolysis produces not only hydrogen but also heat and oxygen, which could be utilized in a number of ways. Similarly, methanation generates excess heat that could potentially be valorised. In the Uppsala case, by-product utilization in wastewater treatment is considered promising due to the location of a wastewater treatment plant in the close vicinity of the biogas plant investigated in this project and the fact that Uppsala Vatten are the operators of the facility. Oxygen can reduce energy demand in wastewater treatment by replacing air in conventional aeration for degradation of organic pollutants, while heat can be used to heat several processes related to wastewater treatment and biogas production.



4 Activities and Results

4.1 WP2: Assessment of a PtG concept for the Uppsala case

During the project, two main activities have been conducted in the frame of this work package. On one hand, a series of data relevant for the case study have been collected and structured in an appropriate manner. On the other hand, the modelling tool has been set up to identify the optimal system configuration and the results have been summarized. To this end, a reference case for the input data and plant configuration has been defined and is presented here. The two activities are described in detail in the upcoming sections.

4.1.1. Material and energy input

Solar irradiation

The data concerning the annual solar irradiation in the city of Uppsala have been retrieved by mean of the renewable ninja database [3]. These data have been used instead of the actual production profile of the PV installation on the roof of the bus depot because the real data were not yet available in the first part of the project, but also because they are at least as reliable as real data.

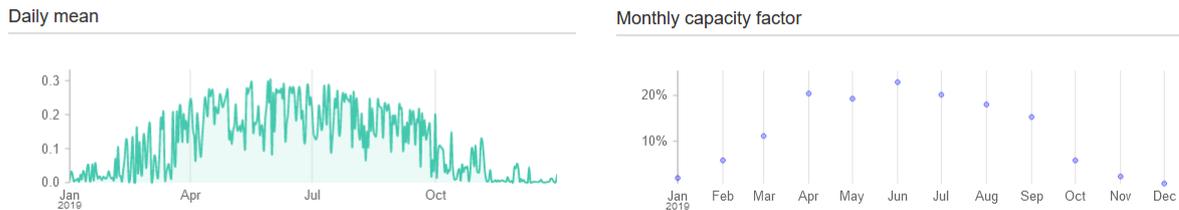


Figure 11: Renewable electricity production (reference year 2019) expressed in kW for the city of Uppsala. [3]

Biogenic CO₂

Uppsala Vatten provided data on biogas production with hourly resolution. The biogas production at the wastewater treatment plant is not included. The delivered data covers the time period from June 2022 to May 2023. In the data, time series for the raw gas stream to the upgrader and the product gas stream from the upgrader. The available CO₂ as shown in Figure 12 is the difference between the two streams.

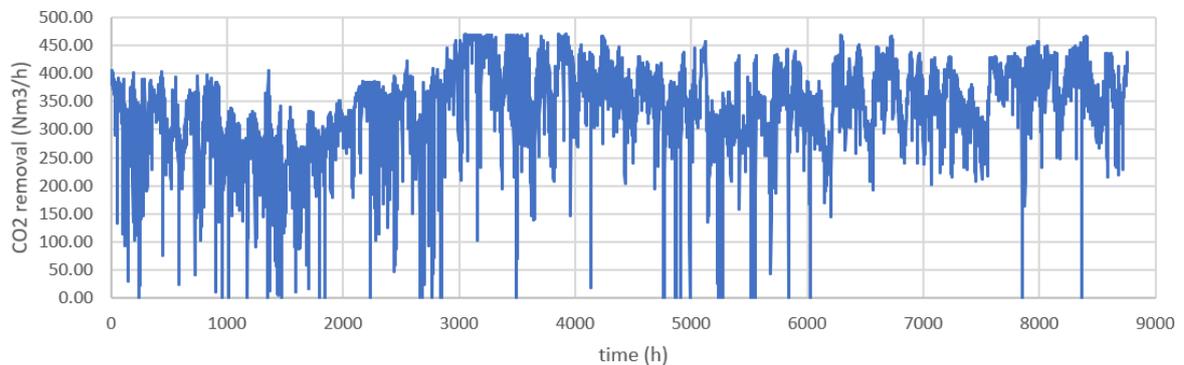


Figure 12: Hourly biogenic CO₂ production from the raw biogas upgrading process obtained by applying the first strategy. Assumptions: the CO₂-rich stream here is considered as pure.

Finally, the data has been re-ordered such that the time-series starts January 1 and ends December 31. Uppsala Vatten has confirmed that the zero values visible in Figure 12 are due to maintenance down-times.

4.1.2. Costs of units

A market study has been conducted, to collect data on the investment costs of the main components of a power-to-gas plant, namely the photovoltaic plant, the battery system, the water electrolyser, the hydrogen compressor and storage system, the methanation reactor and the carbon dioxide compressor and storage facility. The challenges encountered when collecting information on costs are numerous. Beside the low technical maturity of some of the components such as the methanation reactor, the price of raw materials has fluctuated considerably in recent times. Therefore, it has been difficult to define the costs of the various components and a substantial uncertainty is present. To help establish a standard, scientists and experts in the field created a tool called HyJack [4], where data from different sources are collected to deliver information on investment costs of the components involved in a power-to-gas plant. The HyJack data have been compared with cost estimates made available in the frame of different projects and from scientific literature, and then used as main source of data to define the cost of the power-to-gas components. For example, Figure 13 shows the data collected for the electrolyser, where the cost estimates of HyJack for both PEM and AEL technologies are compared with inquiries obtained in the frame of an in-house project (Solafrica) and the data published in several scientific publications or reports (Store&Go Project [5], Holst and al. [6]; BioBoost [7], Gorre and al. [8], Feasibility study Uppsala [9]).

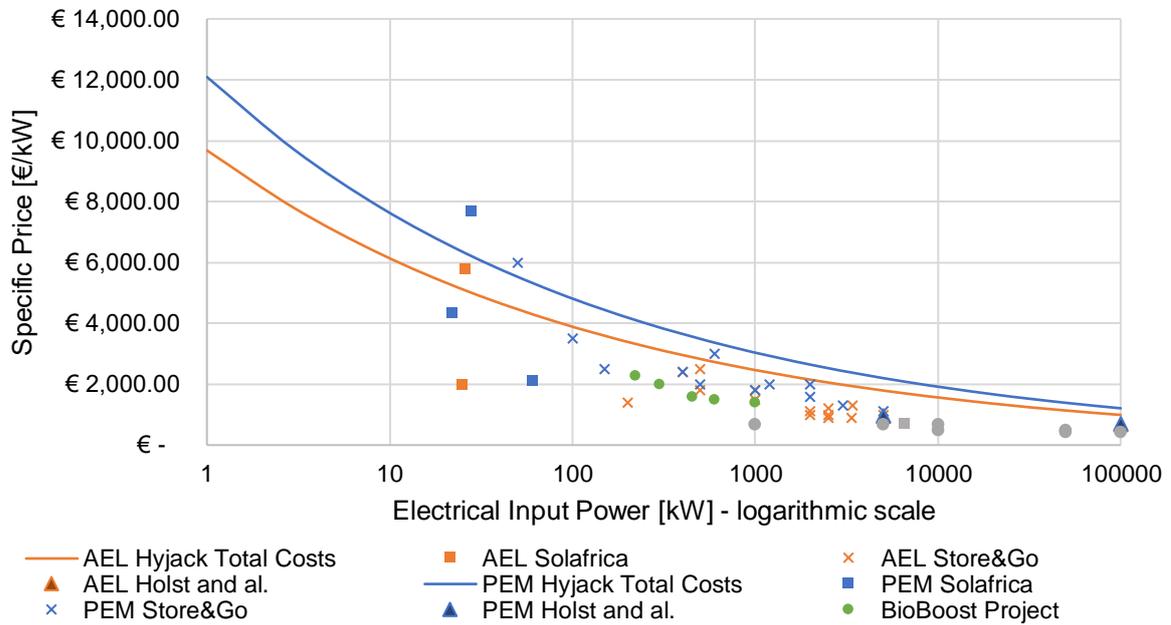


Figure 13: Investment cost of the electrolyser: The orange and blue curves are the data provided by HyJack [9] for Alkaline (AEL) and proton exchange (PEM) electrolysers respectively. The other datapoint are taken from the literature and serve as comparison. [5] [6] [7] [8] [9]

Figure 14 shows a second example of the market study performed: the investment costs for a methanation reactor. Similarly to Figure 13, the cost curve provided by HyJack [4] is displayed alongside datapoints provided by other sources, namely the Store&Go project [5] and Gorre and al. [8]. Since the data from the different sources diverge considerably from one to another, it was decided to implement a regression curve in the WP2 tool instead of using the HyJack function directly like for the other components. The regression curve is calculated by combining the three sources mentioned with the same weight and is assumed to tend to zero.

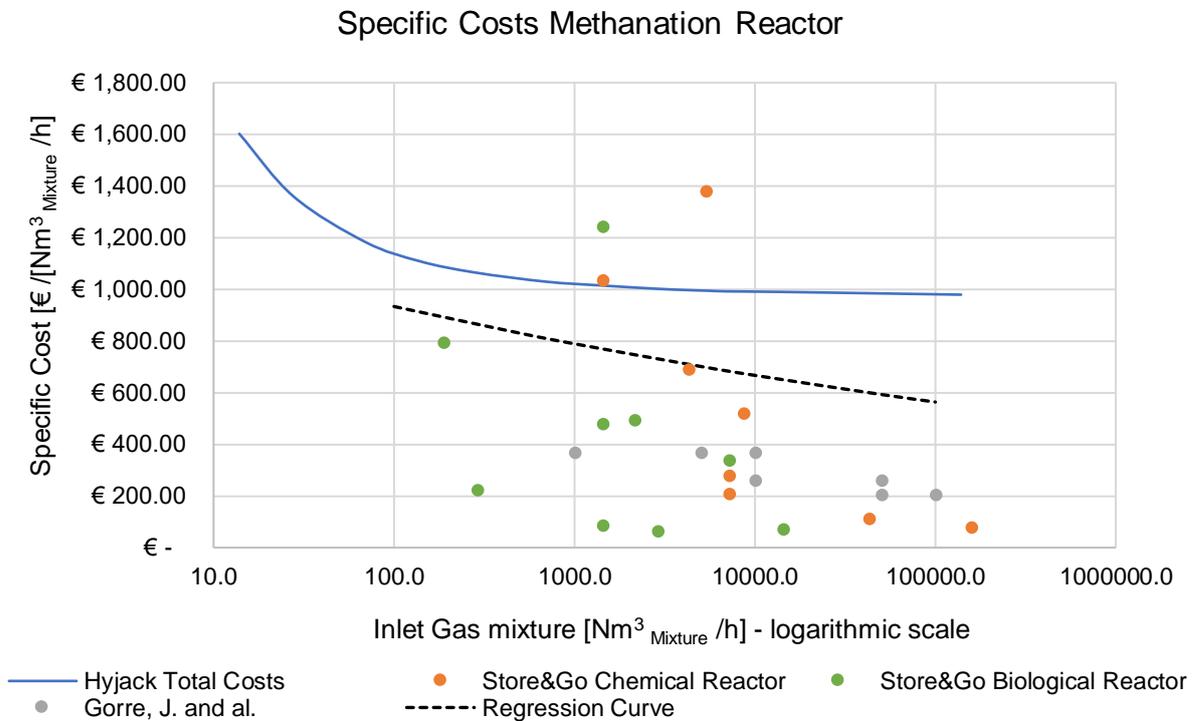


Figure 14: Investment cost methanation reactor. The blue line shows the costs provided by Hyjack [4]. The dots are data from the project Store&Go [5]: in orange the catalytic reactor and in green the biogenic option. The grey dots come from the Gorre and al. study [8].

A third example is given in Figure 15 where the specific costs of solar panels are displayed. The three sources compared are Hyjack [4], a Swiss book on the economics of building a photovoltaic plant [10] and a market study of the Swiss government for the year 2021. As it can be observed, the uncertainty of the data from the three sources is much smaller than for the previous cases. This can be explained by the fact that solar panels are already much more spread than electrolysers and methanation reactors for instance, meaning much more data is available.

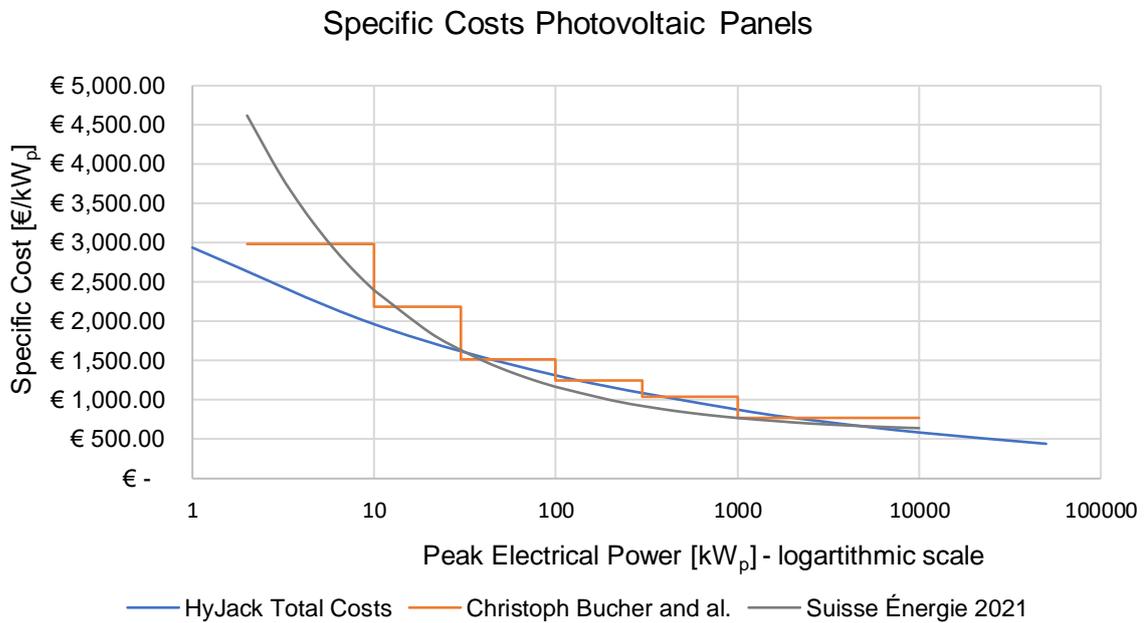


Figure 15: Specific costs of solar panels. The HyJack (blue) curve is compared with other sources [4] [10] [11]

4.1.3. Integration of hourly price of the electricity grid delivered by WP3

As mentioned previously, it is possible to combine the data of the different tools. The electricity prices forecasted by the tool developed at SLU within WP3 can be imported as an input data in the tool developed at OST within WP2. The emission factors in the reference case for the tool, historical data has been used. The calculation of the energy price time series is based on the spot market price of 2018 for bidding zone SE3. Data from 2018 was chosen, because the market fluctuations were not influenced by major political events. Grid usage and other fees like energy taxes are considered by multiplying the spot market price from Entso-E [12] by a factor of 2. This is in good accordance with electricity bills of the biogas plant. The resulting electricity price time series is shown in Figure 16. More details are given in chapter **Error! Reference source not found.**

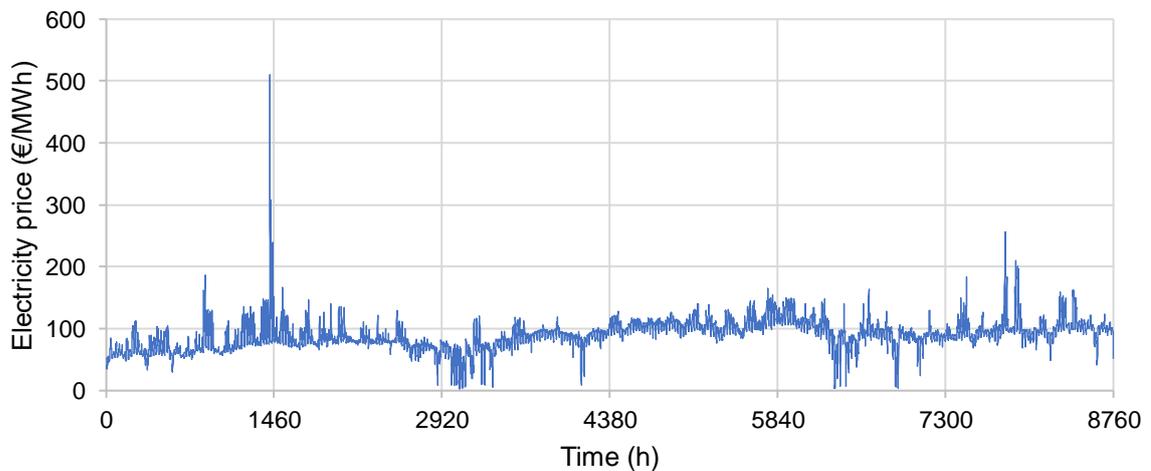


Figure 16: Hourly price of the electricity for the Region of Uppsala in 2018.



4.1.4. Integration of hourly emission factors of the electricity grid delivered by WP4

Similarly to the forecasted electricity prices, the hourly emission factors of the electricity grid, both average and marginal, have been integrated in the WP2 tool. It is, like in the previous case, possible to generate a dataset containing the hourly emission factors of the region of interest with the tool developed by SLU within WP4, and use it as input for the WP2 tool. Data of 2018 is taken as reference case in order to remain coherent with the electricity prices chosen in chapter 4.1.3 (see Figure 17).

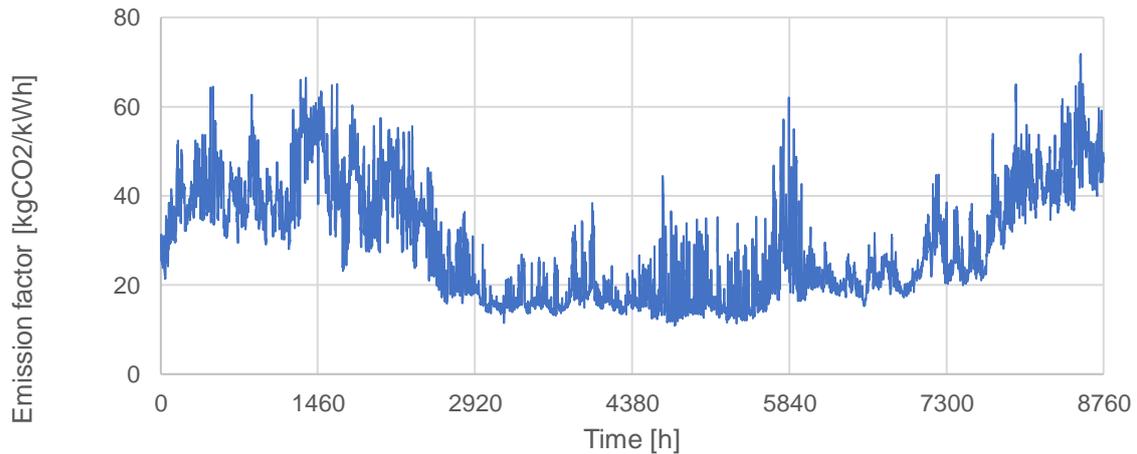


Figure 17: Average hourly emission factors of the electricity grid for the Region of Uppsala in 2018.

4.1.5. The WP2 tool and the implemented methods

To define the optimal design of a Power-to-X plant, the tool offers the possibility to run sensitivity analyses and perform mathematical optimisations.

The model is programmed using python. However, all features mentioned here are integrated into a user-friendly graphical interface, such that the user does not have to cope with the source code when running simulations and performing analysis with the tool. Figure 18 shows a screenshot of the graphical user interface, where a block flow diagram represents the main components of a PtX plant modelled within the tool. The components are sorted from left to right from sources to sinks. Electric energy is used to produce H_2 via the electrolyser. The H_2 is then mixed with the CO_2 and fed into the methanation reactor. The reactor produces CH_4 which is “sold” in the product sink. Mass and energy flows are represented by arrows between the components.

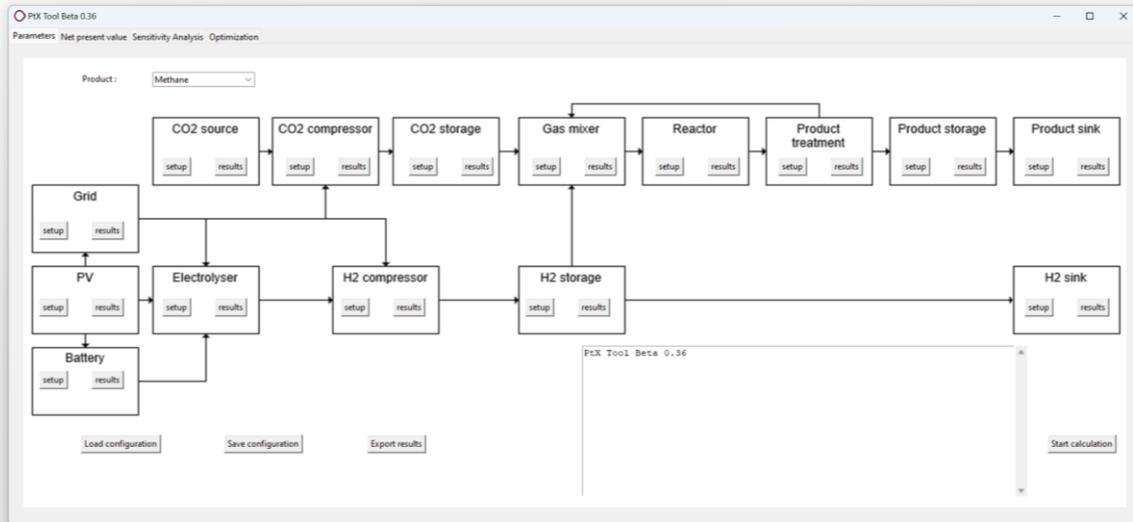


Figure 18: Representation of part of the graphical interface of the WP2 tool.

Each of the components can be parametrized with a combination of scalar parameters and time-series. For example, the nominal power of the electrolyser is a scalar parameter, whereas the CO₂ input stream from the biogas production can be a time-series. All components provide technical as well as economic parameters. The source (Grid, PV, CO₂ source) and the sink components can be parametrized with either time-dependent, constant or unlimited values. Between sources and sinks we find the process and storage components. These are parametrized with a finite capacity. The simulation concept enables a bivalent operation. For example, if the sources are limited but the sinks are not, we have an input-driven system and an output-driven system in the opposite case. The tool also copes with the case that both sinks and sources are unlimited: the system performance is then only limited by the process component with the smallest capacity. In practice, the limiting component (including sources and sinks) can change for each time-step, so the simulation determines the limiting factor in each time step.

The time-discrete simulation calculates the flow of electric energy to the electrolyser and the compressors, as well as all streams of CO₂, H₂, CH₄ and their mixtures at the output of each component. At the end of the simulation run, yearly sums like the total SNG production, and other KPI like total production, capacity utilization or total energy consumption are calculated. The technical results include all streams in the systems and KPI of the components.

The economic viability of a given system configuration is assessed by the net present value method. As seen in the previous chapters, each component provides estimates for non-linear capacity-specific CAPEX, such that economy of scale is taken into account. From the CAPEX, fixed OPEX are calculated with a definable percentage. Variable OPEX are calculated for each component based on the number of full-load hours resulting from the simulation. Expenses for electric energy are calculated separately. The results of the NPV calculation are displayed in tabular form and can be exported for further processing.

The tool offers a highly flexible framework for sensitivity analysis. An input variable can be selected from the range of available component and economic parameters. As output variable, one of the components or the economic result values can be chosen. The tool then automatically calculates the resulting values for a range of values of the input variable and creates a sensitivity plot.

The mathematical optimisation framework of the tool as shown in Figure 19 is based on the DIRECT algorithm [13], [14] that is available in the python package SciPy. This algorithm has been found to deliver good results efficiently for the single-objective, non-linear blackbox optimisation problem at hand. Similarly to the sensitivity analysis, the objective can be selected freely from all available KPI, including



economic results. Accordingly, an arbitrary number of decision variables can be chosen from all available parameters, and each decision variable is provided with a value range. With this flexibility, the tool can be used to answer a large variety of questions. Typically, the optimal dimensioning of the components can be determined for given site conditions. For example, if the CO₂ production and energy price profiles are given, the optimiser finds the optimal sizes of electrolyser, reactor and storage capacities that maximize the NPV. Because the optimiser uses a heuristic algorithm, the delivered optimum is only an approximation of the real optimum. The result can be then refined by narrowing the value ranges of the decision variables.

The screenshot shows a software interface for optimization. It has tabs for 'Parameters', 'Net present value', 'Sensitivity Analysis', and 'Optimization'. The 'Optimization' tab is active.

Objective

Component	Variable	Unit	optimize	Optimal value
Economics	net present value	€	max	10623568

Decision variables remove last row Optimize

Component	Variable	Unit	>=	<=	Optimal solution
Electrolyser	Power rating	kW	5000	10000	7233
Reactor	Inflow capacity	Nm ³ /h	1000	3000	1898
H ₂ storage	Capacity	Nm ³	0	5000	3
CO ₂ storage	Capacity	Nm ³	0	5000	1643
Grid	Energy cost threshold	€/kWh	0	1	0
select component...					

Figure 19: The mathematical optimisation framework in the WP2 tool approximates the optimum with a selectable objective and an arbitrary number of decision variables.

4.1.6. Model Assumptions

The modelling assumptions for the case study in Uppsala are listed in this chapter.

Simulation

The simulation has a time resolution of 1 hour and simulates 1 year (= 8760 hours) of operation.

Energy sources and battery

The electric energy from the grid is considered with three properties: power, cost, and CO₂ emissions. The costs for rectifiers and converters are assumed to be reflected in the CAPEX of the electrolyser. The grid module is parametrized with the time-series for energy tariffs and the emission factors discussed in chapters 4.1.3 and 4.1.4. There are two PV plants considered. First, a PV plant with 400 kWp at the bus depot and second, the free-standing PV plant with 4.5 MWp in the vicinity of the biogas plant. The power profile from renewables ninja [3] mentioned in chapter 4.1.1 is scaled to the peak power of the PV plants, resulting in the photovoltaic energy contribution in each time step. The cost for PV energy is included in the NPV calculation by the CAPEX (see chapter 4.1.2) and OPEX of the PV plants. The battery is modelled using an assumed round trip efficiency of 95%.

Electrolyser

The electrolyser is modelled using a definable nominal power rating $P_{\text{elec,max}}$ and a fixed efficiency



$$\eta_{\text{elec}} = \frac{\dot{m}_{\text{H}_2} \cdot HHV_{\text{H}_2}}{P_{\text{elec}}}$$

with the operational power P_{elec} , the hydrogen mass flow \dot{m}_{H_2} in kg/s and the higher heating value of hydrogen $HHV_{\text{H}_2} = 39.39 \frac{\text{kWh}}{\text{kg}_{\text{H}_2}}$. The electrolyser can be run with partial load and immediately reacts to down-stream hydrogen demand. A pressure of 30 bar is assumed at the hydrogen output, insinuating a PEM Electrolyser. This is also reflected in the CAPEX mentioned in the previous chapters. Periodic stack replacement due to degradation has been considered via a higher OPEX percentage of 5%. For all other components, this percentage is 3%. Stand-by and auxiliary energy demands are neglected. Besides the hydrogen production, the model also calculates the oxygen production.

CO₂ source, compressors and gas storages

The CO₂ availability time-series is retrieved from the data discussed in chapter 4.1.1. In conjunction with the new digester, Uppsala Vatten has decided to build an amine scrubber independently from this project. Consequently, the CO₂ will be produced in either case and its cost is assumed to be zero for the power-to-gas system. Gas storages are simulated for H₂, CO₂ and CH₄ (SNG). A CH₄ storage already exists at the bus depot and is not considered in this model. The storages are modelled as compressed gas storages with a pressure maximum at critical pressure for CO₂ and at 200 bar for H₂. They offer a definable capacity in norm cubic meters and are considered lossless. The sizing of the compressors is based on the necessary throughput. It is assumed that the compressor must be able to process the maximum flow from the upstream component. For the H₂ compressor, this value is given by the maximum hydrogen output from the electrolyser, and for the CO₂ compressor by the simulation. Compressor power is calculated using a source pressure at atmospheric pressure for CO₂, and at electrolyser output pressure for H₂. The output pressure used for the calculation is approximated with the mean of source and target pressure. The calculations are done using the formulas from HyJack [4]. Specific CAPEX for compressors and storages, as described in chapter 4.1.2, are used for the cost calculation.

Gas mixer, methanation reactor, product treatment and sinks

The gas mixer ensures that the reactor receives the correct stoichiometric ratio H₂:CO₂ of 4:1. No over stoichiometric operation is considered. The CAPEX of this component is assumed to be included in the reactor CAPEX, and the reactor is assumed to operate with a constant conversion rate of 0.95. It is modelled without power demand or heat usage from the exothermic reaction. Unreacted gases are separated with a ratio of 0.95 and recycled to the mixer. The product gas separation rate is also assumed to be 0.95. The product sink, i.e. the SNG demand is assumed to be infinite, meaning that the production can be sold completely without intermediate storage. The H₂ sink is set to zero, because all H₂ is used to produce SNG.

Net Present Value calculation

For the NPV calculation, a project lifetime of 20 years is assumed. The imputed interest rate is set to 2.5%. Additional investments and residual value are assumed to be zero. The sales price for the SNG in the base case has been set to 240 €/MWh. This assumption is artificially high to control the optimiser as explained later. According to Uppsala Vatten, the biogas has been sold for 180 €/MWh to the fuelling stations in August 2023. The sales prices to the bus fleet are in general approximately 1/3 lower. The additional purchase of LBG come at a price of about 145 €/MWh. Obviously, this value is of utmost importance for the economic feasibility, so it has been included in the sensitivity study in the next chapter.

4.1.7. Model results

In this chapter, the results of the optimal sizing of the power-to-Gas plant are presented. They then form a base case, which is affected by the high uncertainties in the input values previously described. For this reason, a sensitivity study is conducted to explore the impact of the variation in the input values on the results. As objective value for the optimisation, the NPV is chosen. Other objectives like maximizing



the methane yield or minimizing the CO₂ emissions have been considered, but the first case leads to an over-dimensioned system, while in the second case, the system is minimized to zero. Thus, optimising for these objectives has not been further pursued in this study.

Base Case

The base case maximizes the NPV. Six decision variables have been taken into consideration: The power rating of the electrolyser, the educt gas inflow capacity of the reactor, all storage capacities (H₂, CO₂, battery), and the energy price threshold. The latter is an upper price limit for buying electricity from the grid. All other parameters are held constant during the optimisation. It is important to note, that the product price has been set to an unrealistic high value of 240 €/Nm³. The reason for this is, that with a lower value, the methane is produced with a loss, leading the optimiser to minimize the plant size to 0. Thus, a maximisation of the NPV leads either to a plant size greater than 0, when economic feasibility can be reached, or to a size of 0, when financial losses are inevitable. The optimised results with the given assumptions are summarized in the following table:

Table 2: The optimiser finds the system configuration (base case) shown in this table. The decision variables are marked green.

Variable	Value	Unit
Electrolyser power rating	7'450	kW
Electrolyser efficiency	0.7	-
Electrolyser utilization	7914	FLH
Reactor inflow capacity	1'950	Nm ³ /h
H ₂ storage capacity	0	Nm ³
CO ₂ storage capacity	2'230	Nm ³
Battery storage capacity	0	kWh
Energy cost threshold	0.10	€
PV peak power	4.9	MWp
Total yearly energy consumption	54'480	MWh
Yearly grid emission (based on average emission factors)	1'643	t CO ₂ eq
Yearly grid emission (based on marginal emission factors)	46'326	t CO ₂ eq
Yearly energy from PV	4'790	MWh
Yearly total available CO ₂	2'983'376	Nm ³
Utilized CO ₂	97.4	%
Yearly hydrogen production	11'695'649	Nm ³
Yearly CNG production	2'945'764	Nm ³

The optimiser finds an optimal configuration represented by the values marked green in Table 3. The CO₂ and system utilization are good: Over 97% of the available CO₂ is processed and the electrolyser utilization is near 8'000 full-load hours (FLH). Storage is only recommended for buffering CO₂. And, because over 99% of the PV energy can be consumed directly, an expensive battery does not improve the case. The electrolyser is dimensioned sufficiently powerful to deliver the amount of hydrogen necessary for the methanation of the CO₂ stream from the CO₂ storage, accordingly, a H₂ storage is not recommended by the optimiser.

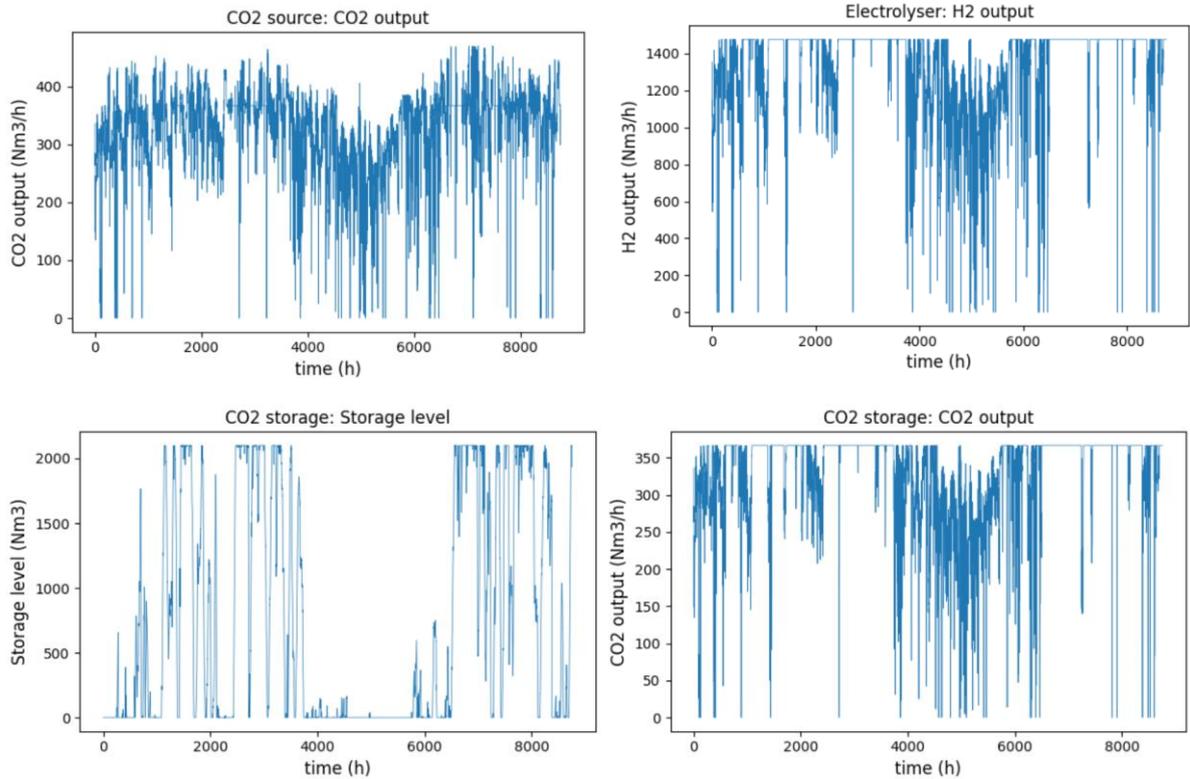


Figure 20: Examples of results from the base case simulation.

With the system described above, a positive NPV is achieved. The total investments sum up to 18.2 million €, the yearly revenues and expenditures are 7.8 and 5.3 Mio. € respectively. The results of the economic calculations are shown in Table 3.

Table 3: Economic results of the base case. The positive net present value has to be read with care as explained in the text.

Investments	€	Expenditures	€/year	Revenues	€/year	NPV	€
CO ₂ source	0	Electric Energy Electrol.	4'736'384	H ₂	0	Total invest	18'282'348
PV	3'267'225	Electric Energy Compr.	41'775	Product	7'805'806	Sum of discounted rev.	121'685'969
Grid	0	CO ₂ source	0			Sum of discounted exp.	83'037'715
Electrolyser	12'753'617	PV	98'017			Residual value	0



H ₂ compressor	0	Grid	0				
H ₂ storage	0	Electrolyser	382'609				
CO ₂ compressor	574'266	H ₂ compressor	0				
CO ₂ storage	252'785	H ₂ storage	0				
Product storage	0	CO ₂ compressor	17'221				
Battery	0	CO ₂ storage	7'584				
Mixer	0	Product storage	0				
Reactor	1'434'687	Battery	0				
Product treatment	0	Mixer	0				
H ₂ sink	0	Reactor	43'041				
Product sink	0	Product treatment	0				
Additional	0	H ₂ sink	0				
		Product sink	0				
Total invest	18'282'348	Total yearly expenditures	5'326'631	Total yearly revenues	7'805'806	Net present value	20'365'906

A positive NPV usually means that the project can be regarded economically feasible. But because the product price has been set artificially high, and because of the uncertainties in the input values mentioned above, this statement must be carefully interpreted. The sensitivity analysis in the following section helps to better understand the impact of variations in input variable on the NPV, and shows that, with a product sales price under 180 €/MWh, only a negative NPV is achieved.



Sensitivity Analysis

For the sensitivity analysis, the impact of a selection of input variables on the NPV is calculated. During the calculation for one specific input variable, all other parameters are held constant. Figure 21 shows a linear dependence of the product sales and energy purchase prices on the NPV. The purchase price of electric energy is crucial in this analysis, because of strong sensitivity and also large price fluctuations. An LCOE of 200 €/MWh can be estimated from the zero-crossing in the left diagram. With a base case sales price of 240 €/MWh, (constant) energy (electricity) price must not exceed 0.11 €/kWh for a positive NPV.

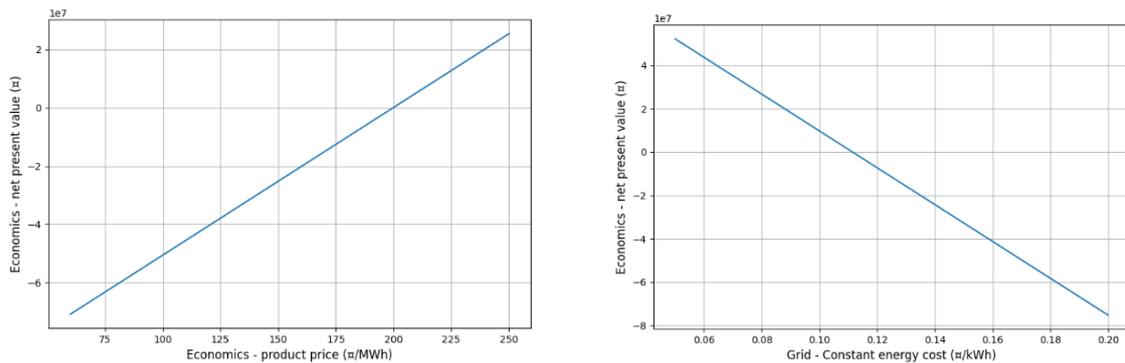


Figure 21: Sensitivity to SNG price and average energy cost. The NPV is particularly sensitive to both. € is the generic currency sign. The currency used is in the calculations is €.

In Figure 22, the power rating and the efficiency of the electrolyser are analysed. For the power rating, the same result as from the optimisation is found, namely the electrolyser should have a power of 7450 kW to maximize the NPV. As for the efficiency, a rather large impact is found, even if only the reduction of the energy requirement and not the possible reduction of size and therefore CAPEX are considered in this example. The impact on the NPV would even be stronger with the reduction of electrolyser size.

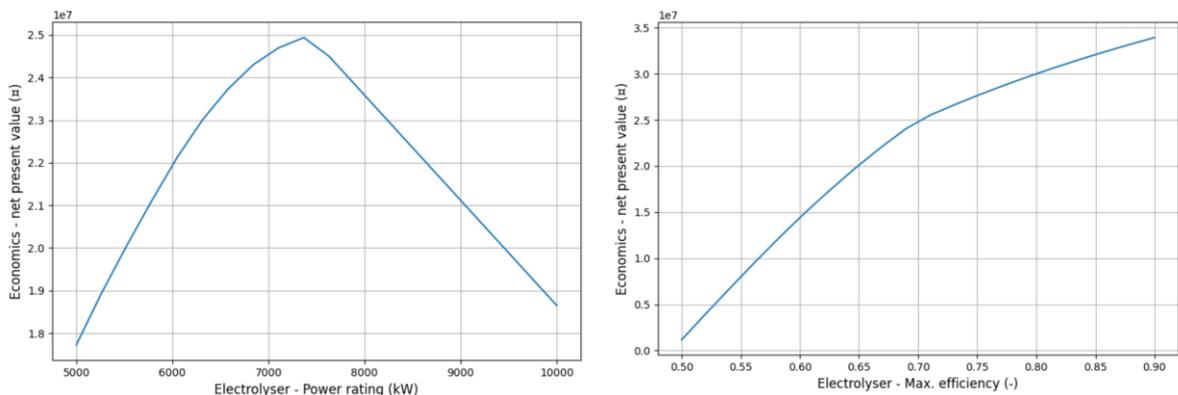


Figure 22: Sensitivity to Electrolyser size and efficiency. € is the generic currency sign. The currency used is in the calculations is €.

The CAPEX, especially of the electrolyser and the methanation reactor are prone to large uncertainties, making them critical values in the overall economic evaluation. Even more so because the interest rate has a significant impact on the NPV, as observed on Figure 23. On the other hand, PV does not seem to improve the base case a lot (see Figure 24). This might be due to the fact that the cost estimates for PV might be a bit higher than reality. More PV capacity would therefore increase the investment costs without bringing cheaper electricity. In the model, additional PV has a positive impact on the CO₂ emissions. Only the CO₂ emissions of grid electricity production are considered, amounting to 1'300 tons, using the average emission factors.

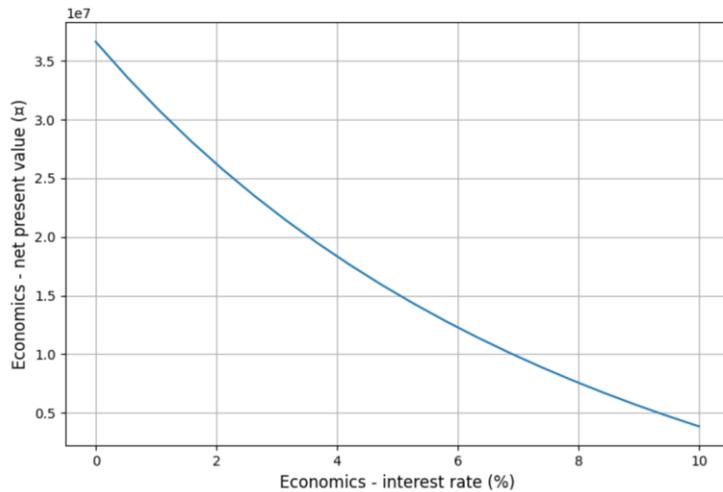


Figure 23: Sensitivity to calculatory interest rate. € is the generic currency sign. The currency used is in the calculations is € .

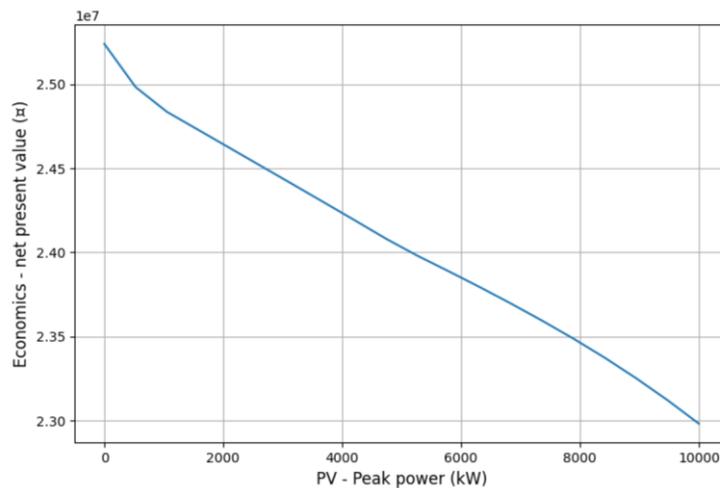


Figure 24: Sensitivity to PV peak power. € is the generic currency sign. The currency used is in the calculations is € .

Conclusion and Recommendations

The base case delivers a positive NPV, because of an artificially high product sales price. With a more realistic sales price, the NPV becomes slightly negative. These results must be considered with caution because the energy market has fluctuated strongly in the past years and is hard to predict. The analysis shows that the NPV depends strongly on the prices of electricity and gas. The interest rate of the base case might be rather low in times of rising rates, and the analysis shows that it has a significant impact. It must therefore not be underestimated.

Apart from these caveats, several opportunities to improve the economics of the system exist. Electrolysers become more efficient with time, which has a large impact. And because they produce heat and oxygen, further investigations could reveal new markets for these by-products (see chapter 4.4). Furthermore, if a good use for hydrogen is found, the electrolyser could be dimensioned larger and provide hydrogen to fuelling stations for HEV for example. With the replacement of fossil-fuelled vehicles by vehicles powered by SNG and hydrogen, the CO_2 emissions can be drastically reduced. In conclusion, the project is worth being pursued both from an ecological and from an economical perspective. With the right parameters, it might even become profitable.



4.2 WP3: Development of a forecasting tool for electricity prices

Within this work package, a tool for the forecasting of electricity prices has been developed. The aim of this tool is to provide information on electricity prices to power-to-X operators, thus allowing them to participate in day-ahead auctions. The model is based on neural networks, where historical hourly values are used for the training (i.e., dry bulb temperature, dew point, hour of the day, day of the week, past loads values, past day-ahead price, hydropower reservoir). Figure 25 shows an example of the collected data for yearly system load during 2013 to 2020.

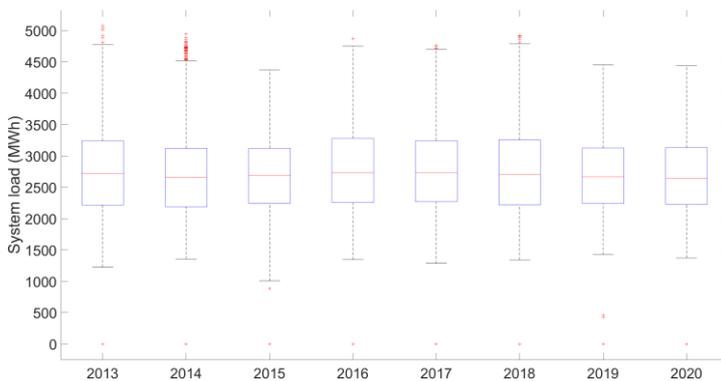


Figure 25: Historical data for system load in MWh in Sweden.

The forecasting accuracy has been evaluated and expressed as mean absolute percent error (MAPE) for a series of years. Figure 26 shows the MAPE for the Swedish bidding zone SE4, which is the region with the highest share of variable renewable electricity (wind, PV). Test set 2016 to 2018 is published in a peer-review journal (Janke et al., 2020) [15], while test set 2019 to 2021 has been calculated after the publication.

Mean absolute percent error (MAPE)

Train set	Test set	Number of layers			
		10	20	50	100
2015	2016	12.15	17.88	22.79	29.39
2014 + 2015		9.26	11.54	11.06	14.79
2013 + 2014 + 2015		9.03	9.68	9.75	13.35
2016	2017	13.10	18.00	35.52	42.01
2015 + 2016		12.32	12.78	13.86	14.68
2014 + 2015 + 2016		10.64	10.99	11.87	12.67
2013 + 2014 + 2015 + 2016		10.26	10.86	10.99	11.57
2017	2018	17.69	20.62	23.29	33.27
2016 + 2017		18.37	18.16	22.98	24.09
2015 + 2016 + 2017		15.15	20.25	18.25	20.82
2014 + 2015 + 2016 + 2017		16.47	20.38	21.44	25.73
2013 + 2014 + 2015 + 2016 + 2017		15.27	14.68	16.68	17.54



2018		22.00	24.51	52.69	72.99
2017 + 2018	2019	21.31	48.51	22.05	24.29
2016 + 2017 + 2018		21.57	28.97	23.09	21.46
2019		90.65	126.75	278.47	144.47
2018 + 2019	2020	108.20	114.63	125.93	243.01
2017 + 2018 + 2019		84.45	80.43	107.75	221.25
2020		68.65	72.40	117.35	146.63
2019 + 2020	2021	77.52	84.37	122.04	83.53
2018 + 2019 + 2020		71.81	83.12	83.65	71.01

Results are given in percentage (%)

Figure 26: Accuracy of forecasted electricity prices for different test years, namely 2016 to 2021. The greener the cell the more accurate is the forecast. The minimum value for each test set is marked with red ink.

To better understand the effect of this accuracy indicator on the operation scheduling, tests have been run where 2018 was chosen as reference year since the average electricity price found for this year was relatively high. This assumption results in a more conservative assessment for the gas production costs. In this example, the power-to-gas route selected is hydrogen production from water electrolysis followed by biological methanation in Uppsala (bidding zone SE3), as published in Janke et al., 2022 [16]. Figure 27 shows the electricity price (in blue the real price and in green the forecasted one) and the corresponding electrolyser load (in grey) for a period of a week. Here, a MAPE of 14% resulted in a synthetic methane production cost of 194.81 €/MWh, and interesting enough by artificially setting the MAPE to 0% a gas production cost of 194.19 €/MWh is obtained. We can therefore conclude that a moderate MAPE has a limited influence on operation scheduling.

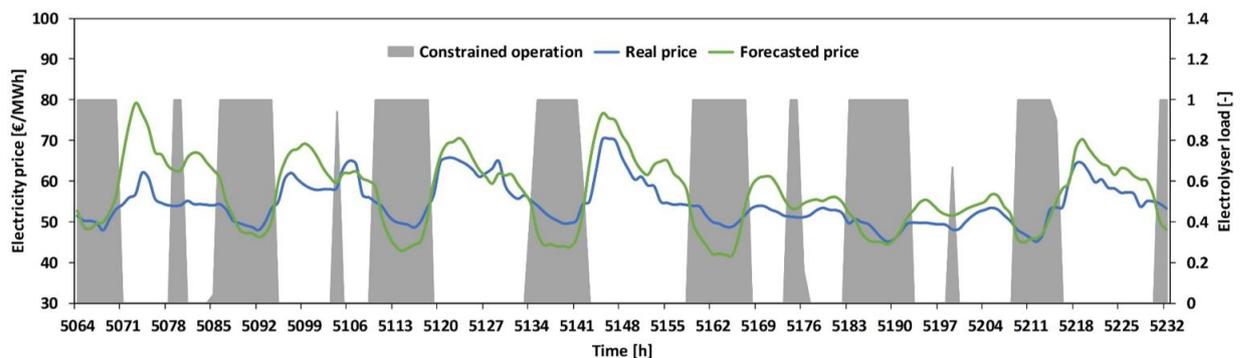


Figure 27: Relevance of forecasting error on the electricity price (real in blue and forecasted in green) and electricity load (grey) showed over a period of a week on a reference year, 2018.

The fluctuations of the electricity price that occurred during 2020 and 2021, however, made it difficult to predict the electricity price with a low MAPE (see Figure 26). Furthermore, the option to include forecasting of dynamic CO₂ emission factors in the model based on the work in WP4 was considered. But the developed neural network model does not appear well-suited to forecast emissions on an hourly basis because factors with high complexity such as electricity import origin and intermittent renewable generation have a significant impact on the emissions. Upon assuming daily foresight of these factors, a decent MAPE could be achieved (10-30 %), but without this, the error increases considerably (40-70 %).

To further develop and improve the tool regarding low MAPE, other input parameters, i.e. natural gas prices, values of wind power production would be needed. But with highly fluctuating electricity prices the challenges are huge to be able to improve the tool and would require resources beyond the extent of this project. Moreover, this was discussed with the stakeholders in the project (Uppsala Vatten and Region Uppsala). Their view was that the value of this forecasting tool will be rather low as they will most likely purchase electricity based on fixed rate agreements. Rather, the value of the electrolyser's by-products (oxygen for wastewater treatment and residual heat for integration in the wastewater treatment plant) is much more relevant considering the overall aim of this project. Therefore, it was decided



to allocate project resources to expand the valorisation of oxygen and residual heat within the integrated system of power-to-gas, including a biological methanation reactor, as well as biogas production from organic wastes and sewage sludge.



4.3 WP4: Hourly marginal carbon emissions of energy storage options.

Nowadays, grid electricity is associated with a considerable carbon intensity. When operating a power-to-X plant, it is therefore important to know the emission factor of the electricity used, or else the rather inefficient production of SNG would generate a lot of carbon emissions. To avoid this, a tool for the estimation of dynamic emission factors of the electricity grid is developed within WP4. Given the complexity of the energy system, two types of emission factors are computed on an hourly basis, namely the average (AEF) and the marginal one (MEF). While in the AEF the emissions are equally distributed across all consumers, the MEF refers to the rate of change in emissions with a small change in electricity consumption. A dynamic perspective is important to account for due to the temporal variations in the electricity mix that are prominent in interconnected and renewable power systems.

Open-source software that define dynamic electricity CO₂ emission factors and prices do exist. Among them, the software *elmada* [17] offers databases specific for Europe. It has thus been selected as reference software within this study. The existing hourly emission factor data present in *elmada* have been adapted to Swedish boundary conditions (i.e., trading system, transmission line limitations and renewable curtailment) to be applied to our case study.

The adapted tool has been tested in a relevant case study, where the emissions factors (both average and marginal) have been applied to a power-to-gas system (see Figure 28). The investigated system uses both grid and renewable electricity to try to minimize both cost and emissions, similarly to the layout proposed within this project.

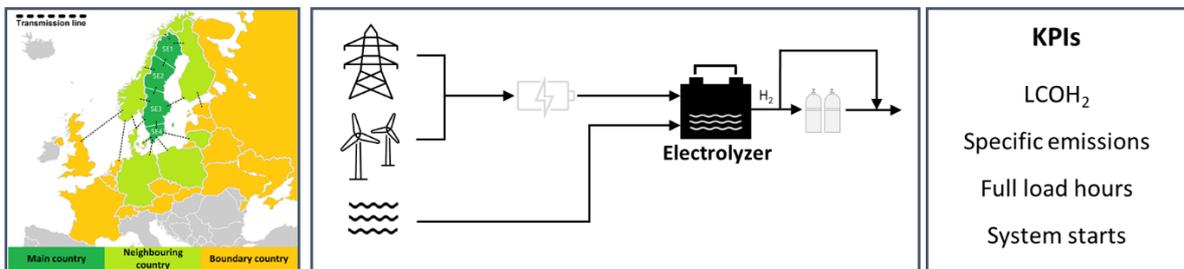


Figure 28: Schematic representation of the system analysed in as base case in WP4: the region of interest is Sweden (dark green in the picture on the left), the energy system analysed is schematically represented in the middle whereas the KPIs used to evaluate the results as summarize on the right.

As shown in Figure 29, there is a remarkable trade-off between costs of hydrogen production and the associated emissions. From these preliminary results we can conclude that by only looking at the average emission factor, an important part of the information is missing. Whereas the marginal emission factor can provide a better insight into the actual dynamic of the system. In the case presented in Figure 29 this translates into the following considerations; up to about 3'000 full load hours of operation, the electrolyser runs only with the electricity produced by the wind park. Above 3'000 full load hours, an amount of electricity proportional to the amount of full load hours must be purchased from the grid. The marginal emissions therefore increase because this electricity is not carbon-free, and its CO₂ footprint varies depending on how it is generated.

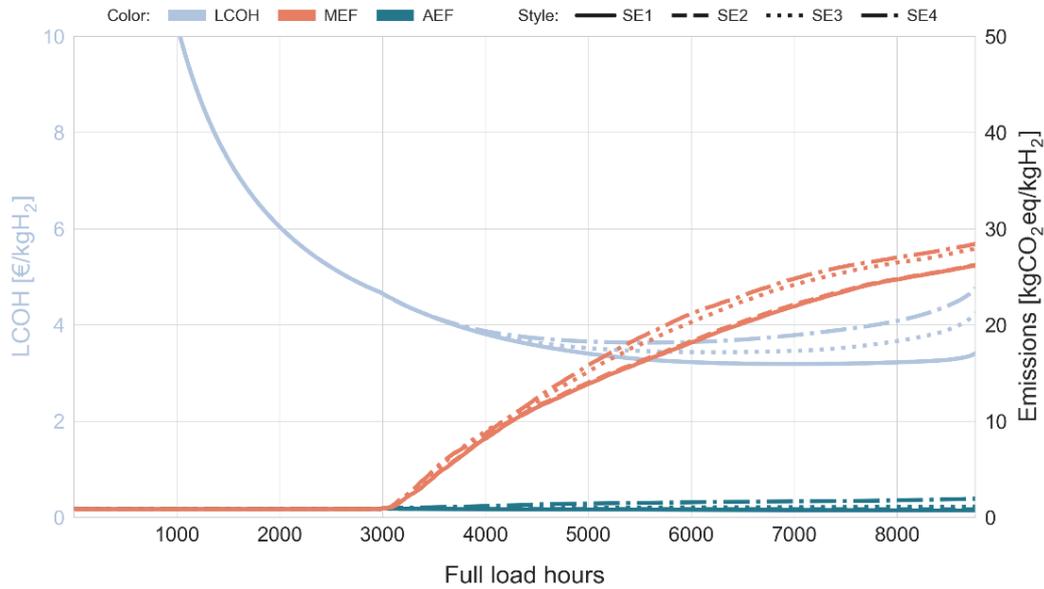


Figure 29: Example results of the analysis performed on the system shown in Figure 28. This graph shows the trade-off between costs of hydrogen production expressed as LCOH and specific CO₂ emissions in the four Swedish electricity bidding zones.

A scientific publication on this topic has been published in the peer-reviewed journal *Energy Conversion and Management* by the team of researchers at SLU (Engstam et al., 2023) [18]. The publication also widens the perspective of our work to a European level by analysing recent EU policy proposals regarding the definition of green hydrogen and highlights the importance of additionality and simultaneity of power-to-gas and renewable electricity generation. The emission factors determined in this study were also used in a follow-up study investigating the impact of power-to-gas by-product utilization (section 4.4).

The methodology to express the emission factors has been included into the WP2 tool and allows for analysis of all regions of interest, Switzerland included. Both research teams cooperated to develop complementary methodologies on system optimisation.





4.4 By-product utilization

Additional activities have taken place within the topic of by-product utilization in wastewater treatment. By valorising oxygen and heat, economic and environmental benefits could be achieved. However, the impact of these benefits on overall power-to-gas system performance depends on the achievable energy savings as well as the relative scale of by-product generation compared to the demand. Furthermore, because of the intermittent operation of electrolyser and methanation systems, and variations in wastewater flow, temporal mismatches in by-product supply and demand may also influence their value.

To investigate these aspects, a techno-economic assessment of by-product utilization in wastewater treatment was conducted. Hourly data for both heat and oxygen demand at the wastewater treatment plant was provided by Uppsala Vatten and applied to an intermittently operated power-to-gas system. The plant configuration was optimised based on the biogas production from both the local biogas plant in Uppsala and from the wastewater treatment plant.

It was found that heat and oxygen use within wastewater treatment could in fact improve the performance of power-to-gas systems, but that local conditions, such as specific energy consumption and relative scale of the processes, were key for determining the feasibility of the integration. The most significant benefits came from heat utilization, which decreased the production costs of SNG by almost 2 % (Figure 30). However, due to a mismatch in scale between the optimised power-to-gas plant and the wastewater treatment plant, only 25 % of the heat was utilized, and larger benefits would thus be possible if additional heat sinks could be found. Due to a low specific energy consumption of the aeration process at the wastewater treatment plant and high investment costs for oxygen equipment, the energy savings from oxygen utilization were minor and oxygen integration led to an almost 1 % increase in SNG cost. However, all generated oxygen could be used, meaning that the scale mismatch between power-to-gas and wastewater treatment was inversed compared to the heat case. Furthermore, it was found that temporal mismatches in by-product supply and demand had only a minor influence on their overall usability, primarily due to the significant scale differences previously mentioned. Sensitivity analysis revealed that the low specific energy consumption of the aeration process, which led to a negative economic impact of oxygen utilization, may be conservative and that performance improvements could be had in other conditions.

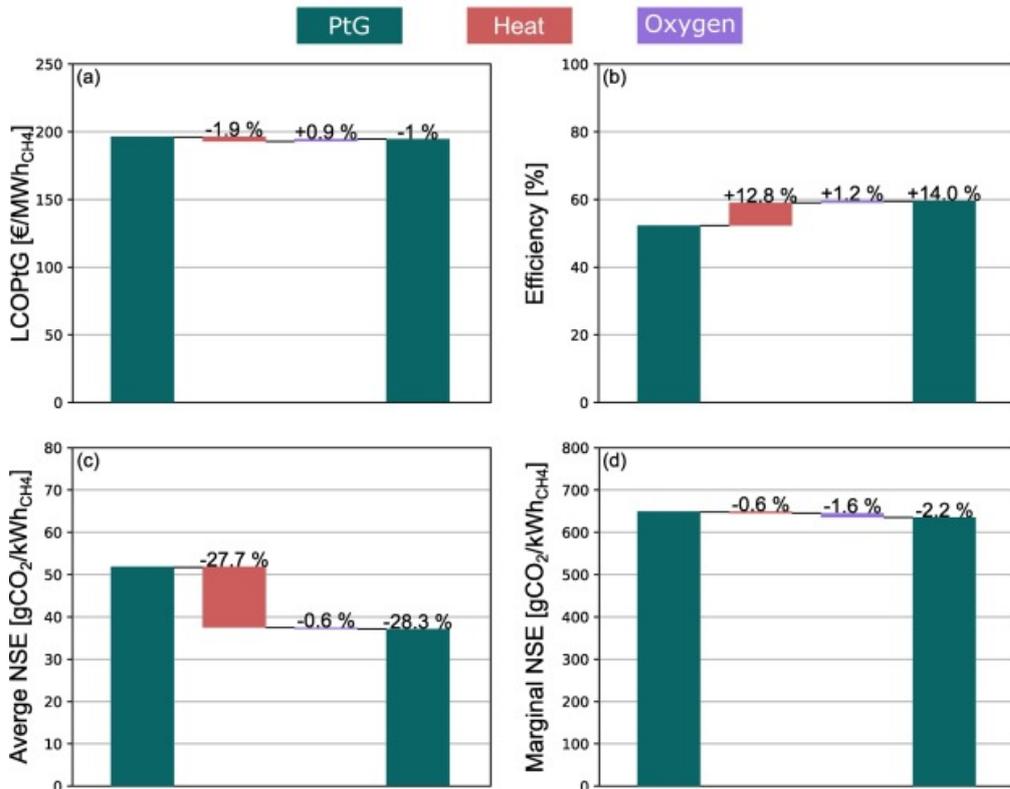


Figure 30: Relative impact of by-product utilisation on (a) levelized cost of power-to-gas (LCOPTG), (b) system efficiency and net specific emissions (NSE) from (c) average and (d) marginal perspectives.

A scientific article describing the methodology and outcome of this study has been published in the peer-reviewed journal *Applied Energy* by the SLU team (Engstam et al., 2025) [19]. The publication also expands on our previous work regarding the influence of electricity supply on the cost and emissions of power-to-gas (section **Error! Reference source not found.**) by analysing the impact of different configurations of wind and solar generation in combination with the electricity grid. For example, it was found that combining wind and solar in configurations where installed generation capacity exceeds power-to-gas capacity may positively influence both economic and environmental performance.



5 Conclusion and outlook

Although it is difficult to determine in what extent the project has influenced the strategic direction taken by both partners Uppsala Vatten and Region Uppsala, they are surely heading towards decarbonization. Indeed, the number of electric and biogas-driven buses increased in the city and in the region of Uppsala over the course of the project, lowering the carbon footprint of the local transport system. In the near future, a hydrogen refuelling station will be put in operation in Uppsala, opening the hydrogen path for fuel cell buses in the city. The biogas production is being increased to fuel more gas buses and reduce biogas import at the same time. In this perspective, the work and studies performed in the P2T-project have given knowledge and insights in the feasibility to expand even more the production of renewable hydrogen and methane associated with the biogas plant on the longer term.

Two highly interesting tools have been developed over the course of the project, one to assess the carbon intensity of grid electricity with an hourly resolution, and one to simulate, design and optimise the power-to-gas plant. Additionally, a methodology for techno-economic assessment of power-to-X facility operation including forecasting electricity prices and valorisation of by-products (oxygen and residual heat) have been developed. These three techniques allowed the team to evaluate the technical and economic feasibility of an extension of the biogas plant with a power-to-gas plant. The results from the project showed it would be technically feasible to increase the methane production by 50 % based on the available carbon dioxide in the biogas, thus replacing the imported biomethane. But for the moment, no definitive construction plan for such a system exists. Instead, the additional biogas required to operate the new biogas buses has been imported for several years and should be covered in the future by the extension of the “classic” biogas plant with a higher feedstock intake. This approach was preferred to the construction of a PtG plant mainly because of the high dependency of the latter to electricity prices, and its higher investment costs. Concrete measures, such as the replacement of the biogas upgrader have still been taken by Uppsala Vatten to facilitate the future implementation of a power-to-gas plant.

In addition to these activities, the power-to-transport project has been involved in the dissemination of the learnings and on the collaboration with various partners. Several internal meetings and workshops were organized in Sweden and in Switzerland, as well as external presentations of the methodologies and tools. Amongst others, the P2T- project has been associated with the Biogas Solution Research Centre in Sweden to share experiences, as power-to-X integrated with biogas plants is a topic addressed also there. One example is the plant at Tekniska Verken in Linköping to inject hydrogen in the post-digester and convert the carbon dioxide to methane (in-situ methanation).

Looking towards the future, the PtX-tool developed by OST is currently being further developed and could be used in follow-up or new projects, and the collaboration with BSRC regarding sector-coupling of hydrogen and biogas will continue at SLU. There is also an initiative from Region Uppsala to collaborate with a region in Finland on developing the different aspects of implementing hydrogen as a vehicle fuel. In general, both Swiss and Swedish teams will be on the lookout for new project chances and potential collaboration, especially on Uppsala’s transport system.



6 National and international cooperation

The Power-2-Transport project is an ERA-Net Project with partners from Switzerland and Sweden. Among the joined activities, three project-specific multi-day workshops have been organized: one in Uppsala in spring 2022, one in Rapperswil at the end of 2022, and a third again in Uppsala in autumn 2024. The research teams from SLU and OST also took part to several ERA-Net events where they could exchange with the community and with researchers working on related fields. In addition to these workshops, further activities were organized in the respective countries.

6.1 Switzerland

The OST team organized a workshop on renewable transport solutions that took place in March 2023. Representative from the private and public sectors were invited to participate, with the ultimate objective to create a stakeholder group that would be formed by people operating in different areas (i.e., policy makers, potential need owners as for example municipalities or logistic companies and researchers). Mostly representatives of government agencies were present in 2023. A second workshop was therefore planned for then end of 2024 with the idea to include the representatives of the industry (logistic companies, bus operators,...). In cooperation with the Advanced Motor Fuels (AMF) project, a survey has been conducted and addressed to these stakeholders. They were asked various questions on their current connection to renewable fuels and theirs plans for the future. Producers as well as retailers and final consumers were included. The results of this survey were used to better understand the requirements still needed to push synthetic fuels forward in Switzerland and lead to various project ideas on the subject.

The P2T project was presented at the March 2022 edition of the ExpertInnengespräch Power-to-X organized by the IET - Institute for Energy Technology in Rapperswil. Internal and external stakeholders interested in the power-to-X technology were present. The tool developed in work package 2 was specifically presented in detail to the IET staff. It is since then available for all employees to be used in any project where the design of a PtG plant is required. In the meantime, the tool is being further developed to include new and complementary features. The tool was also presented at the Imperial College in London in 2022. One of the team members on the OST side took part to a summer school on data driven optimisation and had the opportunity to present the PtX Tool.

6.2 Sweden

The activities carried out within this project are shared with the Biogas Solutions Research Center (BSRC) coordinated by the Linköping University. In occasion of the third and last workshop in Uppsala in October 2024, a one-day joint activity was arranged to enhance the exchange of results and perspectives. In total, 20 persons participated (9 from Power-to-Transport project, from Switzerland and Sweden, and 11 from BSRC). Participants represented universities, regions, companies from the industry, and consultants.

During the morning session, results and experiences from both parties were presented and discussed, including two presentations from the current project. After lunch, a study visit to the hydrogen filling station combined with an electricity charging station for heavy duty vehicles was organized. The station is being built by Uppsala Vatten and Vattenfall, Uppsala's electricity provider. Thereafter, a visit to the company Metacon was arranged. There, Uppsala Vatten's hydrogen gas project was presented followed by a presentation from the CEO of Metacon, which is a supplier of equipment for hydrogen production. The view on biogas and hydrogen development was discussed.



7 Publications and other communications

- Janke, Leandro, S. McDonagh, S. Weinrich, J. Murphy, D. Nilsson, P.-A. Hansson and A. Nordberg, "Optimizing power-to-H₂ participation in the Nord Pool electricity market. Effects on different bidding strategies on plant operation", *Renewable Energy*, no. 156, pp. 820-836, 2020. [15]
- Janke, Leandro, et al. "Modelling synthetic methane production for decarbonising public transport buses: A techno-economic assessment of an integrated power-to-gas concept for urban biogas plants.", *Energy Conversion and Management*, no. 259: 115574, 2022. [16]
- Engstam, Linus, Janke, Leandro, Sundberg, Cecilia, Nordberg, Åke. "Grid-supported electrolytic hydrogen production: Cost and climate impact using dynamic emission factors." *Energy Conversion and Management*, no. 293, 2023. [18]
- Vogel, Benedikt. "Upgrade für Biogasanlagen - Schweizerisch-schwedisches Forschungsprojekt zu Power-to-Gas," *Aqua&Gas*, no. 11, pp. 56-59, November 2024. [20]
- Engstam, Linus, Janke, Leandro, Sundberg, Cecilia, Nordberg, Åke. "Optimizing power-to-gas integration with wastewater treatment and biogas: A techno-economic assessment of CO₂ and by-product utilisation." *Applied Energy*, no. 377, Part B: 124534, 2025. [19]



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