# A future introduction of biohydrogen to the Swedish energy system

## Current developments and opportunities from the multi-level perspective

FRITIOF PRÖJTS ERLANDSSON 2020
MVEM12 MASTER'S THESIS 30 CREDITS
ENVIRONMENTAL SCIENCE | LUND UNIVERSITY

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2020

LUNDS UNIVERSITET

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MVEM12 Master's thesis, 30 credits, Lund university

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Lund 2020

# Abstract

Biohydrogen is increasingly being explored as part of strategies to achieve deep emission reductions. While much research has focused on the technical dimension of biohydrogen, fewer efforts have positioned it in larger contexts. Using literature and expert interviews, this study applies the multi-level perspective to explore an introduction of biohydrogen to the Swedish energy system. The findings show that hydrogen is well-established in applications like biofuel manufacturing but also proposed in new areas such as steelmaking. New networks among incumbent actors, formed around electro-hydrogen, are central to several of these developments. Institutional conditions, a lack of infrastructure and competing technology platforms however constitute challenges that influence the role of hydrogen in applications like transport. The findings furthermore highlight that the degree of maturity of biohydrogen production paths vary significantly. Biohydrogen production via gasification have been explored in several projects and is best introduced at large scale. Costs and technical risk however remain as significant constraints. Biohydrogen production via biochemical conversion constitute comparatively less developed paths associated with higher production costs and great uncertainty. The study does however find evidence that the alignment between certain biochemical paths and the organic waste treatment regime in Sweden can provide opportunities for a future introduction. A key area of importance considering an integration is the need to balance feedstock costs with the need to achieve a viable and stable production process. The outcome of this study indicates that further efforts are called for that investigate were the conditions for an introduction of biohydrogen are most favourable.

# Popular abstract


Biovätgas - nuvarande utveckling kan tala för en framtida integration i det svenska energisystemet

Ett stort fokus ligger idag på att minska våra utsläpp av växthusgaser. Vätgas är sett som ett intressant alternativt bränsle i sammanhanget eftersom dess förbränning bara ger upphov till vatten. Vad färre vet är att produktionen av vätgas orsakar desto större utsläpp av växthusgaser eftersom den ofta är beroende av fossila bränslen. Vid produktion av biovätgas drar man istället drar nytta av väteatomerna som finns i biomassa. Biovätgas är därför en typ av förnybar vätgas som kan tjäna som ett klimatsmart alternativ.

Resultat från den här studien visar att biovätgas kan komma att få en viktig roll i det framtida svenska energisystemet. Studiens fokus har legat på att sätta en rad produktionsprocesser för biovätgas i ett större perspektiv. Processerna skiljer sig åt betydligt, då vissa bygger på att biomassan hettas upp, medan andra drar nytta av mikroorganismers naturliga nedbrytningsprocesser. Resultaten från studien visar att vätgas utforskas i flera nya projekt i Sverige, och att det dessutom finns höga ambitioner att ersätta fossil vätgas med förnybar. Tillsammans skapar detta stora möjligheter för biovätgasen att segla upp som ett alternativ till den fossila. Resultaten fastställer dock också att de olika produktionsprocesser är väldigt olika tekniskt utvecklade. Även om biovätgas kan utgöra ett viktigt alternativ i framtiden behövs det mer forskning och testanläggningar innan en större introduktion kan bli aktuell. Redan idag finns det dock ett antal faktorer som talar för biovätgasen. Sveriges stora tillgång på biomassa från skogen, tillsammans med allt matavfall från hushåll och industrier, kan tillsammans bidra till en framtida biovätgasproduktion. Att de olika produktionsprocesserna har möjlighet att använda olika sorters biomassa är också positivt i sammanhanget, eftersom det kan leda till mindre konkurrens. I det större perspektivet finns det möjligheter att kombinera biovätgas med andra delar av energisystemet, till exempel biogasproduktion. Biovätgasen kan också bli en viktig pusselbit genom det faktum att den till skillnad från annan produktion av förnybar vätgas inte kräver stora mängder elektricitet. Tillsammans med fortsatta studier kan resultaten bidra till att biovätgas uppmärksammas av olika aktörer, och till att processerna utvecklas vidare.

# Abbreviations

AD – anaerobic digestion

CAPEX – capital expenditures

COD – chemical oxygen demand

DF – dark fermentation

FCEV – fuel cell electric vehicle

HPC – hydrogen production cost

HPR – hydrogen production rate

HRS – hydrogen refuelling station

HY – hydrogen yield

MEC – microbial electrolysis cell

MLP – multi-level perspective

OLR – organic loading rate

OPEX – operating expenditures

PF – photo fermentation

SMR – steam-methane reforming

# Contents

# 1 Introduction

Mitigation of climate change and adaptation to its consequences is increasingly viewed as an urgent matter in contemporary society. Global warming as a result of human activities is already estimated to be 1°C according to IPCC and is likely to continue with an increase of 0.2°C per decade (IPCC 2018). Initiatives to address this trend include the international Paris agreement, with its aim to limit the rise in global temperature to well below 2°C (Unfccc 2016). Several measures have been adopted in the EU to limit greenhouse gas emissions and stimulate a clean energy transition. These include the directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, (RED II), with a key target of achieving a 32% share of renewable energy by 2030. RED II also includes specific targets for road and rail transport, where a minimum 14% of consumed energy should be renewable. Other important efforts include National Energy and Climate Plans (NCEP's) for member states (European Commission 2014). A 2050 long-term strategy has also been introduced in the EU, with the main goal being net-zero greenhouse gas emissions. Energy production and consumption is seen as central in this context, as it is responsible for more than 75% of greenhouse gas emissions in the EU. The scenarios developed as a part of the 2050-strategy subsequently emphasize the role of renewables in the future European energy mix (European Commission 2018).

Adhering to these objectives, a draft of Sweden's NCEP was released in early 2019. Key goals include a 50% more efficient energy use in 2030 compared to 2005, a 70% reduction in emissions from domestic transport in 2030 compared to 2010-levels and no net emissions of greenhouse gases by 2045. While Sweden lacks a specific 2030-target for renewables they already constitute a major part of total energy use. Biofuels are especially important, as they represented 56% of total renewable energy use in Sweden in 2015 (Ministry of Environment and Energy 2019).

As reflected in both international and national goals, a transition towards an energy system less dependent on fossil fuels is seen as crucial to limit greenhouse gas emissions. Challenges associated with the current energy system are however not limited to emissions but also include resource scarcity, energy security and increasing needs as populations grow (IEA 2019a). Significant investments and research undertakings are therefore devoted to the development of new energy solutions that can mitigate the outlined challenges. Hydrogen, in this study referring to hydrogen gas, has gained considerable interest in this context for its versatility and potential (IEA 2019b). Key to understanding hydrogen is recognizing its role both as an energy carrier and as a chemical feedstock. While its use as an energy carrier is perhaps most associated with emerging applications like fuel cells, hydrogen is already used in significant amounts as a chemical feedstock. Examples of the latter include the refining industry, where hydrogen is crucial to the production of both conventional fossil fuels and biofuels. One current challenge associated with hydrogen is however the greenhouse gas emissions resulting from its production, which is dependent on fossil fuels. Furthermore, hydrogen faces several barriers that directly influence its wider introduction in new applications. Examples include hindering regulations, a general lack of infrastructure and technology uncertainty (IEA 2019b).

Low-carbon hydrogen is viewed as an option to hydrogen based on fossil fuels, since its production is associated with lower greenhouse gas emissions. Two commonly proposed production paths in this context are electrolysis and the conversion of biomass or organic waste. The latter results in what is known as biohydrogen, owing to its origin. Biohydrogen production can be achieved by both thermochemical and biochemical approaches (García et al. 2017). In the thermochemical paths, the conversion of the feedstock to biohydrogen and other gases is driven by the application of heat under carefully controlled chemical conditions (Balat 2008). Through subsequent upgrading and separation, a pure source of biohydrogen can be realised. Gasification is a thermochemical path that has been especially acknowledged for its future potential (Zech et al. 2015). The biochemical paths much differently employ microorganisms that metabolize the feedstock and produce biohydrogen as a part of this process. One emerging path that has gained recognition is dark fermentation, but since it does not in itself achieve a full conversion of the feedstock, two-step processes are often considered (Hallenbeck & Gosh 2009). Photo fermentation, microbial electrolysis cells and anaerobic digestion are commonly envisioned second steps (Bundhoo 2017). Although promising, both thermochemical and biochemical paths face several challenges associated with technical maturity and require further development become more viable (IEA 2019b).

In light of the outlined challenges, important efforts have been directed towards developing biohydrogen production in the technical dimension (Willquist et al. 2012; Pawar et al. 2013) and while electrolysis is seen as a path with major potential, less is known about the future of biohydrogen (IEA 2019b). Previously cited goals for emission reductions and renewable energy, high expectations for hydrogen and emerging paths for biohydrogen production also call for broader investigations that explore the future of biohydrogen production. The current study will attempt this by exploring a potential introduction of biohydrogen to the Swedish energy system. With the presence of numerous well-defined biomass and organic waste streams (Torén et al. 2019), several policies on emission reductions and clean energy (Ministry of Environment and Energy 2019) and a long history of using renewables (Swedish Energy Agency 2017), Sweden constitutes an ideal case for such a study. With this outline, the thesis can contribute novel learnings that complement the research and development concerned with biohydrogen production at RISE.

## 1.1 Aim and research questions

The aim of this study is to identify how biohydrogen, extensively investigated at RISE, can be integrated to the Swedish energy system. The analysis that contributes to this aim will be achieved by applying the multi-level perspective (MLP) to relate the main advantages and limitations of two selected biohydrogen production paths to the socio-technical conditions of the Swedish energy system. The paths that will be considered are gasification and dark fermentation, were the latter will be addressed as a two-step process coupled to either photo fermentation, microbial electrolysis cells or anaerobic digestion. The main advantages and limitations will be established by considering technical maturity, economics, and feedstocks of the paths in detail. The inherent complexity of the energy system together with the current state of biohydrogen production will be reflected in the scope of the study as well as in the specific assessments made. Emphasis will thus be on identifying possible niches for biohydrogen in the Swedish energy system rather than developing projections addressing how a large-scale integration of biohydrogen can take place. Based on this aim, the following research question and corresponding sub-questions can be formulated:

How can biohydrogen be integrated to the Swedish energy system?

- What is the current role of hydrogen in the Swedish energy system?
- What are the main advantages and limitations of biohydrogen production via gasification and dark fermentation?

## 1.2 Delimitations

- The following definition of an energy system will be used: “All components related to the production, conversion, delivery, and use of energy.” (Allwood et al. 2014).
- The geographical scope of the study is Sweden. International literature and examples will however be used.
- The study includes hydrogen both in its role as an energy carrier and as a chemical feedstock.
- The study is delimited to one thermochemical path - gasification, and one biochemical path - dark fermentation. Dark fermentation will be addressed as coupled to either photo fermentation (DF-PF), microbial electrolysis cells (DF-MEC) or anaerobic digestion (DF-AD). What these paths entail is elaborated on in section 3.1.

# 2 Method

The study was conducted as a literature review, which was complemented with expert interviews. The approach was based on a specified data collection, evaluation, and analysis process along with clearly defined research questions and delimitations. This approach was chosen as it ensured a certain degree of replicability and transparency (Bryman 2016 p. 399). The multi-level perspective, a framework introduced by Geels (2002; Geels, 2004; Geels & Schot 2007), was applied to structure and analyse the collected material. While MLP has been linked to other analytical frameworks such as Strategic niche management (Schot & Geels 2008), it was used on its own in this study. The MLP is introduced in section 3.2 and its function in this study is elaborated on in section 2.3. The work structure is illustrated below in figure 1. As a last step, two semi-structured interviews with were held with experts on the selected biohydrogen production paths for the purpose of validating the findings and providing additional input for the discussion.

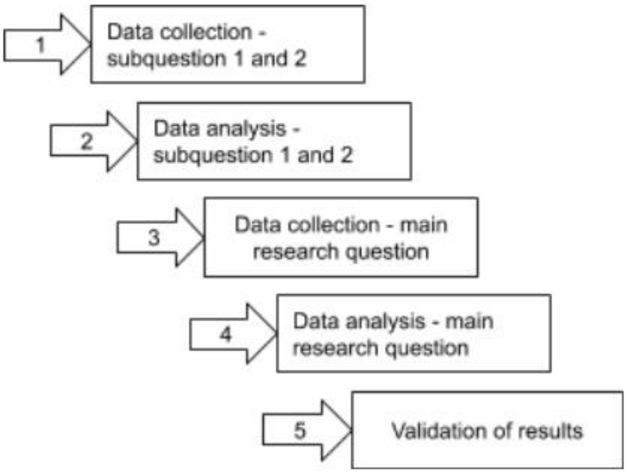


**Figure 1. Data collection and analysis.**

## 2.2 Data collection

Scientific articles on MLP were identified as an initial step to build an understanding of the framework and to design data analysis. LubSearch was employed for this purpose, and the following keywords were used: MLP, “multi-level perspective”, Geels and Swed*. The research questions were addressed using mainly scientific articles in the field of biohydrogen. The scientific literature was complemented with statistics, reports and findings from public agencies, research organisations and other actors related to hydrogen to yield a comprehensive analysis. LubSearch were used in collecting scientific articles, while statistics, reports and other material were identified through Google and the websites of the respective organisations. Scientific articles and reports were also identified and collected via snowball sampling, an approach in which references of previously identified material are utilized (Bryman 2016 p. 415). The following criteria was used throughout data collection to systematize the approach:

- Material in both Swedish and English were included
- Non peer-reviewed scientific articles were excluded
- Newspaper articles were excluded
- Theses were excluded
- Material published before 2005 were excluded from the results and the discussion

The aim of these criteria was to provide an accurate account of the investigated topic based on relatively recent findings. Data that fulfilled these criteria were evaluated firstly based on the title, secondly on the abstract or summary and thirdly on reading the material in its whole.

### 2.2.1 Data collection for sub-question 1

The aim of this initial step was to collect material concerned with the current role of hydrogen in the Swedish energy system. With this in mind, the material needed to address both hydrogen production and applications. Using the keywords outlined in table 1 yielded a significant number of articles, many which were not deemed relevant to answering the sub-question. The search was therefore narrowed down to articles in *International Journal of Hydrogen Energy, Journal of Cleaner Production* or *Energy,* resulting in 217 hits. Reports and statistics on hydrogen production and applications were also collected to account for the larger picture. These were collected via Google and websites using “vätgas”, ”produktion”, “Sverige”, “hydrogen”, “statistics” as keywords. Examples of sources include the Swedish Chemicals Agency, Eurostat and Vätgas Sverige.

**Table 1. Data collection – sub-question 1.**

| Search engine | Keywords | Number of hits | Selected articles |
|---|---|---|---|
| LubSearch | hydrogen AND Sweden AND energy AND system | 217 | 5 |

### 2.2.2 Data collection for sub-question 2

The focus in this part was on the feedstocks, technical maturity, and economics of the selected biohydrogen paths. The scope was inherently international, both in terms of scientific articles and reports. Data collection in this step was divided into the respective paths as shown by table 2, thus ensuring some additional structure. One search focused on GoBiGas, a Swedish gasification-based plant that have yielded recent findings on gasification at a larger scale than previous efforts (Hrbek 2019). Given the main aim of the study, these findings were deemed important to include. Reports on biohydrogen were also collected via Google and websites using “biohydrogen”, “production” and “economics” as search terms. Examples of sources include the International Energy Agency and Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

**Table 2. Data collection – sub-question 2.**

| Search engine | Keywords | Number of hits | Selected articles |
|---|---|---|---|
| LubSearch | “dark fermentation” AND “photo fermentation” | 260 | 9 |
| LubSearch | “dark fermentation” AND “microbial electrolysis” | 41 | 6 |
| LubSearch | “dark fermentation” AND “anaerobic digestion” | 324 | 6 |
| LubSearch | “dark fermentation” AND economic* | 228 | 7 |
| LubSearch | gasification AND biohydrogen | 145 | 5 |
| LubSearch | Gobigas | 22 | 3 |

### 2.2.3 Data collection for addressing the main aim

Data collection and analysis concerning the sub-questions were pursued in parallell, as shown by figure 1. The sub-questions were formulated to be complementary and together provide the bulk of findings needed to address the main aim. Conclusions from the sub-questions however pointed to feedstock availability in Sweden as a crucial topic that needed to be accounted for to produce a complete picture. Two additional searches in LubSeach were subsequently conducted as described below in table 3. These focused on the titles to yield a more defined search. Reports and statistics were collected via Google and websites using “skogsbränsle”, “biomassa”, “matavfall”,” substrat” and “organiskt avfall” and ”pris” as search terms. Examples of sources include the Swedish Energy Agency and RISE.

**Table 3. Data collection – main aim.**

| Search engine | Keywords (title specific) | Number of hits | Selected articles |
|---|---|---|---|
| LubSearch | biomass AND sweden | 212 | 4 |
| LubSearch | “food waste” AND sweden | 7 | 1 |

## 2.3 Data analysis

Data collection resulted in both quantitative and qualitative material. Quantitative material, for example the economics of biohydrogen production, were levelized and adjusted for inflation using the Swedish Consumer Price Index available via Statistics Sweden (Statistics Sweden 2020). Levelization was performed in Microsoft Excel using assumptions and data present in the respective articles and reports. The provided data did not allow for levelization in all cases. These cases are highlighted by “–“ in the tables in the results.

Both quantitative and qualitative material were analysed by applying the MLP. The concepts outlined in the theoretical background, niche, regime, and landscape, were central in this process. While literature on MLP constituted a sound base for data analysis, there was a further need to operationalise MLP in a way that brought together the MLP-concepts with the specific aim and scope of this study. Findings present in the collected material, ranging from technical details on biohydrogen to policies present in Sweden, were assumed to fit into either niche, regime or landscape level, and to explain the dynamics within and between the levels. Aspects related to biohydrogen were assumed to belong to the niche level, owing to the definition of niches given in section 3.2 and the status of both thermochemical and biochemical biohydrogen production paths as developing rather than developed (IEA 2019b). The collected material was however also expected to include information that could be related to the regime-level, as incumbent actors often are involved in niche technologies (van Bree et al. 2010). Incumbent companies and technologies in the Swedish energy system were in the context of the study assumed to belong to the regime level. While the study focused mainly on the niche and regime levels, some findings were also expected to concern landscape developments. An example would be ambitions on reducing greenhouse gas emissions. Table 4 was constructed to highlight the approach.

**Table 4. Operationalisation of MLP.**

| Niche | Regime | Landscape |
|---|---|---|
| Technical characteristics of biohydrogen<br><br>Economics of biohydrogen<br><br>Information on pilot- and demonstration plants<br><br>Other niche technologies related to hydrogen production | Incumbent actors in Sweden<br><br>Incumbent technologies in Sweden<br><br>Major biomass and organic waste applications<br><br>Policy and regulation aligned to the aforementioned | Discourse on emission reductions<br><br>Climate goals and corresponding policy<br><br>Fossil fuel prices |

## 2.4 Validation interviews

Two expert interviews were held as a last step to validate the findings on biohydrogen and its potential introduction. The interviewees were selected to cover both the thermochemical and biochemical paths. Consequently, the interviewee at RISE has long experience working with gasification while the interviewee at Lund University are an active researcher in the field of biochemical hydrogen production. The choices were guided by discussions with my supervisors at RISE and Lund university. A semi-structured approach was used since it provided a clear point of departure while at the same time allowed for follow-up questions based on the answers given (Bryman 2016 p. 468). Both interviews were around 1 hour in length, with one being conducted via phone and the other via Microsoft Teams. Afterwards, they were transcribed and in one case also translated from Swedish to English. The interview-guides, including an English version of the interview held in Swedish, can be found in appendix A and B.

Table 5. Expert interviews.

| Interviewee | Organisation | Date |
|---|---|---|
| Senior researcher | RISE | 21/4 |
| Senior lecturer | Lund university | 24/4 |

## 2.5 Reliability and validity

Two important factors to consider when designing and conducting research are reliability and validity. These two factors can be viewed as addressing the degree of objectivity in research and are closely related. Reliability is the degree to which a certain approach leads to the same results when performed under different circumstances. Validity on the other hand is the degree to which the results can be considered describing the investigated topic accurately. This means that an approach can be perfectly reliable without generating valid results. The opposite is however not possible, as perfect validity requires perfect reliability (Kirk & Miller 1986). Several measures were taken when designing this study to address both reliability and validity. The delimitations, relevant to both reliability and validity, were firstly chosen and then outlined in detail in section 1.2. Data collection and evaluation was performed using certain criteria, with one example being the choice to omit newspaper articles. Keywords were documented throughout the process. Data analysis was importantly structured in a way that made both the approach and underlying assumptions clear. A well-established framework previously used to study closely related subjects were chosen to make comparisons possible, and greatly aided in understanding the framework itself.

## 2.6 Ethical reflection

Substantial efforts are directed towards developing biohydrogen production, and part of these efforts concerns genetically modifying hydrogen-producing microorganisms to increase yields and overall performance (Song et al. 2020). While this has clear ethical implications, the current study did not involve discussions or suggestions regarding the genetic modification of microorganisms. One must also recognize the topic of first- and second-generation biofuels. Developing the latter are considered a high priority in the light of policies like RED II, as they importantly are not competing applications for food biomass. Biohydrogen, as considered in this thesis, is an example of a second-generation biofuel. Safety of use and standardization are other important aspects in the context of hydrogen. Findings presented and analysed in this study should not be considered advice but rather as aspects that must be further investigated. Interviews were performed to ensure that the interviewees understood the aim and context of the study, the purpose of their participation and the way their contributions would be used. Ethical considerations that arose during the conduct of this study was discussed with my supervisors. The considerations described above were not considered limiting to the conduct of the study.

# 3 Background

## 3.1 Technical background

*The level of detail in this section will reflect the scope employed in the results and discussion. The technical and chemical aspects will thus be presented in a generalized way.*

### 3.1.1 Gasification

Gasification is a broad term that encompasses several different approaches. A main difference between gasification and “regular” combustion is the restricted supply of an oxidizing agent, like oxygen or air, in the former (Balat 2008). Pre-treatment, with examples being size reduction and drying, is often necessary before biomass or organic waste can be used as a feedstock in gasification. The configuration of the pre-treatment ultimately depends on the type of feedstock and gasifier involved (Shahabuddin et al. 2020). Gasification as referred to in this study is a multi-step process that takes place inside reactors where the temperature, pressure, chemical conditions, and feedstock supply are carefully controlled to sustain and optimize the individual steps. A mineral or metal-based catalyst can be used to facilitate the conversion (Balat, 2008). Air, oxygen or steam are commonly used oxidizing agents. Using steam as an example, the process (1) can be described in the following simplified way (Nikolaidis & Poulikkas, 2017):

$$Biomass + Steam \rightarrow H_2 + CO + CO_2 + other\ CH's + tar + char \qquad (1)$$

The obtained gas is known as synthesis gas, or syngas for short. It consists of mainly hydrogen and carbon-monoxide but also contains other gaseous products as well as leftover ash, tar, char, and other impurities (Nikolaidis & Poulikkas, 2017). While syngas has many applications, further treatment is needed to achieve pure hydrogen. A filter that removes ash and leftover char can be employed as a first step after the gasification reactor (Zech et al. 2016), followed by a water-gas shift reactor designed to convert carbon-monoxide in the syngas into additional hydrogen. Carbon dioxide is also formed in this reaction (2) (Nath & Das 2003):

$$CO + H_2O \rightarrow H_2 + CO_2 \qquad (2)$$

The remaining tar, water and carbon dioxide can then be cleaned in two subsequent washing steps. As a last step, the now hydrogen-rich gas must be separated into pure hydrogen and waste gases. Pressure-swing adsorption (PSA) is a proposed technique for this purpose (Zech et al. 2016). Alternatives to PSA are solvents or amine systems (Materazzi et al. 2019). After this last step, the hydrogen can either be used directly, stored, or transported.

### 3.1.2 Biochemical conversion

Biochemical conversion processes rely on microorganisms like bacteria and algae. The processes addressed in this work, DF-PF, DF-MEC and DF-AD are achieved in liquid media contained in bioreactors. Each of the process steps, DF, PF, MEC and AD, are associated with certain microorganisms. As in gasification, pre-treatment of the feedstock (often known as substrate in the context of biochemical conversion) constitutes the initial step. Examples include cutting and grinding, while the use of acids or enzymes are two types of chemical approaches. A main objective is to make the carbohydrates present in the feedstock more accessible to the microorganisms (Nagarajan et al. 2020). When industrial effluents are used as a feedstock, the presence of toxic compounds is another factor that can warrant pre-treatment (Kapdan & Kardi 2006).

#### *3.1.2.1 First step - Dark fermentation*

Dark fermentation is an anaerobic, light-independent process. The basic principle of dark fermentation is the microbial conversion of carbohydrates into organic acids, hydrogen, and carbon dioxide. The conversion can proceed via several different metabolic pathways, each resulting in a certain organic acid as the end-product (Levin et al. 2004). The highest hydrogen yield is associated with acetate as the end-product. In that case, 4 moles of hydrogen can be produced per mole of glucose, as shown in reaction 3 (Levin et al. 2004):

$$C_2H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + 2CO_2 \qquad (3)$$

Dark fermentation is associated with different temperatures depending on the microorganisms involved. These intervals are usually referred to as mesophilic

(25-40°C), thermophilic (40-65°C), extreme thermophilic (65-80°C) and hyperthermophilic (>80°C) (Levin et al. 2004). Both monocultures and mixed cultures of microorganisms have been explored. For practical reasons, mixed cultures are considered a more viable option since they do not require sterile conditions and feedstocks. Mixed cultures are however also associated with a lower conversion rate of around 21% (Tapia-Venegas et al. 2015) compared to the ideal rate of 33% shown in reaction 3 above. Other parameters that influence the hydrogen yield are the pH in the fermentation medium, hydrogen partial pressure in the headspace of the bioreactor and the hydraulic retention time. The last refers to how long the medium is kept in the bioreactor before being replaced by a new medium. Related to this, researchers have investigated dark fermentation both as a continuous and as a batch process (Levin et al. 2004).

*3.1.2.2 Second step – Photo fermentation, MEC or Anaerobic digestion*

Photo-fermentation is similarly an anaerobic process but associated with photosynthetic microorganisms. This importantly makes it dependent on available sunlight or artificial light that must be provided to the bioreactor (Ljunggren et al. 2011). Central to photo fermentation is the metabolic conversion of an organic feedstock into hydrogen and carbon dioxide. The general reaction (4), based on acetate, can be described as (Rocha et al. 2001):

$$CH_3COOH + 2H_2O + light \rightarrow 4H_2 + 2CO_2 \qquad (4)$$

Coupling dark fermentation to photo-fermentation (DF-PF) have been shown to increase biohydrogen production by 274% in average as opposed to a single stage dark fermentation process, since the end products of dark fermentation are used as a feedstock in photo fermentation (Bundhoo 2017).

MEC constitutes an alternative second step that can be coupled to dark fermentation (DF-MEC). A MEC is a bioelectrochemical system based on an anode and a cathode. These components are kept in a liquid medium that makes transfer of molecules and ions between them possible. Microbes are present at the surface of the anode where they convert organic matter into carbon dioxide, hydrogen ions and electrons. In an DF-MEC-process, this organic matter would be DF effluents. The positive hydrogen ions then transfer to the cathode via the liquid, where they combine to form hydrogen gas when subject to additional applied voltage (Logan et al. 2008). A rationale for DF-MEC can be found in the higher hydrogen yields and reduced COD in effluents that can be achieved compared to a single stage DF (Laularette et al. 2009).

The third path is DF-AD, where the second step is anaerobic digestion. Anaerobic digestion is a broad term that can be said to include dark fermentation, but it will in the context of the study specifically refer to the process where organic matter is converted into methane and carbon dioxide. This process is commonly used to treat a wide range of organic wastes coming from diverse sources (Klackenberg 2019). Coupling dark fermentation to anaerobic digestion enable the organic acids produced by dark fermentation to be used by the methane-producing microorganisms, thus resulting in a two-step process producing both hydrogen and methane. Such configurations have been shown to result in significantly higher energy yields than one-stage dark fermentation processes (Escamilla-Alvarado et al. 2014). A DF-AD process can be configured to produce either a hydrogen-methane gaseous blend known as hythane, or only biohydrogen through reforming of the methane.

All three paths produce a mixed gas that not only contain hydrogen. This gas must be collected from the bioreactors and then purified. One option is to use PSA, as mentioned in gasification. An alternative approach is to use an amine solution, which has been proposed to effectively remove carbon dioxide from biogas produced by DF-AD (Willquist et al. 2012). After a sufficiently pure hydrogen has been achieved, it can be used directly, stored or transported just as in the case of gasification.

## 3.2 Theoretical background

The complexity of the main aim called for an approach anchored in a proven framework. This framework was found in MLP, which is centred around on transitions in socio-technical systems (Geels 2002). MLP have previously been used to analyse biomass district-heating (Dzebo & Nykvist 2017), biogas (Geels & Raven 2006) and the use of hydrogen in transportation (van Bree et al. 2010) among many others. MLP emphasizes the importance of radical innovations (Geels 2019) but builds upon the central notion that transitions, figure 2 below, come about by interactions within and between three analytical levels – niche, regime and landscape (Geels 2002).

Socio-technical regimes form the middle level of MLP. Regimes are the stable configurations, the status quo, of actors, rules, markets, infrastructure and so forth in socio-technical systems (Geels 2002). A socio-technical system can be illustrated by car-based road transport, consisting of automobiles, fuel infrastructure, car manufacturers, traffic rules, cars users and driver preferences, among others. Actors in this socio-technical system would for example be policymakers, car companies, car users and NGO’s. The rules of a socio-technical system can be both formal, like traffic laws and emissions standards, and informal, like engineering practices (van Bree et al. 2010). The elements of the socio-technical system, including actors and rules, are understood to be aligned to each other and interlinked, thus forming a regime. Forestry, agriculture, or fishery regimes can in a similar way be outlined by analysing the current configuration of actors, technologies, markets, and rules in those areas. Techno-economic factors are important in explaining the stability of regimes, as incumbent actors often have large sunk investments in machines and infrastructure (Geels & Schot 2007). Although stable, regimes can and do change. This however usually is a slow process generating incremental innovation (Geels 2002).

Niches form the micro-level in the multi-level perspective. In contrast to the incremental change and innovation in regimes, niches generate radical innovations and do not exhibit the same rigidity and scale. Niche innovations are often technical in nature, like hydrogen cars (van Bree et al. 2010) or gasifiers (Verbong et al. 2010). The rules, expectations and general conditions present in niches differ to a great extent from those present in regimes, meaning that niches constitute a sheltered environment where learning processes around innovations can take place. This is important, as niche-innovations often have low technical and economic performance (Geels 2002). Funding at the niche level is commonly provided in the form of strategic investment from companies or as government subsidies since niche innovations often aim at solving problems within regimes (Geels 2004). Niches furthermore function as environments for building supply chains and user-producer relationships (Geels 2002). Examples of other radical niche-innovations are solar- and wind energy, biomass stoves and smart electricity meters (Geels 2019).

The socio-technical landscape constitutes the macro-level in the MLP and can be seen as the exogenous environment exerting influence on both regimes and niches. Examples of aspects related to the landscape level include oil prices, environmental discourse and environmental goals (Geels 2002). Developments at the landscape level do however need to be perceived and translated by actors at the regime and niche level to exert influence on them, as they do not have a direct, mechanical impact (Geels & Schot 2007). Change at the landscape level is generally slow. The landscape is important to the understanding of transitions as it put pressure on existing regimes in a way that can lead to the breakthrough of niche technologies (Geels 2002).

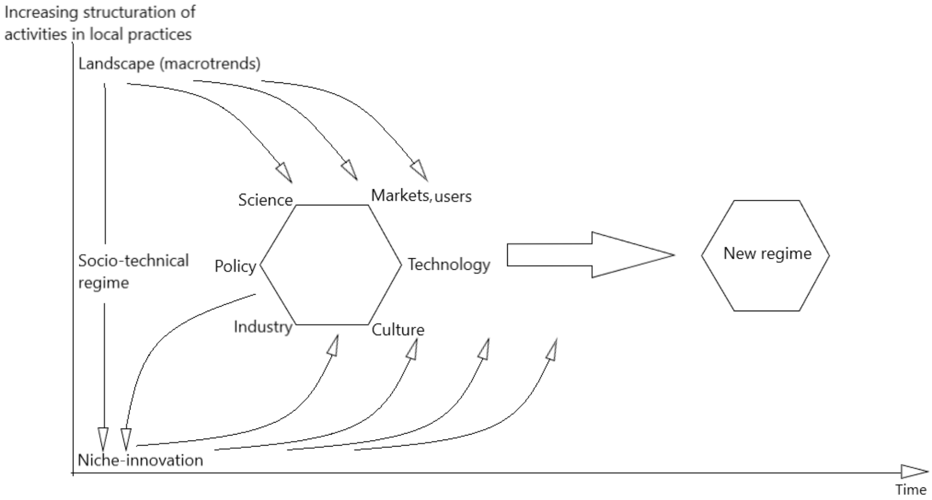


**Figure 2. The multi-level perspective on transitions.** Based on Geels & Schot (2007).

While figure 2 shows an "ideal" transition, the reality is often more complex. Four different transition paths have therefore been distinguished to better account for this complexity (Geels & Schot 2007). The *transformation* and *reconfiguration* paths involve regimes gradually growing out of the old. The latter revolve around a symbiotic relationship between the regime and a niche innovation. In contrast, the *de-alignment and re-alignment* path along with the *technological substitution* path include more radical changes. The former involves competition between several niche innovations under severe landscape pressure, with one eventually forming the base for a new regime. The latter presuppose a developed niche innovation that emerges and forms the base for a new regime, often leading to the downfall of incumbent actors (Geels & Schot 2007). The timing and nature of interaction are two important criteria used in the context of these transition paths. The state of niche-innovations relates to timing. A niche innovation can be seen as ready for a wider breakthrough if a) it has stabilized in a dominant design, b) its price/performance-ratio has improved and show signs of further improvement c) it is used in market niches that cumulatively amount to more than 5% market share d) powerful actors have joined the support network (Geels & Schot 2007). Although useful, it is important to note that the described transitions paths are a) ideal cases and b) not deterministic (Geels & Schot 2007). This means that transitions, which usually takes place over long timeframes, often involve elements of several transition paths. A transition can follow one trajectory initially but later change and become more aligned to another path. Not deterministic means that the sequence of events is not automatic, and that there are no guarantees for a new regime (Geels & Schot 2007).

# 4 Results

## 4.1 Current role of hydrogen in the Swedish energy system

Hydrogen is used in diverse applications, and the annual global production is around 70 Mt (IEA 2019b). While there is a lack of official statistics on hydrogen in Sweden (Energigas Sverige 2017), some conclusions on quantities can be established based on estimations presented in reports and scientific literature. The Swedish Chemicals Agency furthermore collects data on a yearly basis from companies that import or produce chemicals. This allows for a useful overview on the total hydrogen quantities in Sweden, as shown in figure 3 below.

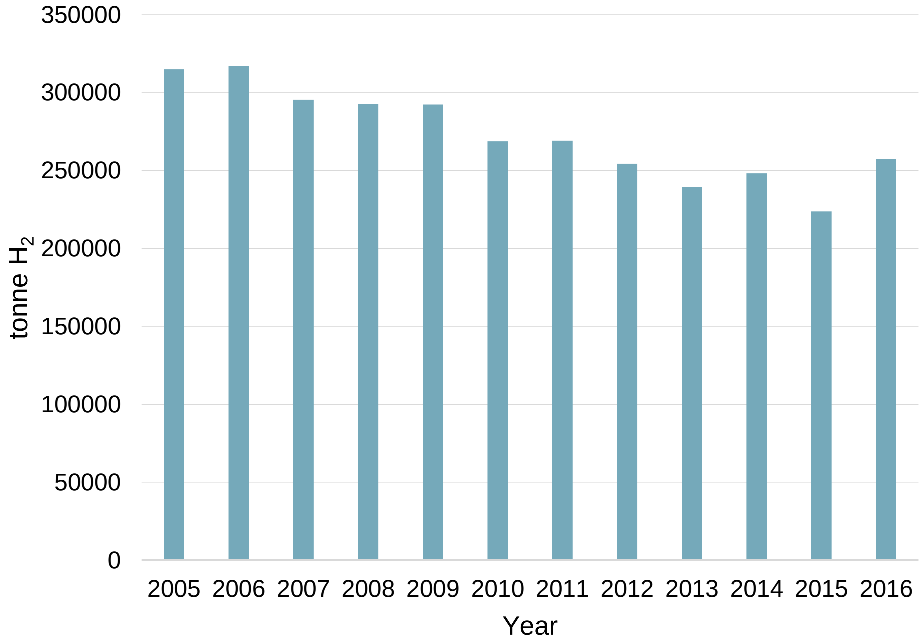


**Figure 3. Annual hydrogen production and import to Sweden 2005 to 2016.** Adapted from the Swedish Chemicals Agency (2020).

Considering hydrogen first in its role as a chemical feedstock, both international (IEA 2019b) and Swedish sources (Wallmark et al. 2014) highlight the importance of hydrogen to the refining industry. Refineries have been previously estimated to represent at least 1/3 of hydrogen production and consumption in Sweden (Rydberg et al. 2010). The recent shift in the transport fuel regime towards an increased use of renewable feedstock in fuel production is increasing hydrogen demand in refineries. Hydrogen is largely used in refineries to remove oxygen and impurities from the feedstock, and since renewable feedstock contain more oxygen and impurities, the hydrogen demand increases (Börjesson et al. 2013). In 2018, biofuels represented 19.5% of the total fuel quantity used in the Swedish transport sector (SPBI 2019). This share is expected to increase in coming years, as incumbent actors like Preem and St1 recently announced a roadmap based on the 2030 and 2045 climate goals (SPBI 2020). One important Swedish policy measure in this context is the Reduction Obligation SFS 2017:1201, aimed at decreasing greenhouse gas emissions from domestic transport by requiring an inclusion of biofuels in petrol and diesel. Consequently, Preem recently started operating a new hydrogen production unit based on steam reforming of methane (SMR) (Preem n.d.). While the increasing hydrogen production is indicating a changing transport fuel regime using more renewable feedstock, SMR is itself a cornerstone of the current hydrogen production regime not aligned with emission reduction ambitions (IEA 2019b).

Initiatives among Swedish incumbents are however not limited to incumbent technologies, as they also concern niche technologies like electrolysers. Two important projects that aim to decrease greenhouse gas emissions are HYBRIT in the Swedish steel regime (Åhman et al. 2018) and Preem's initiative to start using electro-hydrogen alongside SMR (Grahn & Jannasch 2018). Both projects include the Swedish electricity incumbent Vattenfall. New networks among incumbent actors, along with landscape pressure in the form of environmental goals and initiatives, have been identified as important drivers in HYBRIT (Karakaya et al. 2018). The economics of the project nevertheless indicate a need for policy that can mitigate risks associated with both future markets and the high energy and capital costs (Kushnir et al. 2020). While HYBRIT would effectively create a new application for hydrogen in Sweden, the project between Preem and Vattenfall rather aims at introducing electro-hydrogen as an alternative to the incumbent SMR. From a MLP-viewpoint, these two projects would therefore entail different transition paths in the steelmaking and transport fuel regimes. In the case of Preem, hydrogen production cost (HPC) for SMR and electrolysis have been estimated to be 50 €/MWh and 86 €/MWh respectively in the base case, assuming 25-year lifetimes for the electrolysers (Grahn & Jannasch 2018). These numbers would translate to around 1.7 €/kg and 2.9 €/kg.

The use of hydrogen as an energy carrier is also important to highlight. Several processes in the chemicals industry yield hydrogen as a by-product. At AkzoNobel in Sundsvall, this by-product hydrogen is used for heating. A large amount is however also flared. It has previously been estimated that this latter amount theoretically could provide fuel for a fleet of 2500 fuel-cell electrical vehicles (FCEV) (Wallmark et al. 2014). The chemicals industry cluster in Stenungsund, southwest Sweden; Perstorp Oxo, Inovyn, Borealis and AkzoNobel, similarly yield significant amounts of by-product hydrogen in some processes (Maisonnier & Perrin 2007). Some of this hydrogen is utilized for heating processes and facilities (Borealis 2019). Hydrogen is furthermore produced for the merchant market in several Swedish locations by the international gas incumbent Linde. In 2007, each of these plants were estimated to have a daily production of around 100-300 kg $H_2$ (Maisonnier & Perrin 2007). To get the complete picture, it should also be mentioned that hydrogen is produced locally in electrolysers for use in some industries other than the aforementioned (Wallmark et al. 2014).

Hydrogen can be used both in vehicles with internal combustion engines and the aforementioned FCEV's. Hythane has previously been tested in biogas buses in Malmö in southern Sweden. The project had a successful outcome and demonstrated a technical feasibility (Jönsson 2006). FCEV's have gained considerable interest in recent years but are still a distinct niche-technology in Sweden as shown by figure 4 below.

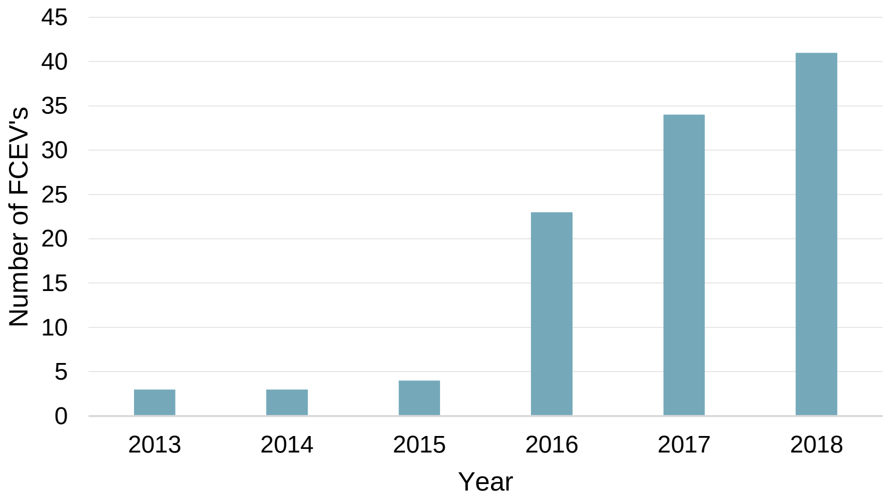


**Figure 4. Number of FCEV's in Sweden 2013 to 2018.** Adapted from Eurostat (2020).

A general barrier to the uptake of hydrogen as a fuel in the transport sector is the lack of hydrogen refuelling stations (HRS') that car owners face along with the lack of FCEV's that HRS-operators (van Bree et al. 2010). There are currently 5 HRS' in Sweden, located in Göteborg, Mariestad, Arlanda, Sandviken and Umeå. The incumbent Linde operates the stations in Arlanda and Sandviken, while the station in Umeå is operated by the smaller niche-actor Oazer (Vätgas Sverige n.d.). Based on previous rollouts of ethanol and biogas, it has been estimated that at least 130 HRS' would be needed in Sweden to solve the "chicken-and-egg" problem and commercialise the market. At the same time, hydrogen production in Sweden would also need to be substantially increased from today's levels to serve such number of HRS' (Gis & Schaap 2018). Previously identified barriers are also a mismatch with consumer preferences due to the difference in performance between FCEV's and fossil-fuel cars (van Bree et. a., 2010). Battery-electric vehicles have been estimated to be more energy efficient than FCEV's in some investigated Swedish scenarios, but FCEV's have nevertheless been identified as an interesting option in more specialised applications like light transport (Larsson et al. 2015).

Policy and regulation are furthermore important to understanding the current role of FCEV's. The directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure (DAFI) is a European directive aimed at accelerating the development of an infrastructure for alternative fuels in member states. While DAFI specifies required infrastructure for several fuels, hydrogen is not one of them. Hydrogen is acknowledged in the Swedish national plan for alternative fuel infrastructure, but specific goals for its introduction are lacking (Government Offices 2016). This is also reflected in a report on policy relevant to hydrogen in Sweden (Aronsson n.d.). The report further concludes that the lack of a national network of HRS' mean that FCEV-manufacturers do not see Sweden as a prioritized market (Aronsson n.d.). Lastly, understanding the current role of hydrogen requires a mention of previous efforts too. Hultman & Yaras (2012) highlight that fuel-cells and hydrogen have been explored in several previous projects in Sweden, many which have involved incumbent actors in varying constellations. The fact that these networks have had very different views of the future role of hydrogen and fuel-cells in the Swedish energy system have subsequently led to the pursuit of different development paths. This can be seen as a challenge according to the authors. Table 6 below summarise the findings on the role of hydrogen in the Swedish energy system.

Table 6. The current role of hydrogen in the Swedish energy system

| Niche | Regime | Landscape |
|---|---|---|
| The FCEV-niche face several constraints related to policy-gaps and a lack of infrastructure<br><br>Electrolysers are emerging as an option to incumbent hydrogen production technologies (Preem – Vattenfall)<br><br>Electrolysers are explored in new hydrogen applications (HYBRIT) | Extensive use of hydrogen in refineries and chemical industries, often based on incumbent technologies like SMR<br><br>Increased use of hydrogen in refineries as an indirect consequence of transport fuel policy<br><br>Use of by-product hydrogen for heating<br><br>Limited uptake of low-carbon hydrogen as of current | Concern with greenhouse-gas emissions and subsequent goals for its reduction is perceived and acted upon by diverse regime actors<br><br>EU-level directives and legislation stimulate changes in the regimes but is at the same time concerned with multiple competing low-carbon fuel options (DAFI) |

## 4.2 Gasification

### 4.2.1 Feedstocks

Addressing the biohydrogen production paths, a first aspect to consider in the context of gasification is feedstocks. Wood chips is a common feedstock in European gasifiers, but alternatives like forestry residues, waste wood and other organic residues are also increasingly explored because of their lower price (Hrbek 2019). Looking specifically at gasification for the purpose of biohydrogen production, numerous different feedstocks have been envisioned in the literature including forestry residues (Zech et al. 2015; Sheth & Babu 2010), wood chips (Jovanovic et al. 2016; Loipersböck et al. 2018) and wastes (Reaño 2020; Materazzi et al. 2019). Feedstocks having a low moisture content are generally seen as preferable, as they lead to a higher efficiency. Wood pellets, with a moisture content of 10%, is clearly favourable from this point of view but also more expensive than alternatives (Thunman et al. 2019).
Apart from a generally higher moisture content, alternative feedstocks can also have more varying moisture contents. This in turn can cause operational disruptions. Commercial gasifiers are therefore expected to include feedstock driers, which allows the moisture content of the feedstock to be carefully

controlled (Thunman et al. 2018). The importance of using a feedstock drier has also been highlighted by other authors (Sentis et al. 2016). Incorporating a feedstock drier nevertheless comes at price, since it limits the amount of heat that could otherwise be used for district heating or other purposes (Ahlstrom et al. 2019). The chemical composition of the feedstock is also crucial, with feedstocks showing large differences in ash-content. The ash-content of wood chips have been shown to be less than 1%, while sludge in contrast reached over 60% in some cases (Ljunggren et al. 2017). Ash is considered a challenge in gasification because it causes technical problems like corrosion. Utilizing feedstocks with a low ash content are therefore important according to some studies (Sentis et al. 2016). Other studies reach a somewhat different conclusion by showing that stable operation of gasifiers could be achieved using an ash-rich feedstock like bark. The rationale for these feedstocks again lies in their lower price (Ahlstrom et al. 2019).

### 4.2.2 Technical maturity

The technical maturity of gasification varies greatly depending on the application it is employed for (Hrbek, 2019). As reflected in recent works done on the topic, gasification is often considered a niche technology in the MLP-frame (Levidow & Upham 2017; Miedema et al. 2018). Looking at the state of gasification in Sweden, a first example is the Swedish company Cortus and their WoodRoll®-platform. It has been investigated at both pilot- and demonstration scale and is currently being tested to produce bio-coke and fuel gas for a steel powder plant in southern Sweden. The intended feedstock is wet biomass, which is dried as a part of the process. Nearly 20 different feedstocks have been tested at pilot-scale. The French energy incumbent Engie have shown interest in using the technology specifically for biohydrogen production (Hrbek 2019). Gasification at a much larger scale was demonstrated in the GoBiGas-plant in Gothenburg. It was in operation for several years with different feedstocks like wood pellets, various forestry residues and recovered wood. Operation with both wood pellets and alternative feedstocks proved successful, but the latter caused some technical problems due to varying moisture contents. The end product was synthetic natural gas (Thunman et al. 2018). The GoBiGas-plant ran at a loss due to conditions in the gas market, the latter which did not develop according to projections. The plant was shut down in 2018 (Hrbek 2019). Plans for a subsequent, commercial plant at 100 MW were not realised because of landscape developments like a low oil price (Peck et al. 2016). The Bio2G-project, also centred around gasification and synthetic natural gas production, is facing the same challenges. Eon, the energy incumbent behind the project, have therefore put the project on hold (Hrbek 2019). A planned gasifier in Örnsköldsvik represents a fourth Swedish example. It was not deemed economically viable in the absence of policy support (Peck et al. 2016).

Looking more specifically at biohydrogen production via gasification, Loipersböck et al. (2018) highlight that gasification in terms of efficiency could be competitive with other means of renewable hydrogen-production like electrolysers and biogas reforming. Identified bottlenecks in the study were the gas cleaning and upgrading steps. Zech et al. (2015) estimate the net efficiency of a 3 MW gasifier to be 42.4% while a larger 9 MW gasifier would reach 48.3%. Sentis et al. (2016) similarly state that efficiency increases with process scale and apply an efficiency of 50% in their assessments on biohydrogen production via gasification. The authors however also note that smaller gasifiers, <5 MW, can be more feasible taking into consideration the significant biomass quantities needed for larger plants along with the greater need of social acceptance for such plants. Jovanovic et al. (2016) address the potential of biohydrogen production from a current biomass gasifier located in Austria. The 8 MW plant was in operation for several years but is now on hold due to economic reasons (Hrbek 2019). The output from the gasifier was heat for the district heating system and electricity. If biohydrogen-production were to be pursued, a WGS-reactor, a gas drying, and cleaning step and a PSA-system would have to be added to the existing infrastructure. Electricity and heat would still be produced in the modified plant (Jovanovic et al. 2016).

### 4.2.3 Economics

Many studies have investigated the economics of gasification, but this section will focus on findings that specifically address the economics of biohydrogen production. As established in Geels & Schot (2007), the economic performance of a niche-innovation is important for understanding possible future developments. It is important to note that the estimations presented in this section are based on modelling. As for CAPEX, Sentis et al. (2016) highlight the effect of process scale by estimating it to be 740 €/kW for a 1 MW-gasifier and 1890 €/kW for a 100 kW-version. The study envision a 20-year lifetime for the gasifier and conclude that the location of the gasifier should be guided by a secured feedstock supply and hydrogen offtake for this timeframe. Personnel and feedstocks costs were estimated to make up the majority of OPEX. Furthermore, the authors state that HPC is heavily dependent on process scale (Sentis et al. 2016). Figure 5 highlight some of these findings.

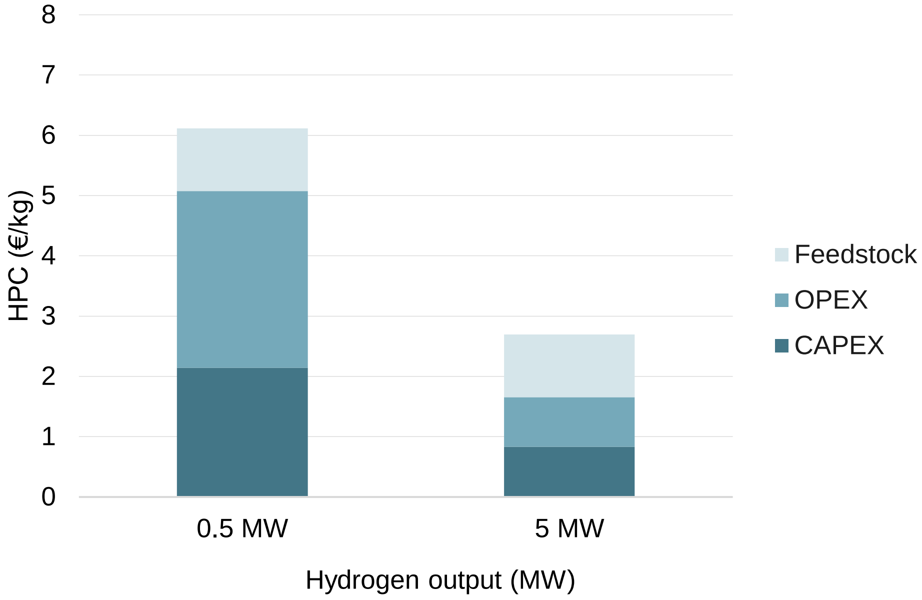


**Figure 5. Hydrogen production cost and cost breakdown for gasification at different process scales.** Based on Sentis et al. (2016).

Salkuyeh et al. (2018) addressed different types of gasifiers at a much larger scale of 600 MW and also explored the effects of a coupling to carbon-capture (CC), another niche technology. The largest share of CAPEX was found to be associated with the gasifier itself. Including CC would increase CAPEX with 9-32% depending on the type of gasifier and lead to a marginal increase (3-11%) in HPC. The captured $CO_2$ would generate some additional income, as the authors assumed establishing sales channels for this by-product. The results however also show that coupling SMR to CC would be an economically superior option to biohydrogen production via gasification, unless a very cheap feedstock could be used (Salkuyeh et al. 2018). The weight given to feedstock cost is however disputed by some authors. Lee (2016) assess the economics of biohydrogen and find evidence for rapidly decreasing HPC in a future case. Results from that study also emphasize the importance of controlling CAPEX and other OPEX-related costs rather than feedstock cost. Zech et al. (2015) investigated gasification at a smaller scale of 3 and 9 MW and include hydrogen distribution costs in the assessment. The assumed lifetime of the gasifier was 15 years. The results indicate that a third of HPC could be related to feedstock costs. This is line with findings from GoBiGas, which show that feedstock costs contribute a large part of production costs (Thunman et al. 2019). The hydrogen distribution costs were shown to have a large influence on the total costs associated with biohydrogen production and provision. Assumptions associated with the distribution costs were a transport distance of 150 km and a capacity of 955 kg hydrogen per tanker trailer (Zech et al. 2015). Lastly, results by Albrecht et al. (2015) highlight a general trend towards lower HPC for larger plants. The authors also point out the importance of feedstock homogeneity. According to the authors, a way forward for biohydrogen production via gasification would be to use scrap wood as a feedstock, as this would increase future competitiveness when demand for high quality organic feedstocks increase. CAPEX for gasification is shown to be high compared to SMR and electrolysis, and feedstock cost is shown to be a major driver of OPEX (Albrecht et al. 2015). The economic findings on biohydrogen production via gasification are summarised below in table 7.

**Table 7. Economics of biohydrogen production via gasification.**

| Reference | Hydrogen production (MW) | Feedstock cost (€/MWh) | HPC (€/kg) |
|---|---|---|---|
| Zech et al. (2015) | 3 | 17.5 | 6.7 |
| Zech et al. (2015) | 9 | 17.5 | 4.8 |
| Albrecht et al. (2015) | 33 | 18.5 | 3.5 |
| Salkuyeh et al. (2018) | 630 | 16.7 | 3.1 |
| Salkuyeh et al. (2018) | 630 | 16.7 | 2.8 |
| Sentis et al. (2016) | 0.05 | 15.7 | 10.4 |
| Sentis et al. (2016) | 0.5 | 15.7 | 6.1 |
| Sentis et al. (2016) | 5 | 15.7 | 2.8 |

## 4.3 Biochemical hydrogen production

### 4.3.1 Feedstocks

Shifting the focus to biochemical hydrogen production, Kapdan & Kargi (2006) highlight cost, biodegradability, availability, and carbohydrate content as being important criteria when assessing feedstocks for these paths. Recent studies have to a large extent focused on second-generation biomass such as animal compost, harvest remains, stalks, brewery- and dairy wastewaters and wastewater sludge (Sharma et al. 2020). Wastewaters have been identified as especially promising feedstocks because of their abundance, availability and low-cost (Kapdan & Kargi 2006). Sewage sludge also seems feasible, either as it is or co-digested with other feedstocks like food waste or plant straw (Yao et al. 2018). A high moisture content is importantly beneficial in the biochemical paths (Sharma et al. 2020), which distinguish them from gasification in this dimension. On the importance of biodegradability, Soares et al. (2020) note that a high lignin content has a negative effect on biochemical hydrogen production. Furthermore, Phanduang et al. (2019) show that while energy intensive pre-treatment might be needed to achieve high energy yields, it can at the same time lead to a net negative energy balance when considering the whole process.

Looking specifically at the investigated biochemical paths, there is significant overlap when it comes to explored feedstocks (Abreu et al. 2019; Niño-Navarro et al., 2020; Marone et al. 2017). This is to be expected, as all paths include DF as the first step. Marone et al. (2017) investigated DF-MEC using several different agro-industrial wastewaters and by-products as feedstocks, including paper mill-, sugar production-, spirits production-, and fruit juice-production wastewater. The highest hydrogen yield in the DF-process was obtained with cheese whey, which was also the feedstock richest in soluble sugars. Considering the performance of the combined DF-MEC process, fruit juice wastewater led to the highest hydrogen yield. While feedstocks might be more or less optimal from a chemical standpoint, Marone et al. (2017) note that some investigated feedstocks already have established applications, a challenge when considering the bigger picture. Dhar et al. (2015) similarly assessed DF-MEC. The feedstock was sugar beet juice, with a very high carbohydrate content. While the process achieved a relatively high energy recovery compared to previous efforts, the authors point to several avenues for improvements. The results showed that both steps contributed Like DF-MEC, DF-PF has been studied extensively using many different feedstocks. Examples include corn-stover (Zhang et al. 2020) along with fruit and vegetable waste (Niño-Navarro et al. 2020) and paperboard mill wastewater (Elsharkawy et al. 2020). The PF-process is however very sensitive to the dilution of the DF-effluents, highlighting the complexity introduced by a coupled process (Niño-Navarro et al. 2020). The colour of the feedstock is also particularly important in a DF-PF-process since a darker colour inhibits PF due to lower light flux (Boodhun et al. 2017). This would not be a problem for DF-MEC and DF-AD-systems. Like the other two paths, feedstocks investigated in DF-AD are diverse and include sludge and food waste (Liu et al. 2013), agricultural residues (Pawar et al. 2013) and garden waste (Abreau et al. 2019) among others.

### 4.3.2 Technical maturity

Regarding technical maturity, IEA have previously identified the biochemical hydrogen production as being far from commercialisation (Miyake 2013) This conclusion is also reflected in more recent works on the topic (Soares et al. 2020; Aiken et. al 2019). Thi et al. (2016) point to an important, general challenge which is the difference between hydrogen yields obtained at lab-scale and pilot-scale. DF-MEC has mostly been studied as a batch process, reflecting the need to address optimal operating parameters and the general feasibility of different feedstocks. Examples of continuous processes are however more valuable for scaling-up, and such studies are fewer. Nevertheless, it is important to note that much research on the DF-MEC-path has used actual DF-effluents in the subsequent MEC-process (Bakonyi et al. 2018). Addressing MEC's specifically, attempts to scale up the technology have met severe challenges, with pilot-scale studies displaying low hydrogen productivity and a performance being far from viable in commercial applications (Aiken et al. 2019). This indicates that MEC's have a long way left to go (Rousseau et al. 2020). Kadier et al. (2020) reached a similar conclusion, stating that the MEC-technology are in its infancy facing several basic challenges.

DF-PF has been studied extensively at lab-scale (Trchounian et al. 2017) but also at pilot-scale (Zhang et al. 2018). Ljunggren et al. (2011) modelled a sequential DF-PF process with a total HPR of 1243 kg/h. Results show that the process would require very large amounts of water and chemicals, necessary to both the DF- and PF-steps. Reaching the intended HPR would require a very large PF-process because of its low hydrogen productivity and very small volume-to-area ratio of the bioreactor, the latter needed to achieve necessary illumination. Main bottlenecks for the DF-PF process was estimated to be the low HPR and high demand of chemicals for process control (Ljunggren et al. 2011). More recent results by Niño-Navarro et al. (2020) on DF-PF again highlights the challenges associated with low HPR and DF-effluent dilution when using real-world feedstocks. The DF-effluent have indeed been acknowledged as a key factor influencing the subsequent PF-step, and this constraint among others need to be further investigated before practical applications of DF-PF-processes (Hitit et al. 2017). Considering DF-PF as performed in the same bioreactor, i.e. not sequential configurations, the different pH-requirements of DF- and PF-microorganisms have been identified as a major obstacle (Zagrodnick & Laniecki 2015).

Like the two other biochemical paths, DF-AD has been studied both at lab-scale (Weide et al. 2019; Pawar et al. 2013; Pisutpaisal et al. 2014) and pilot-scale (Cavinato et al. 2012). Results by Phanduang et al. (2019) show a significantly higher energy recovery in a DF-AD-process compared to a DF-PF-process. Pawar et al. (2013) demonstrated biohydrogen and methane production in an uncoupled DF-AD process. The results show a reasonably efficient process capable of producing hythane from commonly available agricultural residues, and the authors point to the potential technical synergies in combining DF with AD. Other studies highlight a superior energy recovery in a DF-AD-process compared to a one-stage AD-process (Pisutpaisal et al. 2014). Weide et al. (2019) similarly found evidence for better energetic yields in an DF-AD-process compared to an AD-process for some investigated feedstocks. The authors however also note that the results must be verified to assess the potential of DF-AD more accurately.

### 4.3.3 Economics

Examining the economics of biochemical hydrogen production, there is generally great uncertainty since most results stems from lab- and pilot-scale processes and modelling. The latter must especially be emphasized to avoid misunderstandings in the following section. Considering the feedstocks from an economic standpoint, organic waste or wastewater have been identified as preferable to make biochemical hydrogen production more economically viable (Chandrasekar et al. 2020). Ljunggren et al. (2011) found that very large shares of CAPEX and OPEX were associated with the PF-step in their modelled DF-PF-process. Large costs were also associated with the chemicals needed for pH-control. Urbaniec & Grabarczyk (2014) reported similar conclusions regarding an DF-PF process; the PF-process was associated with very high costs and contributes most of the CAPEX. Han et al. (2016) investigated the economics of a standalone DF-process used to treat food waste. The assumed scale was 10 tonnes of food waste per day. While biohydrogen sales would provide the bulk of revenue, the business model was also dependent on the sales of by-product carbon dioxide and undigested food waste as fish feed. An important share of revenue would also stem from the food waste treatment fees. Yun et al. (2018) investigated DF at a larger scale were 100 tonnes of food waste were treated per day. The assumed technical performance includes a yield of 2.26 mol $H_2$/mol hexose and an OLR of 100 kg COD/$m^3$/d. The process achieved a relatively low HPC compared to the other examples given in table 7. The authors state that this could stem from the high technical performance assumed in this study.

Randolph et al. (2017) assessed the economics of a central hydrogen production facility based on DF. The economic performance was projected both as a current case, using the year 2014-state of DF, and as a future case, using estimated improved performance by 2025. HPC, with or without additional revenue from by-products, was shown to decrease significantly in the future case. Including by-product sales in the business model would decrease HPC somewhat. Both CAPEX and feedstock costs were found to have a large influence on the economics of the plant. The authors conclude that the technical performance would have to be improved substantially in several dimensions for biochemical hydrogen production to become more economically viable. Results by García et al. (2017) highlight an HPC around ten times higher for DF than for gasification. This would hold even if the DF-process were configured to yield ethanol as a main by-product. The feedstock and chemicals cost were a major contributor to HPC in DF. The authors conclude that biochemical hydrogen production require a higher productivity than is currently the case, and that thermochemical paths like gasification are more economically feasible and have a higher energy efficiency (García et al. 2017). Results by Chang and Hsu (2012) indicate that an integration of DF as part of a wastewater treatment system can be more feasible than operating it as a stand-alone process. The most profitable application for the biohydrogen would be to sell it at low purity. The authors also highlight the importance of establishing sales channels for the by-product carbon dioxide. Hsu & Lin (2016) similarly showed that operating DF as a part of a wastewater treatment system could be a possible way forward. The proposed business model would however be heavily dependent on economic support schemes and the ability to secure long-term sales contracts for the hydrogen.

Zech et al. (2015) except for gasification also investigated biogas reforming, relevant to the AD-step in the DF-AD-path. The results show that biogas reforming could achieve a lower HPC than the gasification paths. The assumed feedstock was a combination of organic waste, maize silage and manure. The authors point to the importance of using a negatively priced feedstock, organic waste, and state that a substitution for additional maize silage, at a positive price, would increase HPC significantly. Biogas reforming is identified by the authors as a path with little technological risk compared to gasification. Braga et al. (2013) note that biogas reforming represents a viable way of producing biohydrogen as it importantly shares technical characteristics with the incumbent SMR but at the same time results in lower greenhouse gas emissions. In a more recent study on biogas reforming, Di Marcoberardino et al. (2018) note that an application like HRS for the biohydrogen will incur a cost penalty since it would require the hydrogen to be pressurised. Low pressure applications could instead make biohydrogen competitive with that of large scale hydrogen production (Di

Marcoberardino et al. 2018). Lastly, as for MEC's, Escapa et al. (2016) note that a main appeal is the expected energy savings they are expected to bring about compared to conventional wastewater treatment, the latter which is energy intensive. Aiken et al. (2019) however highlight that CAPEX would be significantly higher for a system based on MEC's than a conventional wastewater treatment process, something that could hinder a future commercialization. The study nevertheless also found evidence of lower energy costs in MEC compared to a conventional treatment process. Another conclusion was that revenues from biohydrogen sales would have a small impact on the economic feasibility of the process. Proposed targets by the authors require a significant reduction in mainly CAPEX (Aiken et al. 2019). Table 8 below highlight the economics of biochemical hydrogen production.

**Table 8. Economics of biochemical hydrogen production.** AD+R refers to biogas reforming, relevant to the DF-AD-path.

| Reference | Type | Hydrogen production (MW) | Feedstock cost | HPC (€/kg) |
|---|---|---|---|---|
| Yun et al. (2018) | DF | - | -91.6 €/tonne | 2.9 |
| Randolph et al. (2017) | DF | 694.4 | 14.0 €/MWh | 8.9 |
| Han et al. (2016) | DF | 0.06 | -15.3 €/tonne | 26.6 |
| García et al. (2017) | DF | 2.2 | 1.6 €/MWh | 33.2 |
| Randolph et al. (2017) | DF | 694.4 | 14.0 €/MWh | 70.1 |
| Urbaniec & Grabarczyk (2014) | DF-PF | 2 | - | 34.0 |
| Ljunggren et al. (2011) | DF-PF | 41.8 | 19.3 €/MWh | 54.7 |
| Zech et al. (2015) | AD+R | 6 | -37.3 €/tonne | 4.1 |
| Di Marcoberardino et al. (2018) | AD+R | - | - | 5.1 |
| Braga et al. (2013) | AD+R | - | - | 8.6 |

## 4.4 Summary – biohydrogen production paths

Considering advantages and limitations, one can point to several in the case of both gasification and the biochemical paths. A certain degree of feedstock flexibility can be expected in all production paths, given the diverse feedstocks explored and the possibility to use pre-treatment as a way of further enhancing this capability. Gasification is a considerably more developed niche technology, as highlighted by the presence of several demonstration plants (Hrbek 2019) and comparatively narrow range of estimated HPC's (2.8-10.4 €/kg). This constitute a clear advantage. A challenge even for gasification is however the technical risk (Zech et al. 2015) and sensitivity to landscape developments like oil price fluctuations (Peck et al. 2016). Key challenges for the biochemical paths are a low hydrogen productivity (García et al. 2017; Randolph et al. 2017), discrepancy between results obtained at lab-scale and pilot-scale (Thi et al. 2016) and the very high costs associated with both PF (Ljunggren et al. 2011; Urbaniec & Grabarczyk 2014) and MEC (Aiken et al. 2019). HPC's in the biochemical paths are subsequently very uncertain and range from 2.1-70.1 €/kg depending on path and scenario. Of the biochemical paths, DF-AD stands out as being advantageous to the other given the lower technical risks associated with AD (Zech et al. 2015) and potential advantages to stand-alone AD indicated by Weide et al. (2019).

## 4.5 Integration of biohydrogen in the Swedish energy system

### 4.5.1 Gasification

Feedstock availability and price, with an emphasis on forest fuels, was shown to be important to gasification in the previous section. Major applications for forest fuels in Sweden are combined heat and power-production (CHP) and process heat production in industries (Swedish Energy Agency 2017). CHP notably constitute an important part of the Swedish heat-energy regime (Dzebo & Nykvist 2017). The price of forest fuels has varied over time, partly due to the use of waste feedstocks in CHP (Swedish Energy Agency 2017). As of late 2019, the price of wood chips was around 20 €/MWh non-taxed. Waste wood and by-products were cheaper at around 17.5 €/MWh and 10 €/MWh respectively (Swedish Energy Agency 2019). These numbers are quite aligned with the assumed feedstock prices in table 7 on gasification, indicating that the HPC's reported in these studies can be given some weight in a Swedish setting. Looking at the future situation in Sweden, Börjesson et al. (2017) conclude that the domestic demand for forest fuels can outpace the domestic supply due to increased use in applications like biofuel manufacturing. Developments counteracting these trends can however be found in electrification and improvements in energy efficiency. The authors also highlight several landscape factors that can potentially hinder an increased use of forest fuels, including consumer preferences, a low oil price, an opposition to intensified forestry (Börjesson et al. 2017). Liptow et al. (2015) reach a similar conclusion while investigating gasification for the purpose of chemical production in Sweden. If new forest-fuel applications at industrial scale are to be introduced, the move towards alternative feedstocks like forest residues could be insufficient to cover the demand. The acquisition of feedstocks like forest residues, which are very dispersed, will furthermore represent a large part of the total greenhouse gas emissions associated with gasification-based processes (Liptow et al. 2015). In general, trends highlighted by Hrbek (2019) including the move towards alternative, cheaper feedstocks are probably crucial if biohydrogen production via gasification is to be introduced in Sweden. Competing regime applications (Swedish Energy Agency 2017) and the risk of unfavourable landscape developments (Börjesson et al. 2017) will however introduce significant uncertainty regarding feedstock availability.

Apart from feedstocks, it is also important to address process size and biohydrogen applications. Table 7 indicate that the case for larger processes is strong given the trend towards lower HPC's. Previous experiences with gasification in Sweden similarly highlight that the difference in production cost between a 20 and a 100 MW process could be significant (Thunman et al. 2019). Process scale is related to the intended biohydrogen application, of which there are several theoretical ones. Projects like HYBRIT can be an option but the strong emphasis on electro-hydrogen is a challenge. Both Sentis et al. (2016) and Albrecht et al. (2015) envision HRS as an application for gasification-based biohydrogen. Sentis et. al. (2016) also note that the constrained FCEV-niche is a general challenge in these cases. This conclusion is very important in the Swedish case, and figure 4 show that proponents of biohydrogen production at a large scale must look beyond FCEV's to find a viable application. Findings by Kjarstad & Johnsson (2016) nevertheless indicate that a future Swedish transport system fully dependent on biofuels can be difficult to realize given the very large biomass needs associated with such developments. Battery-electric vehicles and possibly FCEV's might therefore play an important role in a future case according to them. Findings by Gis & Schaap (2018) highlight the need for additional Swedish policy measures that can mitigate the constraints associated with FCEV's. If the case for FCEV's grows stronger and a larger network of HRS' is pursued, gasification-based biohydrogen could become an important option to electro-hydrogen. The location will have to be carefully assessed in that case to balance the high costs associated with hydrogen transport (Zech et al. 2015) with the greenhouse gas emissions associated with the transport of dispersed feedstocks like forestry residues (Liptow et al. 2015).

Brau & Morandin (2014) point to a possibility of integrating gasification for biohydrogen production at refineries. This would like the case of FCEV's as application still be influenced by the success of other niche technologies. An estimated cost for electro-hydrogen in the case of Preem is around 86 €/MWh (Grahn & Jannasch 2018), corresponding to 2.9 €/kg, which is around the lowest HPC's reported in table 7. Even lower costs for electro-hydrogen could however be expected under conditions with a low electricity-price and decreasing CAPEX (Grahn & Jannasch 2018). There are several other hydrogen applications that theoretically could use biohydrogen. IEA (2019b) identify the chemical sector as an important hydrogen market, were the largest amounts are used in ammonia and methanol production (IEA 2019b). In a Swedish setting, the latter application has been investigated with both biohydrogen (Liptow et al. 2017) and electro-hydrogen (Grahn & Jannasch 2018). Bruce et al. (2019) highlight three other potential hydrogen applications: synthetic methane production and injection into the gas grid, direct injection of hydrogen in the gas grid or local storage of hydrogen or methane. Electro-hydrogen is again often envisioned in these scenarios because of expected future electricity surpluses (Bruce et al. 2019), but synthetic methane production was importantly demonstrated in a Swedish context in the Gobigas-plant (Thunman et al. 2018). Considering hydrogen-injection in the Swedish gas grid, it would in practice be limited to a small amount under current conditions (Bruce et al. 2019) and thus constitute a limited application. Lastly, the fact that the Swedish gas grid is concentrated to some parts of Sweden (Klackenberg 2019) would also have implications for the location of the gasifier if one of these latter applications were to be pursued.

### 4.5.2 Biochemical hydrogen production

As for the biochemical paths, addressing a potential introduction in Sweden requires an initial assessment of feedstock availability. Investigating the possibility to use food waste to produce bio-based chemicals and materials in Sweden, Torén et al. (2019) mapped and assessed a wide range of waste streams. Waste from crop production is estimated to be available in very large quantities, and it also possess a high carbohydrate content. A barrier towards valorisation of these feedstocks however lies in the associated pre-treatment needs (Torén et al. 2019). This barrier is also acknowledged in research on biochemical hydrogen production (Soares et al. 2020). Municipal food waste represents another significant waste stream, and it is in many cases covered by obligatory sorting requirements (Andersson & Stålhandske 2020). It has been shown to possess a high carbohydrate content but is at the same time a heterogeneous waste stream

(Rex et al. 2017). Except for the heterogeneity, another challenge in the case of biohydrogen production would be present in the continuous introduction of competing non-hydrogen producing microorganisms (Yun et al. 2018). Investments from municipalities in biogas plants and long-term contracts with biogas producers have furthermore been identified as barriers that can hinder this waste stream to be used in new applications (Rex et al. 2017). A third category of feedstocks includes waste streams from the food industry, which can be relatively homogenous and uncontaminated. Examples include by-products from the dairy industry, sugar processing plants, breweries, and distilleries (Torén et al. 2019). Results by Weide et al. (2019) indicate that some of these feedstocks have favourable energetic yields in an DF-AD process compared to a single-stage AD-process. While wastewaters from the dairy and sugar industry showed significantly higher energetic yields in a single stage AD compared to DF-AD, starchy wastewaters from the food- and textile industry showed higher potential in the latter. Torén et. al. (2019) however note that several of these waste streams from the food industry in Sweden have established applications in biogas production and as animal feed, which can constitute a challenge for new applications. While the established applications represent a clear barrier if these feedstocks are to be used in DF-AD, they nevertheless seem to have the greatest potential when considering an introduction of biochemical biohydrogen production.

The price of these organic waste feedstocks varies to a high degree and many can be expected to have a positive price (Torén et al. 2019). At the same time, there is a clear emphasis on utilizing negatively priced feedstocks in several studies that address biochemical hydrogen production (Zech et al. 2015; Yun et al. 2018; Chang & Hsu 2012; Han et al. 2016). Zech et al. (2015) highlight that using feedstocks at a positive price can be detrimental to HPC, even if the biohydrogen is produced through biogas reforming, a path with relatively low technical risk. Torén et al. (2019) note that homogeneous feedstocks closer to primary production largely differ in price from inhomogeneous, variable, and contaminated feedstocks closer to consumers. The formers are associated with a positive price while the latter carry a negative price. Vestman et al. (2014) similarly report that biogas producers can charge a fee for treating feedstocks that the owner otherwise would have to pay for to get rid of. Examples include municipal food waste along with some types of manure. The treatment fee has previously been estimated to range from 0-60 €/tonne depending on the pumpability of the feedstock and other characteristics (Vestman et al. 2014). This range has some overlap with the feedstock costs reported in table 8.

Interactions between the niche and regime-levels are also important to analyse in the context of an integration. The incumbent path for food waste treatment in Sweden is biogas production (Klackenberg 2019), and this route is also institutionalized (Rex et al. 2017). Biogas is subject to economic support schemes in Sweden, and proposed goals include an annual production of 7 TWh via AD by 2030 (Biogasmarknadsutredningen 2019). This would be a sharp increase from the current annual biogas production, which was around 2 TWh in 2018 (Klackenberg 2019). Based on these findings, a DF-AD-process would clearly be more aligned with the current organic waste treatment regime than DF-PF or DF-MEC. It would also be the subject of economic support schemes, and importantly contribute to Swedish goals on biogas production. The presence of a symbiotic niche-technology, in this case DF, that add to the current regime without substituting imply that an introduction along the transformation path might be possible for DF-AD (Geels & Schot 2007). A DF-AD process can be configured to yield either biohydrogen and biogas or only biohydrogen through subsequent reforming of the biogas. This gives DF-AD a certain degree of flexibility. Projects like HYBRIT, though mainly focused on electro-hydrogen, are at the same time expected to increase biogas demand in Sweden (Karakaya et al. 2018), yielding an alignment between these niches. Furthermore, as shown by table 8, reforming of biomethane is believed to achieve relatively low HPC's.

Analysing an introduction further, the existing infrastructure for biogas production in Sweden can be seen as enabling, especially for the DF-AD-path because of the technical overlap. One example is the current presence of PSA-systems (Klackenberg, 2019), which have also been proposed in biochemical hydrogen production (Zech et al. 2015; Yun et. al., 2018). The picture however gets more complicated when considering biohydrogen applications. Zech et al. (2015) highlight the importance of a secure biohydrogen market and feedstock supply in the location of any actual project development. One way of securing feedstock supply is to implement an DF-AD process at a food industry, given the fact that some of these feedstocks seem promising for this purpose (Weide et al. 2019). The same food industry could subsequently use the biohydrogen for heating, given the fact that this is an established hydrogen application in Sweden (Borealis 2019; Wallmark et al. 2014). As for other applications, the large scale of refineries and chemical production (Brau & Morandin 2014) indicate that biohydrogen production via gasification could be a more viable option than the biochemical paths. FCEV's and injection in the gas grid can as in the case of gasification be other potential future applications, with the location again being important in both cases considering the limited gas grid in Sweden (Klackenberg 2019) and the high costs associated with transporting hydrogen (Zech et al. 2015). Lastly, Chang & Hsu (2012) mention electricity generation by fuel cells as an application for biohydrogen from biochemical production. The authors however emphasize the importance of establishing an economic support scheme for making this path more viable. One can draw a parallel between biohydrogen and biomethane in this context, as recent reports highlight the large effect that economic support schemes in some countries have on steering biogas use to applications like electricity generation (Gustafsson et al. 2020).

# 5 Discussion

## 5.1 Validation

The findings on biohydrogen and its potential introduction were further analysed through two interviews with experts on the included production paths. These interviews filled an important function given the diverse material collected in the literature review. The information provided in the interviews was generally aligned with the results, but importantly also provided some novel learnings. As for gasification, the senior researcher at RISE notes that the main technical challenges are known, and to a large degree centred around achieving removal of contaminants such as tars from the gas stream. The general lack of experience with commercial plants also means that considerable technical risk remains. Another challenge is present in the expensive equipment needed for the removal of contaminants. Aligned with the conclusions by Sentis et al. (2016), the ash content is highlighted as a potential problem that can limit the ability to operate with alternative fuels like sludge and other residues. The potential competition for forest fuels, as outlined in studies by Börjesson et al. (2017) and Liptow et al. (2015), are also emphasized in the interview as being a possible constraint. According to Hrbek (2019), this challenge is increasingly present in existing gasifiers. An important conclusion based on table 7 is that a large scale would be the way forward for biohydrogen production via gasification due to the lower HPC. This conclusion is reflected in the interview. The uncertainty associated with changing policy frameworks is also brought up, as this can be expected to have a negative effect on the viability of gasification projects. Experiences with gasification in Sweden point in the same direction (Peck et al. 2015).

Looking at the biochemical paths, the senior lecturer at Lund university points to the overlap with the current waste treatment system as speaking for DF-AD, with DF-MEC being a more viable option in the longer-term. This view on MEC resonates well with the conclusions by Aiken et al. (2019) and Kadier et al. (2020). One option could be to integrate biohydrogen production by adding a DF-process to the existing waste treatment infrastructure, as identified in the results. This would allow for learnings on biohydrogen production and it could also improve the stability of the AD-processes. These conclusions were not identified in the results but is important to emphasise as a synergy between the biohydrogen niche and the organic waste treatment regime. Several challenges associated with PF brought up in the section 4.3.3, like the high CAPEX (Ljunggren et al. 2011), is emphasized in the interview. For all biochemical paths, an increased performance through a higher hydrogen production is crucial before any commercialisation can take place. The feedstock cost is also highlighted as very important. Suitable feedstocks can be found in the food industry and in agriculture, possibly along with marine feedstocks like algae. While some of these waste streams currently have a negative price, this can be expected to change once they become established in commercial applications like biogas production. Another important conclusion, not present in the results, is the fact that an integration of biochemical hydrogen production in the food industry can utilize the excess heat that is available in many cases to heat the bioreactor. The ability to utilize municipal food waste will depend on if viable co-cultures can be established, as some of the currently studied microorganisms only metabolise carbohydrates and not proteins and fats. Lastly, the respondent also points to the general lack of hydrogen infrastructure as being a constraint in the context of biohydrogen. This view is well-aligned with recent reports on hydrogen (IEA 2019b).

## 5.2 Niche technologies – competition and synergies

A general conclusion based on the results, and further confirmed in the interviews, is the importance of using a low-cost feedstock in biohydrogen production. This will naturally have to be balanced against the need to achieve a technically and chemically viable production process. Based on the results and the interviews, there appears to be a limited overlap between the feedstocks envisioned in the biochemical paths and in gasification, which can mitigate competition between these niche technologies in this dimension. Recent experiences with gasification in Sweden indicate that using alternative forest fuels like bark could be possible in the future (Ahlstrom et al. 2019) but a move towards sludge and other feedstocks typically associated with biochemical conversion is probably less feasible, as highlighted in the interview on gasification. Considering forestry residues, market conditions rather than the Swedish forest policy framework have been shown to influence extraction levels. The practice is furthermore much more common in southern compared to northern Sweden (Johansson & Ranius 2019). While the current policy framework in Sweden acknowledges the environmental risks associated with an increased extraction of forestry residues, it is at the same time largely consisting of recommendations and voluntary schemes with few binding regulations (Johansson & Ranius 2019). An introduction of gasification could fix the extraction of forestry residues at a higher level by making the practice more economically attractive, and the different extraction levels in southern compared to northern Sweden could furthermore have implications for the location of future gasifiers. Landscape developments, for example concerns about of an intensified forestry, must as highlighted by Börjesson et al. (2017) however also be considered. Indeed, studies have identified several knowledge gaps that limit a thorough understanding of the environmental effects associated with an intensified forestry (Ranius et al. 2018). These concerns can have a direct impact via RED II. This directive clearly emphasizes the importance of biodiversity, soil quality and life cycle emissions when considering renewable feedstock like forestry residues. Together, these landscape developments can speak for radically different approaches where regime actors use other niche technologies to achieve a reduction in greenhouse gas emissions. One example of such niche technology is carbon-capture, which Swedish fuel incumbent's are committed to developing as recently highlighted in their plan for achieving carbon-neutrality by 2045. A demonstration plant for carbon-capture is currently being built in southwest Sweden (SPBI 2020). Salkuyeh et al. (2018) furthermore report that coupling fossil hydrogen production like SMR to carbon-capture can be an economically attractive option to biohydrogen production based on gasification, especially if the feedstock costs in gasification are high.

One can also expand on the possible interaction between gasification and the biochemical paths in context of applications and process scale. Gasification for biohydrogen production is considered more feasible at a large scale, as reported in the interview and table 7, which indicates that chemical production, refineries, and other large processes constitute possible applications. Less is known about the biochemical paths since they are not as developed. National initiatives among Swedish biogas producers emphasize scaling up from the size of today's processes to achieve lower production costs (Energigas Sverige 2018). At the same time, a recent report on biogas production in Sweden highlights the challenge of securing capital for investments (Biogasmarknadsutredningen 2019). Both MEC and PF are estimated to be very capital intensive (Ljunggren et al. 2011; Aiken et al. 2019) but DF-AD could fare better under the current conditions.

Looking beyond biohydrogen, electro-hydrogen is emerging in new applications in Sweden as highlighted by table 6. At this stage, it is difficult to determine how, or even if, a niche competition between biohydrogen and electro-hydrogen in certain applications will materialise. The viability of electro-hydrogen is inherently dependent on electricity cost since it makes up a major part of HPC (Grahn & Jannasch 2018). Current developments in Sweden will lead to higher share of variable electricity production in the future, which in turn will cause challenges related to the balance between electricity supply and demand. Hydro- and nuclear power production complement variable production, but developing these incumbent technologies are nevertheless associated with significant challenges. For example, raising hydropower production capacity in Sweden from today's 65 TWh/year to 100 TWh/year would entail production in all watercourses currently protected from this (Byman 2016) and is therefore unlikely. The variations in electricity availability drive projects like HYBRIT to develop demand-side flexibility through hydrogen storage. This storage can act as a buffer for when electricity costs deter electro-hydrogen production (Åhman et al. 2018). While this approach might mitigate a main drawback associated with electro-hydrogen and increase its current advantage, the development of hydrogen infrastructure could also facilitate an introduction of hydrogen in general. The lack of hydrogen infrastructure is an important current constraint, as reported by both IEA (2019b) and highlighted in one of the interviews. Worth to notice is also the potential technical synergy present between electro-hydrogen and gasification, as oxygen yielded from the former can be used in the latter.

The results identify a number of possible applications for biohydrogen, among them synthetic methane production. The latter have been extensively investigated, and also demonstrated at the Gobigas-plant. Power-to-gas (PtG) is an alternative approach where electrolysers allow utilization of the aforementioned surplus electricity associated with variable electricity production. The electro-hydrogen, along with carbon dioxide, can then be further converted into methane via a biological or chemical methanation process. Using by-product carbon dioxide from biogas production in the methanation process, and simultaneously heating the bioreactor with excess heating from the electrolyser, results in several synergies (Mohseni et al. 2017). The same synergies could be realised if PtG were to be coupled to biohydrogen production, since both gasification and biochemical paths yield by-product carbon dioxide. The excess heat could be used for feedstock drying in the gasification-path or to heat the bioreactor in the case of the biochemical paths. While there are many other industrial processes available that similarly yield by-product carbon dioxide, it is important to note the inherent need of carbon dioxide separation in biohydrogen production to achieve pure biohydrogen. In contrast, implementing carbon dioxide separation in industrial processes like cement production have been associated with high additional costs (Mohseni et al. 2017).

## 5.3 Biohydrogen in a larger perspective

Verbong et al. (2010) highlight the issue of regime stability by noting that highly unstable regimes similarly to highly stable ones can limit the opportunities for niche technologies. The transport fuel regime in Sweden is changing incrementally in one sense via the inclusion of biofuels in fossil fuels, and long-term policies like the Swedish reduction obligation (SFS 2017:1201) is perceived by incumbents as providing adequate conditions for investments (SPBI 2020). Projects among incumbents concerned with electro-hydrogen production and carbon-capture indicate that the regime conditions might indeed be stable enough for niche technologies to emerge. It remains to be seen if the level of stability can motivate biohydrogen projects too. The fact that gasification-plants in some cases have been associated with a lifetime of 30 years (Salkuyeh et al. 2018) can make even long-term policy measures insufficient. The reduction obligation SFS 2017:1201 can be perceived very differently when looking at other hydrogen applications like FCEV's. The policy measure is clearly not technology neutral, as it is centred specifically on the blending of certain biofuels in fossil fuels. This leaves out options like FCEV's, which would require much different policy measures.

A general constraint for biohydrogen can be identified in the fact that companies are reluctant to take the role of "first-mover" and invest in niche technologies because of the risks of technical failure associated with them (Lewidow & Upham 2017). This barrier is overcome by electro-hydrogen, given its commercial introduction, but is highly relevant to the biohydrogen paths. Economic support schemes and an involvement of incumbents could be crucial here. The importance of timing and windows of opportunity should also be emphasized. In the case of municipal solid waste-gasification in the UK, operational reliability and subsequent interest from investors was achieved just as an economic support scheme was being phased out. This caused a clear temporal mismatch (Lewidow & Upham 2017). Differentiating between gasification and the biochemical paths, one can point to a niche technology as having to overcome "two valleys of death", where the first one is proving the technology and second one is commercialising it (Lewidow & Upham 2017). Seen in this way, the current challenges associated with the biochemical paths are related to the first while the challenges of gasification increasingly are more related to the second. Timing is perhaps most associated with challenges, but there are also opportunities. Given the fact that only 5 HRS' are present in Sweden (Vätgas Sverige n.d.) means that lock-in effects and sunk costs associated with this hydrogen application still are very limited. A sustained development of biohydrogen via demonstration scale processes and price/performance improvements can therefore allow biohydrogen to represent a viable option in a future case where hydrogen applications experience more rapid growth.

## 5.4 Method discussion

Turning to the method in the study, it is important to highlight that the aim did not explicitly rule out any approach in data collection. Conducting a literature review complemented with interviews instead of mainly interviews was however seen as the better option given the clear lack of experiences with an actual integration of biohydrogen, or even commercial plants, in Sweden or elsewhere. A presence of commercial biohydrogen production processes would clearly have provided opportunities for a study more extensively based on interviews. Scientific articles and reports used throughout the study however constitute secondary data and using this type of material is associated with less control over data quality, among others (Bryman 2016 p. 115). One example would be the fact that techno-economic assessments, extensively cited in this study, can be conducted using different system boundaries and levels of detail. This is likely to influence the findings and conclusions. Looking at the larger picture, a challenge was certainly the rather wide and explorative scope of the study. Considering reliability and validity, a systematic literature review with tighter inclusion criteria on a narrower topic, say the problem of ash in gasifiers, would clearly have been a better option. Given the diverse material collected throughout the study, especially on biohydrogen, the expert interviews filled a very important function and acted as a way of crosschecking and expanding on the findings. Nevertheless, the interviewees have experience mainly with the technical aspects of gasification and biochemical hydrogen production. This can be seen as an issue given the actual aim of the study. Regarding the interviews, more accurate conclusions could possibly have been achieved by conducting more interviews.

As for data analysis, applying MLP provided structure to a diverse collection of data and analytical depth to the results. The operationalisation, represented by table 4, is however an aspect of key importance since it can introduce systematic bias (Esaiasson et al. 2017 p. 55). This risk could be partly mitigated by the fact that MLP have been tested in many different contexts, producing a significant number of previous cases for which to base the understanding and operationalisation of MLP on. Another challenge again became apparent in the gap between the narrow and technical scope of articles on biohydrogen and the MLP, the latter taking more into consideration than the technology in question. This challenge was especially present when analysing the literature on feedstocks, technical maturity, and economic performance in section 4.2-4.4 of the results. These aspects are however nevertheless acknowledged as being important to understand the niche technology in question (Geels & Schot 2007). Furthermore, there are several alternative frameworks that could have been used for data analysis. One example is the technology innovation systems (TIS) framework that similarly to MLP focus on emerging technologies and the larger context they are a part of. Using an TIS-approach could have provided further possibilities to analyse functions like market formation, legitimation and resource mobilization related to the biohydrogen niche (Hekkert & Negro 2009). This would have allowed to delineate between the biohydrogen production paths on a somewhat deeper level than economics, technical maturity, and feedstocks.

While MLP undoubtedly is useful to explore complex transitions, it nevertheless has received several criticisms. One of these concerns the analytical levels, especially regimes. Some see the concept of regimes as problematic since it can be applied to different empirical levels. To take an example; a regime change in hydrogen production can be perceived as only an incremental change when seeing the whole energy system as a regime. As a response to this, proponents of MLP have emphasized regimes as merely an analytical concept that can be applied to empirical topics of different scope. The previously mentioned criticism would instead relate to the general problem of defining the scope of a study and setting boundaries (Geels 2011). Delimiting the geographical scope to Sweden has been crucial to allow for more detailed conclusions, but one can argue that the increasing integration between national energy systems provide a rationale for broader investigations too. Lastly, it is important to mention that several biohydrogen production paths were omitted from the thesis. The results and conclusions can therefore not in any way be seen representative for biohydrogen.

## 5.5 Outlook

An improved technical performance is crucial to achieve for all biohydrogen paths but should be pursued with attention to the larger context. For biochemical hydrogen production, this would entail more detailed assessments that focus on low cost feedstocks streams with suitable chemical compositions. Waste heat availability and existing technical infrastructure that can be modified are other aspects that should be further addressed. Food industries clearly constitute interesting cases based on the findings in this study, but they should be investigated on a case-by-case basis. For biohydrogen production via gasification, future efforts will to a large degree have to focus on the economics and proving the technology at commercial scale. Feedstock availability will be crucial, and Sweden constitute a promising location in this sense. An interesting topic to explore in further detail would be the role of policies like RED II in shaping the future extraction of forestry residues and other renewable feedstocks. Future efforts should also continue to investigate potential synergies between biohydrogen production and more established niche technologies like electrolysers, as this can mitigate competition.

# 6 Conclusion

The findings highlight that gasification and the biochemical paths constitute very different production paths in terms of both feedstocks, technical maturity, and economics. Gasification is currently envisioned to achieve lower hydrogen production costs than the biochemical paths and is also more technically mature. Forestry residues are often emphasised in the context of gasification, but feedstock costs nevertheless have a great influence on production cost. Envisioned production costs and process sizes vary significantly in the biochemical paths, reflecting a need for further development to yield dominant technical designs that can be commercialised. Dark fermentation as coupled to anaerobic digestion show the greatest potential of the biochemical paths because its associated with lower technical risk and costs. Organic waste and wastewaters constitute commonly envisioned feedstocks in all biochemical paths, but associated pre-treatment needs, competing applications and a lack of experiences with larger processes clearly warrant further investigations.

New hydrogen applications and niche technologies are extensively explored in the Swedish energy system by networks of incumbent actors. The emphasis in these contexts is currently on electro-hydrogen, but the findings show that the future case can comprise applications for biohydrogen too. The alignment between the niche biochemical paths and the organic waste treatment regime in Sweden indicate that an introduction is best pursed as an incremental process driven by synergies between the niche and the regime. This is furthermore crucial to allow for further learnings on dark fermentation. Biohydrogen production based on gasification is best realised at large scale, indicating that an incremental introduction associated with lower risk is difficult to achieve. A way forward may thus be in applications less impacted by landscape developments and shifting policy frames.

# Acknowledgements

I would like to express my gratitude to RISE and Miljöbron for giving me the opportunity to write this thesis, it has been an incredibly rewarding journey. My supervisors at RISE, Karin, Kristina, and Lina, thank you for all the interesting discussions and valuable suggestions. It has been great working with such a knowledgeable and committed team. I would like to thank Philip, my supervisor, for the support and input. The discussions with you have helped my greatly throughout. Helena at Miljöbron, thank you for supporting me during the conduct of this thesis. Thank you also to the interviewees who contributed and shared their views on the included production paths. Last but not least, I want to thank friends and family for the support and encouragement during this semester.

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## Personal communication

Senior researcher, Lund university, communication via phone 2020-04-24.

Senior lecturer, Research Institutes of Sweden (RISE), communication via Microsoft Teams 2020-04-21.

# Appendix

## Appendix A

**Validation interview – gasification – 21/4 2020**

1. Vilka huvudsakliga tekniska utmaningar står förgasning inför?

   (What are the main technical challenges associated with gasification?)

2. Vilken av dessa utmaningar ser du som det största hindret för ett fortsatt införande av förgasning i Sverige?

   (Which of these do you view as the most important challenge influencing a sustained introduction of gasification in Sweden?)

3. Vilka huvudsakliga aspekter påverkar ett bränsles lämplighet vid användning i en förgasare?

   (Which are the main aspects influencing the suitability of a fuel used in gasification?)

4. Hur uppfattar du att konkurrensen om bränslen påverkar ett fortsatt införande av förgasning i Sverige?

   (How do you think that the competition for fuels influence a sustained introduction of gasification in Sweden?)

5. Vilka möjligheter tror du det finns i att använda olika typer av slam, restprodukter från skogs- och jordbruk samt returträ som bränslen i förgasning?

   (What possibilities do you think that there is in using different types of sludge, forestry- and agricultural residues and reclaimed wood as fuel in gasification?)

6. I vilka applikationer tror du att potentialen för förgasning är som störst?

(In what applications do you think that the potential for gasification is the largest?

7. Går det att dra några slutsatser kring i vilka skala förgasning bäst introduceras?

   (Is it possible to draw any conclusions about which scale to best introduce gasification in?)

8. Finns det något du skulle vilja tillägga?

   (Is there anything you would like to add?)

# Appendix B

**Validation interview – biochemical hydrogen production – 24/4 2020**

1. In your opinion, what are the main challenges that biohydrogen production via the following paths face?

   DF-PF

   DF-MEC

   DF-AD
2. Which of these challenges do you view as the most crucial to address before achieving a future integration of biochemical hydrogen production in Sweden?
3. Which criteria do you find to be most important when assessing substrates for use in biochemical hydrogen production?
4. How do you think that the general competition for substrates will influence an integration of biochemical hydrogen production?
5. What commercial applications do you envision for biochemical hydrogen production and the produced biohydrogen itself?
6. How important do you think it is to establish applications also for by-products like $CO_2$?
7. Which of the DF-PF, DF-MEC and DF-AD-paths do you think have the greatest potential in a larger perspective?
8. Is there anything you would like to add?

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