REPORT

f3 2016:10

ANALYSIS OF P2G/P2L SYSTEMS IN PITEÅ/NORRBOTTEN FOR COMBINED PRODUCTION OF LIQUID AND GASEOUS BIOFUELS

Report from an f3 project

October 2016

Photo: SP/ETC Piteå.

Authors: Anna-Karin Jannasch, Roger Molinder, Magnus Marklund & Sven Hermansson, SP Technical Research Institute of Sweden

THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

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- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities,
- Carries through system oriented research related to the entire renewable fuels value chain,
- Acts as national platform stimulating interaction nationally and internationally.

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SUMMARY

Power-to-gas (P2G) means that power is used to split water into hydrogen and oxygen by electrolysis. The technology achieves much attention today in Europe as it enables storage of electrical power in energy gas and can thereby be an efficient way for storage of excess electricity from renewable wind-solar-or wave power. The hydrogen can either be used directly as the fuel or raw material it is, or be reacted further with carbon monoxide and/or carbon dioxide into a biofuel/biochemical, e.g. methane or methanol. When the end-product is a liquid, the technology is termed *Power-to Liquid (P2L).* Today, there is one commercial P2L-plant on Iceland and around 40 pilot and/or demonstration P2G/P2L-plants in Europe, mostly located in Germany. There is not yet any P2G/P2L plant on place in Sweden, but the interest for the technology is growing also here and several inititives and desk studies have been carried out and/or are on-going for evaluating the possibilities and potential benefits of the technology with respect to different Swedish conditions/ locations. At the time of publication of this report, a new EU project was initiated (in November 2016) whose aim is to establish and evaluate a P2-methanol pilot plant in Luleå in which carbon dioxide rich blast furnace gas from SSAB's steel production will be combined with renewable hydrogen from intermittent electricity production.

The purpose of this study is to identify, analyse and suggest different possibilities for P2G/P2L in Norrbotten with respect to the regional electricity market and hydrogen demands, having the biorefinery infrastructure in Piteå as a starting point. In the analysis, both current conditions and different future scenarios are considered. The investigation is a continuation of an ÅF-study from 2015 that pointed out Piteå- Luleå- Norrbotten as one of the three most appropriate locations for demonstrating P2G / P2L in Sweden.

In the report, the region's expansive plans for renewable power generation (≥ + 10 TWh /yr) is described, which in turn will require that new investments in transfer capacity, regional large-scale energy storage and / or energy conversion processes (eg P2G / P2L) are implemented. As one of the first steps for demonstrating the possibilities of P2G/P2L in the region, it is proposed to supply renewable hydrogen to the pilot plants available at the SP ETC in Piteå, possibly also a future nearby municipal filling station for hydrogen. This would result in a complete biorefinery in pilot scale, which would include and open up for the possibility to demonstrate how power peaks orginating from wind power can be converted into hydrogen and be utilized directly as fuel in fuel cell buses, for increasing the efficiency of thermochemical processes of biomass for the production of various biofuels/biochemicals and for various chemical processes such as biomass hydrocracking, see Figure below.

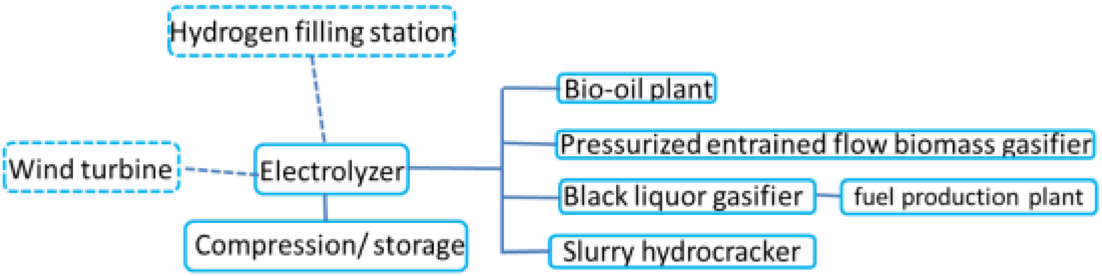


Figure. Schematic of the suggested P2G/P2L demonstration plant in Piteå.

The analysis shows that one should strive for and should be able to support all processes with hydrogen from a single electrolyzer (~ 1 MW_e), possibly self-sustained by a local wind turbine (3-5 MW_e). Pipelines for hydrogen distribution between the various inherent processes should be minimized for cost reasons. In a first stage, the most mature and cheapest electrolysis technology, the alkaline type (AEC), shall be the choice of preference, to later be replaced by the much less mature, but considerably more efficient high temperature SOEC technology, which would be integrated and provided with (residual) heat from the biorefinery. The analysis also shows that the suggested demonstration plant shall be designed for continous operation for simulating expected industrial large-scale operation conditions. This, however, demands for improved power transfer opportunities within the grid and/or the installation and use of hydrogen compression and storage, where the latter is identified, after the electrolyzer, as the most costly P2G/P2L related component. An opportunity that can provide an income at the same time it can contribute to keep the energy balance of the system is to trade on the regional electricity market (regulating power and / or spot), i.e. another issue that in the study is raised as an important parameter to investigate further and demonstrate with the suggested plant.

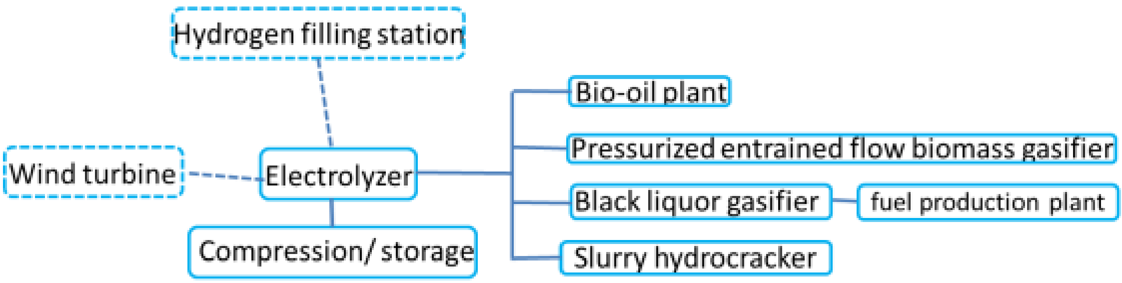
In addition to the hydrogen needs of the biorefinery infrastructure and the hydrogen filling station in Piteå, the interest and values of and plausible future need of renewable hydrogen of the regional steel (5-10 TWh/yr) and biogas industry (up to 30 GWh/yr) are presented and shortly discussed. It is clear that if the steel industry´s plausible hydrogen need would be realized, the entire regional electricity market would change. Most likely this would also incur that an infrastructure for renewable hydrogen is built up in the region, which other regional industries benefitting from hydrogen supply, such as biogas plants, could greatly profit from.

SAMMANFATTNING

El-till-gas (*eng. Power-to-gas, P2G*) innebär att el används för att sönderdela vatten till vätgas och syrgas med hjälp av elektrolys. Tekniken får idag mycket uppmärksamhet ute i Europa då den möjliggör lagring av el i form av energigas och kan därmed vara ett effektivt sätt för lagring av överskottsel från förnybar vind-sol- eller vågkraft. Vätgasen kan antingen användas direkt som det bränsle eller råvara som den är, eller låtas reagera vidare med kolmonoxid och/eller koldioxid till ett biobränsle/biokemikalie, t.ex. metan eller metanol. När slutprodukten är i form av en vätska går tekniken under benämningen *Power-to-Liquid (P2L)*. Idag finns det en kommersiell P2L-anläggning på Island samt ett 40-tal P2G/P2L pilot eller demonstrationsanläggningar ute i Europa, mestadels placerade i Tyskland. I Sverige finns ännu ingen P2G/P2L-anläggning på plats, men intresset för tekniken växer även här och flera initiativ och studier har genomförts och/eller pågår för att utvärdera teknikens möjligheter och potentiella nyttor utifrån olika svenska förhållanden/lokaliseringar. Vid tidpunkten för publicering av denna rapport så initierades ett nytt EU-projekt vars syfte är att etablera och utvärdera en P2metanol-anläggning i Luleå i vilken masugnsgas från SSAB:s stålframställning kombineras med förnybar vätgas från intermittent el.

Denna studie syftar till att identifiera, analysera och ge förslag på systemmöjligheter med P2G/P2L i Norrbotten med hänsyn till regionens elmarknad och vätgasbehov, med utgångspunkt från den bioraffinaderiinfrastruktur som finns i Piteå. I analysen beaktas såväl dagens förutsättningar som olika framtida scenarier. Studien är en fortsättning på en ÅF-studie från 2015 som pekade ut Piteå-Luleå-Norrbotten som en av de tre mest lämpliga lokaliseringarna för att demonstrera P2G/P2L i Sverige.

I rapporten beskrivs regionens expansiva planer för förnybar kraftproduktion (≥ + 10 TWh/ år), vilket i sin tur kommer kräva att nya investeringar i överföringskapacitet från elområdet, regionala storskaliga energilager och/eller energiomvandlingsprocesser (t.ex P2G/P2L) genomförs. Som ett av de första stegen till att visa på möjligheterna med P2G/P2L i regionen föreslås förnybar vätgastillförsel till de pilotanläggningar som finns vid SP-ETC i Piteå, möjligtvis också till en framtida närliggande kommunal tankstation för vätgas. Detta skulle resultera i ett komplett bioraffinaderi i pilotskala och skulle inkludera och öppna upp för möjligheten att demonstrera hur effekttoppar från vindkraft kan omvandlas till vätgas och brukas direkt som drivmedel i bränslecellsbussar, öka effektiviteten på termokemiska processer av biomassa för produktion av diverse biodrivmedel/biokemikalier och för kemiska processer såsom hydrokrackning av biomassa, se Figur nedan.



Figur. Schematisk illustration av föreslagen P2G/P2L-demonstrationsanläggning i Piteå.

Analysen visar att man bör sträva efter och bör kunna försörja alla processer med vätgas från en och samma elektrolysör (~1 MW_e), möjligtvis självförsörjd av ett lokalt vindkraftverk (3-5 MW_e). Vätgasledning mellan de olika ingående processerna bör av kostnadskäl minimeras. I ett första skede skulle den mest mogna och billigaste elektrolystekniken, den alkaliska (AEC), vara förstahandsvalet, för att i ett senare skede bytas ut mot den betydligt mindre mogna, men avsevärt effektivare högtemperatur SOEC-tekniken, som skulle integreras och förses med (rest)värme från bioraffinaderiet. Demonstrationsanläggningens bioraffinaderiprocesser skulle designas för kontinuerlig drift för att efterlikna förväntade storskaliga driftvillkor. Detta ställer emellertid krav på ökade överföringsmöjligheter till elnätet och/eller installation och användning av vätgaskomprimering och lagring, där den senare identifieras, efter elektrolysören, som den mest kostsamma P2G/P2L-relateterade komponenten i systemet. En möjlighet som kan ge en inkomst samtidigt som den kan bidra till att upprättahålla anläggningens energibalans är att agera på den regionala elmarknaden (frekvens- och/eller spot), vilket är en annan parameter som i studien lyfts upp som viktig att undersöka vidare om och demonstrera med föreslagen anläggning.

Förutom vätgasbehoven till bioraffinaderiet och tankstationen i Piteå beskrivs och diskuteras även intresset/nyttan av och potentiella framtida vätgasbehov till regionala stål- (5-10 TWh/år) och biogasindustrin (upp till ca 30 GWh/yr). Det är tydligt att om stålindustrins uppskattade vätgasbehov skulle förverkligas så skulle hela den regionala elmarknaden förändras. Troligtvis skulle detta också medföra att en infrastruktur för förnybar vätgas byggs upp i regionen, som andra, industrier med nytta av vätgas, såsom biogasanläggningar, skulle kunna dra stor fördel av.

CONTENTS

1 BACKGROUND

In 2015, an investigation carried out by ÅF identified the Piteå-Luleå-Norrbotten area as one of the three most suitable locations for demonstrating the utilities of Power-to-gas/Power-to-Liquid (P2G/P2L) in Sweden [1]. This was motivated by several reasons: First, the access to electricity is very good in the region. Norrbotten is a part of the electricity area 1 (SE1) which already has large electricity production compared to the use. There exists far-reaching plans for significantly further expanding the wind power, implying that the regional intermittent electricity surplus will continue to increase and that the transfer capacity southward (i.e. SE2 and so forth) and/or to our neighboring Nordic countries must be strengthened and/or that the surplus electricity has to be converted and/or stored to a significant higher extent. Second, the region has good prospects for future development of biorefineries. Not least because of the large supplies of forest biomass and the related long experience in value creation of the commodity chain. As a future upshift in the field, extensive expertise in the production of biofuels and bio-oil, respectively, has been built up in the region, centered around the R&D-sites SP-ETC AB and LTU Green Fuels, whose processes (i.e. methanol and/or DME production from biomass through gasificaton, bio-oil production by biomass pyrolysis, slurry hydrocracking) would all greatly benefit from a renewable hydrogen supply. In addition to the hydrogen needs of the different biorefinery processes, there is also an interest from Piteå municipality to enable conditions for operating a renewable hydrogen filling station, initially for supplying one or two fuel cell busses for public transportation. Piteå municipality has also shown interest in utilizing hydrogen for up-grading of locally produced biogas into biomethane [2]. Finally, SSAB has recently announced that they will work towards significantly reducing their use of fossil fuels in their steel production plants, out of which one plant is situated in Luleå. The non-fossil dependent process techniques to be investigated would in turn demand huge volumes of renewable hydrogen [3].

Overall, it can be stated that there are several strong reasons to further investigate how P2G/P2L best can be utilized in the Piteå-Luleå-Norrbotten area in terms of solving optimal sustainable hydrogen supply for existing and future regional fuel supply and industrial production processes.

2 AIM OF STUDY

The overall objecitve of the study is to increase the knowledge about improving the opportunities for efficient production of biofuels from Swedish forest raw materials and / or renewable electricity. The aims are to identify, analyse and suggest different possibilities for P2G/P2L in the Piteå-Luleå-Norrbotten area with respect to the regional electricity market and hydrogen demands. Both current conditions and possible future scenarios are considered. The starting point and the primary focus of the work is the pilot-scale biorefinery infrastructure in Piteå, but other regional industries that have been identified as possibly hydrogen needy are also shortly presented and discussed. The results will be used in further, more in-depth, optimization studies for final selection of P2G/P2L-systems in Piteå, so also in the validation of P2G/P2L in other comparable systems, such as other biorefinery systems in Sweden.

3 WORKING METHODOLOGY

The project was carried out as an investigation of possible P2G / P2L-systems in the Piteå-Luleå-Norrbotten area with the aim of recommending one or a combination of several system(s) having the pilot-scale biorefinery infrastructure in Piteå as a starting point. Both technical and economic aspects were considered. The project was divided into five different work packages and the report is structured thereafter, including:

- A short literature survey on P2G/P2L and electrolysis (WP1)
- Analysis of regional electricity market (WP2)
- Identification, description and analysis of possible regional uses and needs of renewable hydrogen, with a focus on those located in Piteå (WP3)
- Technoeconomical indata associated with P2G/P2L (WP 4)
- Suggestions for a P2G/P2L-system in Piteå (WP 5)

The analysis was based on current conditions and plausible future scenarios, where the utilised inputs are in-house data at SP-ETC and Luleå University of Technology, respectively and/or given by different technical suppliers, and/or found in the open literature. Additional valuable inputs to the project were supplied by Stefan Nyström (Preem), Erik Persson (Piteå municipality) and Erik Furusjö (Luleå University of Technology), who all contributed with in-kind to the project, so also by the project´s reference group, which consisted of the following persons:

- Lia Detterfelt (Renova)
- Maria Grahn (Chalmers)
- Farzad Mohseni (Sweco)
- Tomas Rydberg (IVL Svenska Miljöinstitutet)
- Simon Harvey (Chalmers)
- Peter Leisner (SP)
- Magnus Brolin (SP)
- Markus Norström (SP)

4 P2G AND P2L – WORKING PRINCIPLE AND STATUS

Power-to-gas (P2G) means that electricity is used to split water (H_2O) into its constituent hydrogen (H_2) and oxygen (O_2) through electrolysis, according to the reaction:

$$2\,H_2O \longrightarrow 2\,H_2 + O_2 \qquad \text{[eq. 1]}$$

The P2G concept attracts much attention today as it enables large-scale storage of electricity in energy gas and can thus be an effective way to store cheap surplus electricity from renewable wind, solar and wave power (Figure 1).

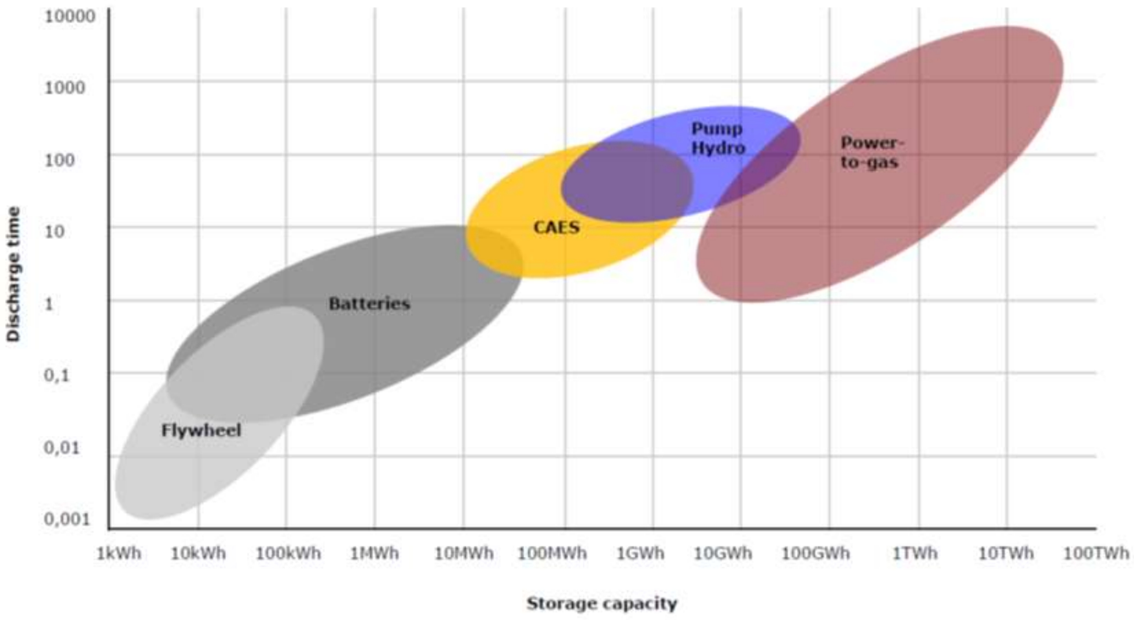


Figure 1. Comparison between different storage techniques for electric energy. Source: Fraunhofer Institute. The discharge time on the y-axis is given in seconds in logaritmic scale.

The produced hydrogen can be used directly for different energy purposes (e.g. fuel in fuel cell vehicles, reactant/raw material in industrial processes) and/or be reacted further with carbon dioxide and / or carbon monoxide into various gaseous (e.g. methane) and/or liquid hydrocarbon fuels/chemicals (e.g. methanol). When the final product is in gaseous phase, the technique is herein referred to Power-to-Gas (P2G), whereas when the final product is in liquid phase, the terminology Power-to-Liquid (P2L) is used. In the literature, a commonly used term in this field is also electrofuels, which is a generic umbrella name for all carbonaceous fuels originating from P2G and/or P2L. A schematic drawing illustrating the working principles of P2G/P2L and production of electrofuels are shown in Figure 2. For more details about the different processes, see for example reference [4].

Today, there is to our knowledge one commercial P2G/P2L plant up-running in the world, and that is Carbon Recycling International´s methanol plant on Iceland [5]. In addition, there are around 40 demonstration and/or pilot P2G/P2L-plants in operation or under construction in Europe. The majority of these plants are located in Germany, where the main driving force is the German energy roadmap plan *Energiwende* and where the objective is to establish P2G/P2L as a reliable, cost-efficient and large-scale multi-purpose option at least by the beginning of 2020/2025 with at least

1000 MW of electrolysis power installed [6]. So far, there is no demonstration or pilot plant for P2G/P2L on place in Sweden, but the interest in the technology is growing and there have been a few Swedish desk studies performed, investigating the potential of P2G/P2L from a Swedish perspective [1, 7], and a few new Swedish projects, besides this one, are also on-going [8-11]. At the time of publication of this report (Nov 2016), a new EU-project called FreSMe was granted and initiated, which aims to establish and evaluate a P2methanol-plant in Luleå, in which carbon dioxide rich blast furnace gas from SSAB's steel production will be combined with renewable hydrogen from intermittent electricity production.

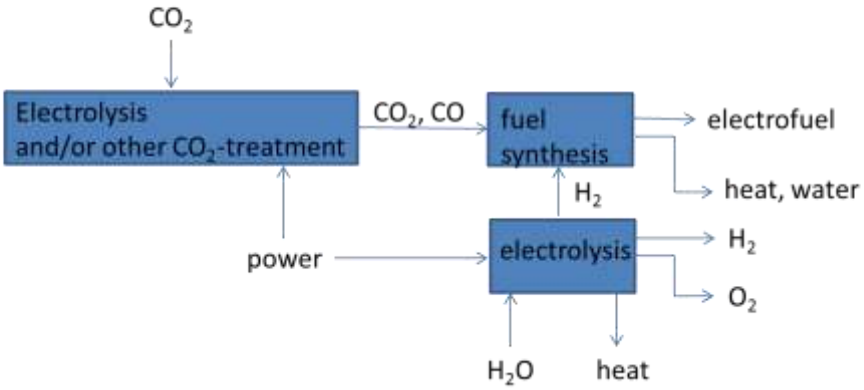


Figure 2. Schematic of the working principles of P2G/P2L and the production of electrofuels (i.e. generic umbrella name for all carbonaceous fuels orgining from P2G and/or P2L). The technology for carbon treatment and fuel synthesis steps varies depending on the carbon source and the desired end product (e.g. methane, alcohols, DME, FT-diesel, etc).

5 STATE-OF-THE-ART ELECTROLYZERS

As illustrated in Figure 2, the core of a P2G/P2L-system is the electrolyzer. It is also most often one of the most critical components to consider in the system from both a technical and an economical perspective [12], and thus requires special attention during the design phase. For facilitating the system understanding presented and discussed in the following chapters in this report, a summarizing description of different electrolysis technologies are given in this section.

In principle, there are today three different electrolysis technologies, which are either commercial or pre-commercial. They are named after the type of the electrolyte used. The different technologies are Alkaline Electrolysis Cells (AEC), Polymer Electrolyte Membrane (PEM) cells and high temperature Solid Oxide Electrolysis Cells (SOEC). The characteristics of these cells are summarized in Table 1, where also examples of suppliers of the different electrolysis technologies are included. In addition to these three types, some recent laboratory investigations have also been obtained with reversed high temperature Molten Carbonate Fuel Cells, i.e. Molten Carbonate Electrolysis Cells (MCEC) [13]. However, since the latter technology is still in such an early stage of development, no further information about this technology will be given in this report.

Table 1. Summary of the typical characteristics of different electrolysis technologies incl. example of suppliers [14, 15, 16].

	AEC	PEM	SOEC
Type of electrolyte	20-30 % KOH in H2O (l)	Polymer, e.g. NAFION®	Ceramic of yttria-stabilized zirconia (YSZ)
Type of electrodes	Ni-based	Pt/C-based	Ni-based (H2) Perovskite (Air)
Type of membrane	Asbetos or asbestos free polymer	Same as the electrolyte	Same as the electrolyte
Operation temperature, °C	60-90	50-80	600-1000
Operation pressure, bars	< 30-40	< 30-40	Under evaluation
Power density, W/cm²	≤ 1	≤4	Under evaluation
Part load range, %	20-40	0-10	0-10
Efficiency (based on LHV), %	60-80	60-80	90-95
Power consumption kWh/Nm³ H_2	~ 4-7	~ 4-7	~3-4
Start-up time (cold/hot condition)	From 1 h to 10 minutes	seconds	hours
Products	H_2, O_2	H_2, O_2	H_2, O_2 (water electrolys) CO, syngas (water and carbon dioxide electrolysis)
Maturity	commercial	commercial	Pre-commercial
Capital cost (SEK/kW$_e$)	≤ 10 000	≥20 000	-
Operation and maintenance cost	100-200 SEK/kW/y or approx. 4 % of the capital cost	1000-5000 SEK/kW/y	-
Life-time (hours)	100 000	10 000-80 000	-
Ex. of manufacturers/ suppliers	Hydrogenics, ELT, H2 Logic, Statoil	Hydrogenics, ITM Power, Siemens, ProtonOnsite	Haldor Topsoe

AEC has been in industrial use for decades (e.g. the Chlorine alkali-process) and is by far the most mature and the most applied electrolysis technology worldwide. With regard to P2G/P2L-systems, the AEC is for example in operation at E.ON´s P2G-plant in Falkenhagen and in the Danish Bio-Cat-project in Avedore [6]. It is the cheapest electrolysis technology with regard to investment costs. It is also the technology with the longest life time. PEM however has the ability to operate at up to four times higher power densities than AEC, resulting in more compact systems, whilst simulatenously allowing for start-ups in seconds and operation at very low loads (down to a few percent of rated power). Altogether, this makes PEM a very suitable electrolysis technology for intermittent P2G/P2L-operation. The investment cost of PEM is however still significantly higher due to the expensive membrane and electrode materials. Another disadvantage is the relatively short life time. The PEM-electrolyzer is today used at a number of P2G/P2L-demonstartion plants in Europe, for example in Wiessmann´s P2G demonstration in Alledorf [17]. Furthermore, from the perspective of efficiency, SOEC is the most promining electrolysis technology. It is however the less mature technology and still not yet commercially available. Besides the high efficiency, another important advantage of SOEC is the high operating temperature that enables not only production of pure hydrogen from water but also synthesis gas (CO and hydrogen) by co-electrolysis of steam and CO_2. The disadvantages of SOEC are however that it requires access to high-grade heat during start-up, and its relatively long start-up time from cold condition. The technology is thus best suited for continuous operation. Finally, an advantage that is usually highlighted with PEM and SOEC over AEC is that these two technologies can also operate in reversed mode, i.e. fuel cell mode, and thus also enable power production if desired. In practice, this alternating mode of operation is however not recommended today by any electrolysis supplier as it leads to significantly lower performance in both modes of operation. Consequently, if both hydrogen production and hydrogen-to-power (G2P) is requested, two separate units (i.e. one designed for P2G and one for G2P-mode, respectively) still need to be installed.

6 RESULTS AND DISCUSSION

6.1 REGIONAL SUPPLY AND DEMAND OF ELECTRICITY

Piteå and Luleå are situated in electricity area 1(abbreviated as SE1), which includes the whole of Norrbotten county but also parts of Västerbotten county, see map in Figure 3. In 2015, the power production of SE1 was around 22 TWh. Virtually all of this power is today derived from the hydropower with an installed capacity of around 4300 MW (~20 TWh/yr), whereas the wind power is the second largest power generation type in the region with an installed capacity of 483 MW (1.5 TWh/yr) [18] (Figure 4).

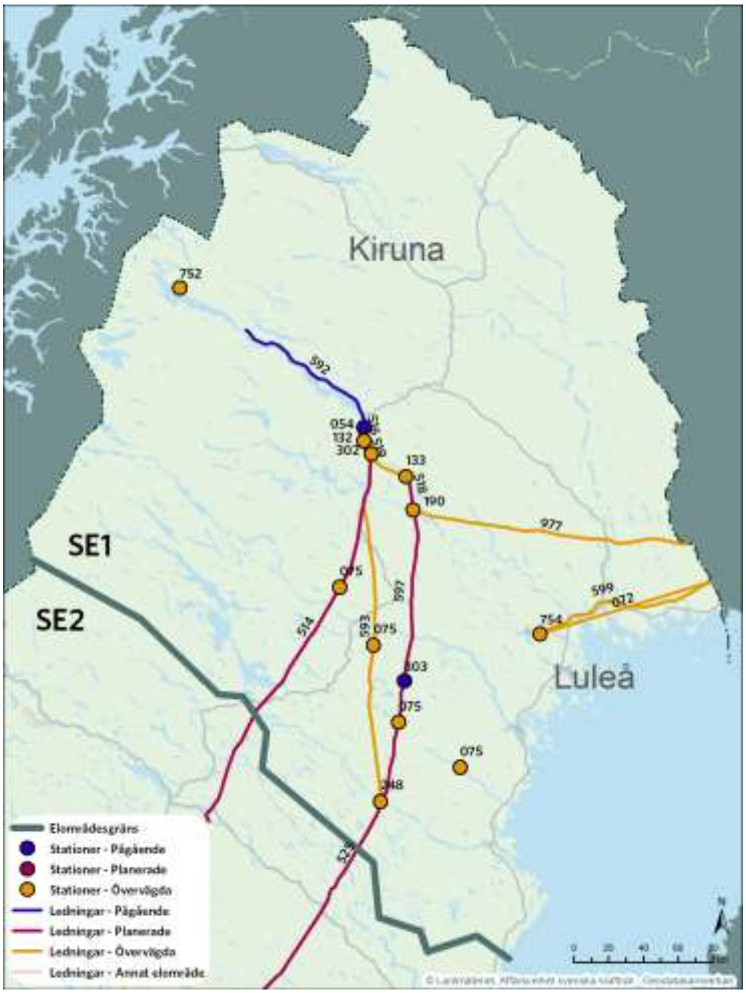


Figure 3. Map of the electrical area 1 (SE1), supplied by and published with permission of Svenska Kraftnät AB.

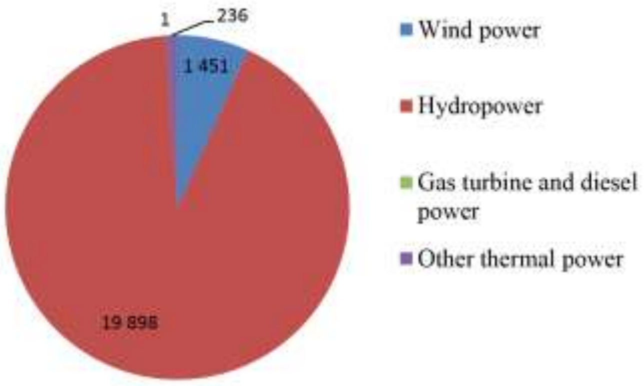


Figure 4. Electricity production (GWh) in SE 1 (2015) broken down per type of power source [18].

SE1 is today a large net electricity export area with an electricy consumption less than half of the total electricity production, i.e. around 10 TWh/yr including losses, giving a total regional electricity excess of around 12 TWh/yr (2015). Normally, this regional electricity excess is exported southward and also to some extent to our neighboring countries as shown in Figure 5. As indicated in this figure, the maximum Net Transfer Capacity (NTC=The max. exchange between two areas compatible with security standards applicable in the 2 areas and taking into account the technical uncertainties of future network conditions [19]) from SE1 to SE2 equals 3300 MW (via four 400 kV lines) plus an additional net transfer capacity to Norway and Finland of totally 1745 MW (via two 400 kV lines to Finland and a 400 kV line to Norway); altogether amounting to a maximum NTC of 5045 MW out from SE1 (dated 2016-07-06).

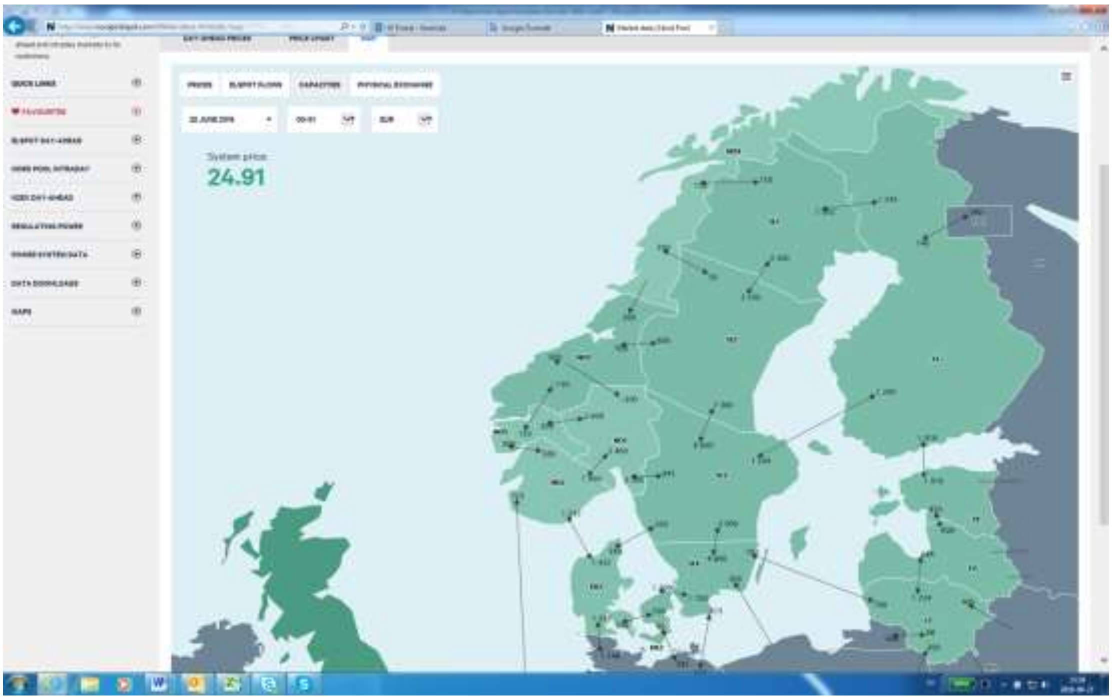


Figure 5. Screen shot of http://www.nordpoolspot.com/Market-data1/#/nordic/map [20] illustrating the net transfer capacities (NTC) in between SE1-4 and our neighboring countries.

The electricity spot price is based on the current supply and demand, simultaneously as it is well established that the cost of P2G/P2L is highly dependent on the electricity price and its availability [21]. Against this background, it seems reasonable to believe that a first rough indication of the prospects for large-scale P2G/P2L in SE1 could be discussed from the comparison between (i) the regional electricity surplus and (ii) the net transfer capacity out from SE1 (herein given by the maximum NTC). The situation as of today is therefore illustrated in this way in Figure 6. According to this plot, it seems as there is, today, no problem to match electricity generation with electricity demand. Consequently, there is no obvious need for, or value in, building up and implementing P2G/P2L or any other type of large-scale energy storage in the region, at least not from an energy storage perspective.

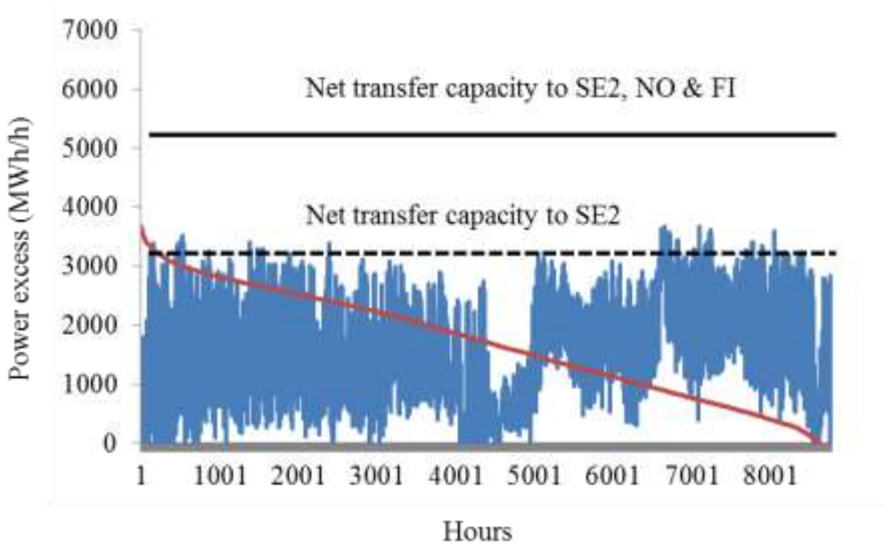


Figure 6. Regional power excess (MWh/h) in SE1 (2015). The red line is the blue data sorted plotted as a duration curve [18]. The net transfer capacity from SE1 to SE2 (3300 MW via four 400 kV cables) and from SE1 to SE2 with the cables to Finland and Norway included (5045 MW) are marked with a dotted and a solid line, respectively.

In practice, the situation is however more complex and the actual transfer capacity can from one day to the other change significantly depending on the prevailing operation conditions and the electricity pricing in the connected electrical areas. It should in this respect be especially noted that the maximum NTC from SE2 into SE1 is as large as in the reversed direction and that there could even be situations where power is imported into SE1 from SE2. In fact, SE2 is today an even greater net electricity producer than SE1 with a regional power production of as much as 31 TWh larger than the regional consumption (2015). Bottlenecks in electricity transfer between SE2 and SE3 occurs on a regularly basis. Naturally, this situation leads to hourly varying needs to import electricity from SE1, which in turn also affects the spot price in SE1. In 2015, the average spot price in SE1 was 214 SEK/MWh, with temporary, but very short-lived, variations between 30 and 1400 SEK/MWh (Figure 7).

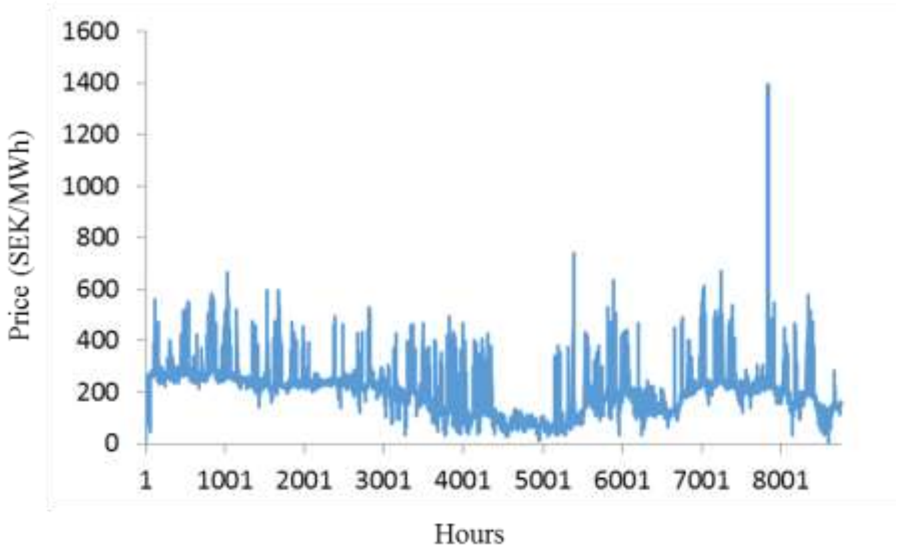


Figure 7. The hourly variations of the electricity spot price in SE1 during 2015 [22].

As for the future, there are strong indications of that the situation of SE1 will be quite different compared to today. First, there are far-reaching plans for significantly expanding the wind power in the region, with one of the largest wind power projects, Markbygden, situated west of Piteå. In this project, there are plans to build up to 1100 wind turbines within an area of 450 km^2, corresponding to a total installation capacity up to 4000 MW. So far, Markbygden Vind AB has been given the permission, by the Environmental Advisory Board, to install 754 wind turbines, corresponding to a wind power installation of 2500 MW, i.e. five times that of today, corresponding to an annual production capacity of around 7,5 TWh [23]. Motivated by the national govermental goal of having 100 % renewable power production by 2040 [24], these will most probably be erected already in between 2017-2021 [25]. In the case that also the fourth (and last) planned phase of the project will be granted, the wind power production at this site could be extended to as much as 12 TWh/yr. Simultaneously, there are plans for largely expanding the wind power production in adjacent SE2 [26], so also significant investments in new power production capacity in both Norway and Finland. An example of the latter is not least the nuclear power plant in Pyhäjoki only150 km from Piteå. Furthermore, the regional hydropower is expected to increase only marginally (+10 % to 2025) at the same time as projections indicate that the regional power consumption will only sligthly increase (up to +10 % to 2025) [26]. Finally, there is also an interest to expanding the regional solar power installation motivated by the documented high regional ratio of solar radiation. As a start, PiteEnergi will before the end of 2016 dispose three solar power installations for a project called SolEL aimed to develop a testbed environment for solar power installations in cold climates, to test both state-of-the-art technology and the next generation of solar electricity [27].

Together, the above mentioned developments points towards an increase in excess regional power production, and it is clear that this in turn requires new investments in transfer capacities from SE1, regional large-scale energy storages and/or energy conversion processes (e.g. P2G/P2L) in order to use the production resources efficiently. Svenska Kraftnät AB is presently exploring the possibilities to strengthen the transmission capacity southward through the construction of an additional 400 kV cable and/or increasing the capacity of the existing cables from SE1 to SE2, so also from SE2 to SE3. There are also ongoing analyzes of conditions for a third 400 kV line between SE1 and Finland [28]. The permissions of such large investments as establishment of new and/or strengthen of existing cables has however considerably longer lead times than the erection and commissioning of wind turbines. Consequently, larger amounts of regional intermittent power will most probably be available in the near future, as illustrated in Figure 8a-b, which in turn would presumably result in significantly longer periods of time with low cost electricity available on the market in SE1. As a result, energy storage in fuels/chemicals through P2G/P2L could during this scenario, among other storage alternatives (e.g. electrical vehicles), be of high interest for the region.

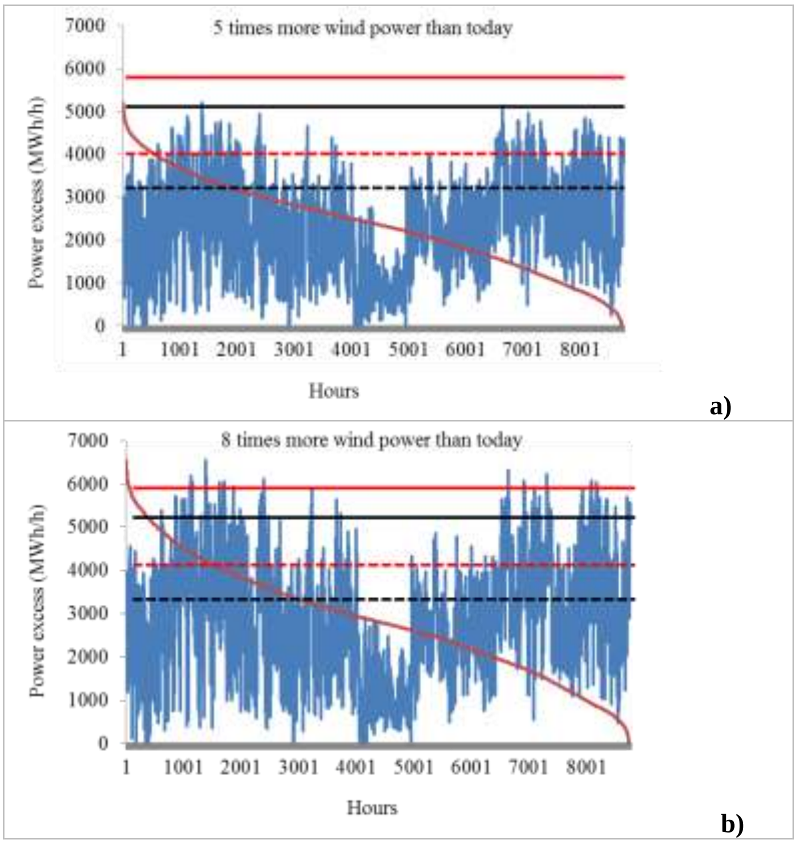


Figure 8a-b. Regional power excess (MWh/h) in SE1 assuming a) 5 times more wind power than today, b) 8 times more wind power than today based on collected data för 2015 [18]; otherwise all constant conditions. The factors 5 and 8, respectively, correspond to Markbygden´s different wind power expansion plans. The red line is the blue data plotted as a duration curve (sorted). The net transfer capacity from SE1 to SE2 (3300 MW via four 400 kV cables) and from SE1 to SE2 with the cables to Finland and Norway included (5045 MW) are marked with a black dotted and a black solid line, respectively. The corresponding red lines assume an additional transmission cable of 400 kV with a NTC of 825 MW.

6.2 LOCAL AND REGIONAL DEMANDS OF HYDROGEN

In the following chapter, the local and regional hydrogen demands are estimated as of today and of the future. Local hydrogen demands refer hereby to the estimated local hydrogen needs for different R&D plants at Industrigatan 1 in Piteå, partly hosted by Piteå Science Park which houses both SP Energy Technology Center (SP ETC) and LTU Green Fuels as well as for a potential hydrogen filling station in Piteå. The regional hydrogen demand refer to the plausible future use and/ord demand for hydrogen in the steel and biogas production industry in Norrbotten county. First, an envisioned future industrial scale biorefiney in the Piteå/Luleå/Norrbotten area is presented which forms the basis for the future hydrogen demands in the area. Second, R&D plants at Industrigatan 1 are described and their hydrogen needs are explained and estimated. Then the background to and the most recent developments on the subject of a hydrogen filling station in Piteå is presented. Finally, the two herein identified regional hydrogen needs are discussed and roughly estimated.

6.2.1 Vision of an industrial scale biorefinery

Today's regional value chain of forestry biomass has a long history and consists of players who are well integrated in the regional economy. The end products produced today are sawn and processed wood products, pulp and paper products for packaging and bags, as well as biofuels. The region has also carpentry and house builders, which further refines timber products. However, the value chain in recent years has been supplemented by a new product in the form of pine diesel from tall oil (Sunpine in Piteå). This addition of new viable industry, relatively small but well within the scope of the future bioeconomy in the regon, is a very important example in a transforming market to more sutstainable products. The current players in the forest industry: forest owners; wood products industry; pulp and paper; and biofuel producers, all live in symbiosis and are dependent on each other for the whole value chain, both from the material flow perspective and in terms of revenue streams. If any part of the existing value chain is negatively affected, the rest will also be directly affected and viable conditions for new “transforming” activites may be severely hampered, or even become impossible. Furthermore, the forest industry is often under financial pressure and is suffering from a very tough competitive situation, where many providers are fighting for the same market. With small margins and large volumes, which largely go to export, the forest industry is sensitive to relatively small market changes. Hence, a transformation to a biobased economy in larger extent has to consider this current situation of a fragile industry.

Investigations of the commercial conditions for a new biobased industry in the region has been carried out within a project led by Piteå Science Park, internally presented (in Swedish) in the final report ”*Kommersiella förutsättningar för ny biobaserad industri i regionen BD & AC*”. This work has further resulted in the start-up of a cluster initiative: Bothnia Bio Industry Cluster (BOBIC) with the general objective of creating an arena where the region's "triple helix" players can interact (industry, research institutions / academia and society). The cluster as a whole should consider the value chain perspective to ensure that the right conditions are created for both existing and new players in a strengthened bio industry in the region. For example, an inventory of the current material streams among the forest industry in the region has been carried out and showed that Piteå is strategically placed considering the possble use of sawdust as the basic raw material in refined value added biobased products. Considering all the saw mills within a ~150 km radius around Piteå there is roughly 1,5 TWh of sawdust produced, which has low value today and is hardly not refined at all (more the in form of pellets). This is a low hanging fruit and could be a starting point for establishing new products and new industries, if the whole value chain perspective is carefully considered.

The future hydrogen demands in the Piteå-Luleå-Norrbotten area are connected to an envisioned future industrial scale biorefinery in the same area. This biorefinery would consist of gasifiers of around 500 MW_{th} connected to synthesis gas upgrading plants capable of converting biomass raw material to liquid transportation fuel. It would further comprise of a bio-oil production plant (e.g. via fast pyrolysis) connected to a slurry hydrocracker for production of bio-crude oil from the same biomass raw material. A possible scenario for producing bio-crude in the region could be to have a hub in Piteå that could ship this to Preem in the same manner as Sunpine supply their raw tall diesel to Preem. The future industrial scale biorefinery will make use of the biomass resources in the region and will greatly benefit from the logistics infrastructure that are already in place to supply the pulp and paper industry in the region. It will also make use of the renewable electricity in the region, both the current wind and water power and also the additional wind power that is planned (Section 6.1). The industrial scale biorefinery will also need a supply of renewable hydrogen, both for direct use but also for improvements in efficiency. It would also be able to take advantage of peaks of high wind to produce excess hydrogen for storage. It could be self-sufficient with regard to power for hydrogen production, i.e. have its own wind farm. That would also make it possible for the full scale biorefinery to participate on the spot and/or regulating power market. Electricity and hydrogen flows would be redirected in response to local wind conditions.

6.2.2 Local hydrogen demands

Four out of five local hydrogen needs in Piteå as of today and tomorrow are related to R&D plants for the production of renewable biofuels, which are described in detail below. These are (i) a pressurized entrained flow biomass gasifier (PEBG pilot), (ii) a black liquor gasifier connected to a DME/Methanol production plant (DP-1 BLG/BioDME demo plant), (iii) a slurry hydrocracker (SHC pilot), and (iv) a cyclone based fast pyrolysis bio-oil pilot plant (POC pilot). These plants are operated by SP ETC and LTU Green Fuels and are all situated on the same site, partly hosted by Piteå Science Park on Industrigatan 1 (Figure 9). Today, the only existing renewable hydrogen demand in the region is the hydrogen demand of the slurry hydrocracker (SHC), while the others are hydrogen demands based on various far-reaching plans or future scenarios under consideration and/or discussion.

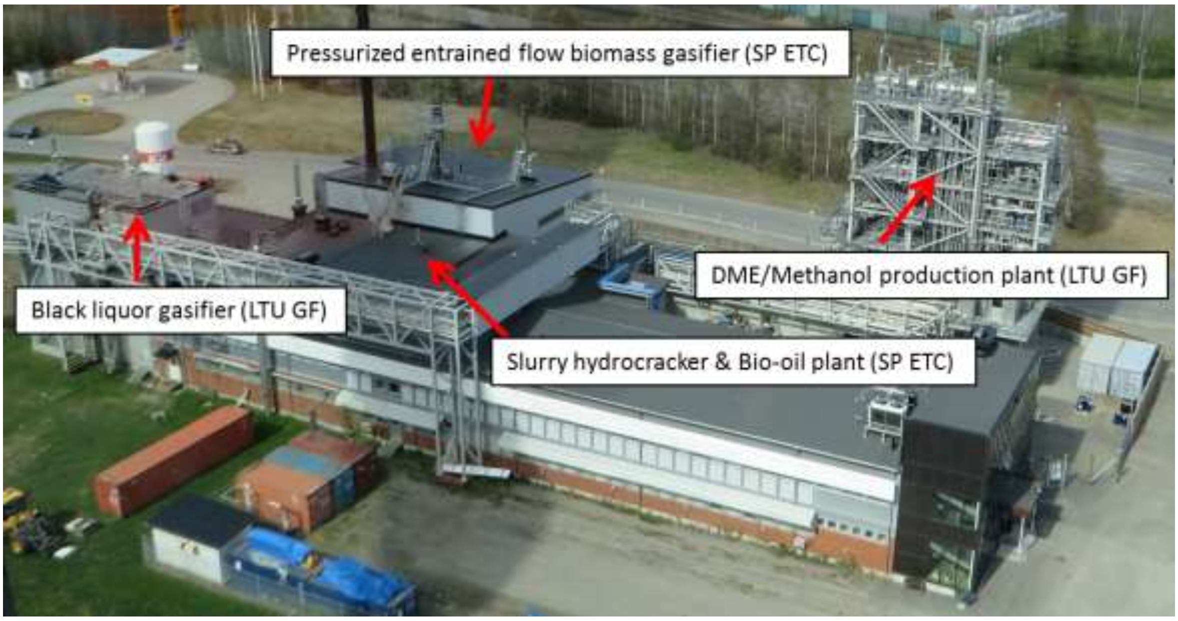


Figure 9. The site in Piteå on Industrigatan 1 where the local R&D plants for the production of renewable biofuels are located. The arrows show the locations of the R&D plants at the site, which are operated by SP ETC and LTU Green Fuels.

6.2.2.1 Doping of synthesis gas for improved production efficiency of bio-fuels and bio-chemicals through gasification

Entrained flow gasification can be used to efficiently produce bio-fuels and bio-chemicals in the following way: Biomass (either solid, in the form of a powder or liquid) is added to a heated gasifier (1200-1500 °C) together with oxidizing gasoues media in form of a combination of pure oxygen, steam, and carbon dioxide. The latter (CO_2) will most likely be used in optimized future plants through separation from the raw syngas in the process and used for pressurization and purging. This results in the formation of a low-tar containing synthesis gas (syngas) mainly consisting of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and methane (CH_4). This syngas is then cleaned and suitably conditioned (e.g. shifted with respect to hydrogen to carbon monoxide ratio) in order to be upgraded downstream the gasifier through catalytic synthesis steps to produce liquids such as methanol and/or DME.

Hydrogen doping of the synthesis gas produced through entrained flow gasification can be used to increase the efficiency of the downstream catalytic processes and thereby increase the production of bio-fuels and/or bio-chemicals from the same amount of feed-stock supply. The pressurized entrained flow biomass gasifier (PEBG) (Figure 10) has been used for the production of synthesis gas from solid biomass such as wood powder [29], biorefinery lignin residue [30], torrefied wood residue [31], but also from bio-oil [32].The PEBG is a 1 MWth pilot gasifier and can be operated up to at 10 barg. A full scale commercial PEBG would be in the order of 500MW_{th} and operate at >30 bar [33]. However, for a next demonstration step in the current region of interests a 100 MW_{th} plant would be realistic.

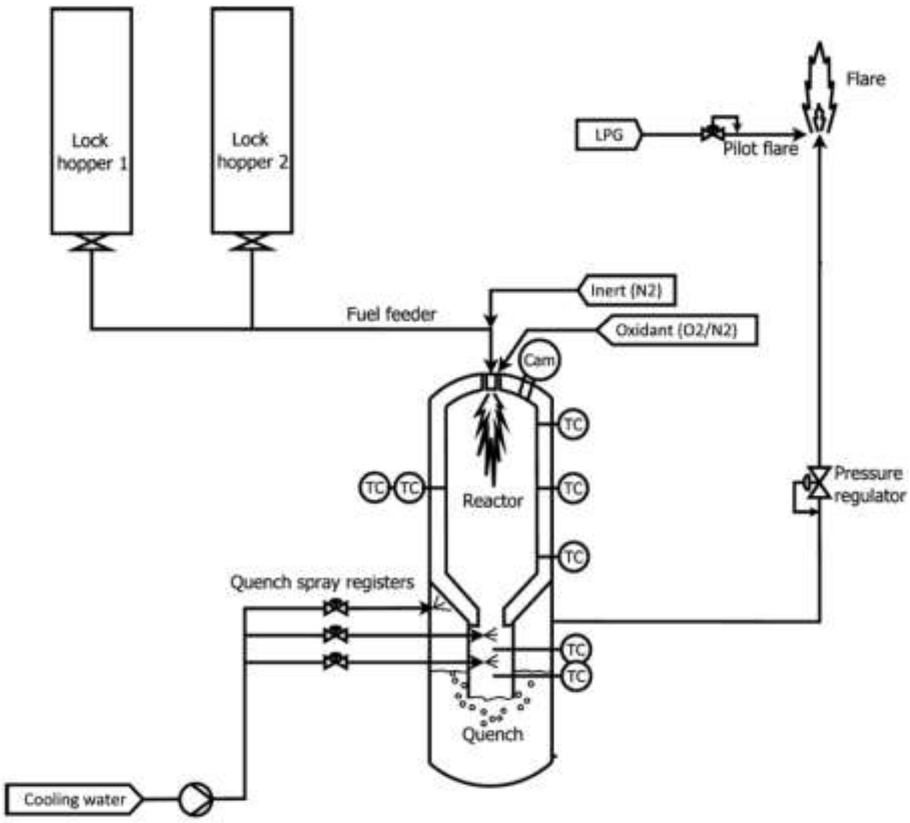


Figure 10. Schematic of the 1 MW_{th}, 10 barg pressurized entrained flow biomass gasifier (PEBG) situated at Industrigatan 1 in Piteå, operated by SP ETC [29].

The DP-1 BLG gasifier (3 MW_{th}), owned by LTU Green Fuels [34], has been in operation in between 2006 and May 2016 (the BioDME plant since 2011) (Figure 11).

The main biomass feedstock during this time has been black liquor (BL) from the nearby Smurfit Kappa kraftliner and blends of BL and bio-oil aimed at producing a clean synthesis gas processed on to methanol and/or DME in a downstream plant [35]. During normal operation, 1 wt% of the total black liquor production at the mill was fed to the DP-1 gasifier. This corresponds to approximately 1250 kg h-1 (or approx. 3 MWth). The last experimental campaigns in the DP-1 plant aimed at producing synthesis gas for synthesis in the BioDME plant from a mixture of black liquor and bio-oil [36]. If the technology were to be scaled up it would use an estimated 100 wt% of the black liquor produced in a pulp mill, hence completely replacing the conventional steam generating recovery boiler to produce transportation fuels instead (equivalent to approx. 300 MW_{th} feed through put). However, the black liquor gasifier and the DME/Methanol production plant are since May 2016 not in operation. Funding is currently being sought to mothball both plants so they can be reopened as soon a funding for a new research project is secured [36].

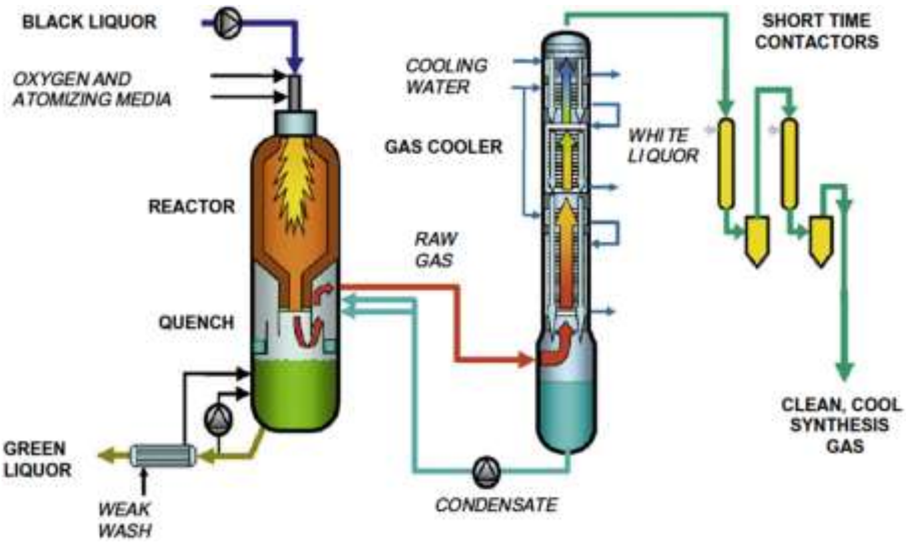


Figure 11. Schematic of the black liquor gasifier situated at Industrigatan 1 in Piteå, operated by LTU Green Fuels. The resulting clean, cool synthesis gas (bottom right) is upgraded to methanol and/or DME in downstream catalytic process steps [34].

For the production of methanol using entrained flow gasification, the ideal synthesis gas should in this case contain only H_2 and CO with a molar ratio of 2:1 (H_2:CO). However, the synthesis gases produced by the PEBG concept and the black liquor gasifier have H_2:CO molar ratios lower than 2:1. Synthesis gas composition varies depending on gasifier operating conditions and during gasification of wood powder in the PEBG at a flow of 40 kg h-1 (corresponding to approx. 0.2 MWth) the H2:CO molar ratio of the synthesis gas is 0.5:1[29]. Under the operating conditions noted above (black liquor flow of 1250 kg h-1, corresponding to approx. 3 MWth) the synthesis gas produced using the black liquor gasifier has a H2:CO molar ratio of 1.7:1 [38]. The H_2:CO molar ratios of both synthesis gases thus both need to be adjusted (shifted) prior to fuel synthesis step(s). Today, the molar ratio is adjusted through the water gas shift (WGS) reaction (Equation 2).

$$CO + H_2O \leftrightarrows H_2 + CO_2 \qquad \text{[eq. 2]}$$

Alternatives to WGS are to (i) remove CO or, (ii) add hydrogen to the synthesis gas. However, both the WGS option and CO removal incur a loss of carbon with subsequent reduced methanol /DME production and process efficiency loss. Adding hydrogen is therefore potentially a better option for synthesis gas adjustment as no carbon is lost. If this hydrogen is produced through water splitting into H_2 and O_2 by electrolysis, further improvements in process efficiency can be made as the O_2 stream can be used as oxidizing media in the gasifier. O_2 is neeed in the gasifier process to burn a portion of the feedstock in order to produce heat. O_2 production contributes significantly to the energy requirements of an entrained flow gasifier [39]. The capital cost investment for such a solution would involve installation of an electrolyzer and a hydrogen storage unit. Additionally, pressure regulation between electrolyzer and syngas lines might be nessecary.

Based on the H_2:CO and on the mass flow of the synthesis gas from the PEBG and the black liquor gasifier, the hydrogen flow that would be needed to achieve the correct H_2:CO are 52 and 67 (n)m^3 h^{-1} for the PEBG and the black liquor gasifier, respectively. Note that, the PEBG requires more hydrogen per MW due to the lower H_2:CO ratio of the produced PEBG synthesis gas. Details can be found in the Appendix. A summary of hydrogen needs for doping of synthesis gas for improved production efficiency of bio-fuels and bio-chemicals through gasification is given in Table 2 (based on the latest available PEBG pilot data for sawdust, without any possible process modifications). Future needs are calculated by mupliplying todays need per MW with the effect of the estimated full scale plants.

Table 2. Hydrogen needs (today and tomorrow) for doping of synthesis gas for improved production efficiency of bio-fuels and bio-chemicals through gasification (unit: (n)m^3 h^{-1}).

Technology	Today	Tomorrow
PEBG	52	26 000
Black liquor gasifier	67	6 700

Note that the hydrogen need for a pilot scale plant is more intermittent than for a full scale version of the same plant. The 1 MW_{th} PEBG pilot plant is normally operated on a daily basis (8-10 hours per day), but also 2-3 days per week campaigns can be carried out. A demonstration or full commercial scale PEBG plant would however run continuously for around 8 000 hours per year. The DP-1 black liquor gasifier has been operated continuously, in the same way as a full scale plant.

6.2.2.2 Direct use of hydrogen in a slurry hydrocracker for fuel upgrading

Slurry hydrocracking (SHC) is a catalytic chemical process for upgrading different liquefied fuel feedstocks; so far mainly applied with fossil feedstocks. It involves mixing the fuels with catalytic material and introducing hydrogen at temperatures in the range 260-430°C and high pressure (35-200 bars). Under these conditions the hydrocarbons with high boiling points in the feed cracks into smaller ones with low boiling points and at the same time removes oxygen and impurities such as sulphur and nitrogen from the fuel feed. Today, the SHC technology in combination with renewables such as lignin starts to get much interest by the Swedish chemical industry as they foresee that this could be a future way for producing large volumes of biofuels in the country. Preem estimates that about 2-3 millions tons lignin could be extracted from the existing pulp industry in Sweden every year which would be equivalent to a biofuel volume as large as a fifth of the total volume of fuel in Sweden [40].

A slurry hydrocracker (SHC) pilot will be erected and commissioned at SP ETC in December 2016. It will resemble the slurry hydrocracker shown in Table 2 and will initially be used to upgrade liquefied kraft lignin. The SHC at SP ETC will convert ≈ 1 (n)L of slurry per hour and it will be run for one or a few days at a time. The hydrogen need is 1 (n)m^3 h^{-1}. A full scale SHC would be more than 300 times larger [41] but such a large plant is currently not being envisioned for Piteå. However, a demonstration plant 10 times larger could be possible which would require a hydrogen flow of 10 (n)m^3 h^{-1}.

Figure 12. A slurry hydrocracker similar to the one which will be built and commissioned in December 2016 at SP ETC.

Table 3. Hydrogen need (today and future) for direct use in a slurry hydrocracker (SHC) for fuel upgrading (unit: (n)m^3 h^{-1}).

Technology	Today	Future
Slurry hydrocracker	1	10

6.2.2.3 Use of hydrogen for production of bio-oil using catalytic pyrolysis

Bio-oil can be produced through fast pyrolysis [42] which can be used as a substitute for fossil oil after upgrading, e.g. in a slurry hydrocracker (Section 6.2.1.2). Bio-oil production is currently carried out at SP ETC on Industrigatan 1 in Piteå (Figure 13) using N_2 as a carrier gas but the process can also be carried out using hydrogen which then acts as both a carrier gas and a reduction agent. This has been shown to increase bio-oil yield and reduce oxygen content [43, 44]. The bio-oil plant at SP ETC is 0.2 MW_{th} [42] and the carrier gas flow is 45 (n)m^3 h^{-1} [42]. It is estimated that a full scale bio-oil plant (distributed units) would be in the size of 4 MW_{th} and require a carrier gas flow of 900 (n)m^3 h^{-1} [45]. The carrier gas can be in form of inert nitrogen, pure hydrogen, or a mix of recirculetad non-condensible process gases and hydrogen/steam. However, as hydrogen also functions as a reduction agent, part of the hydrogen gas is consumed in the process. Also, the hydrogen would need to be recirculated to reduce costs. Therefore, the hydrogen need given here is a first estimate which will need to be adjusted through a more detailed analysis.

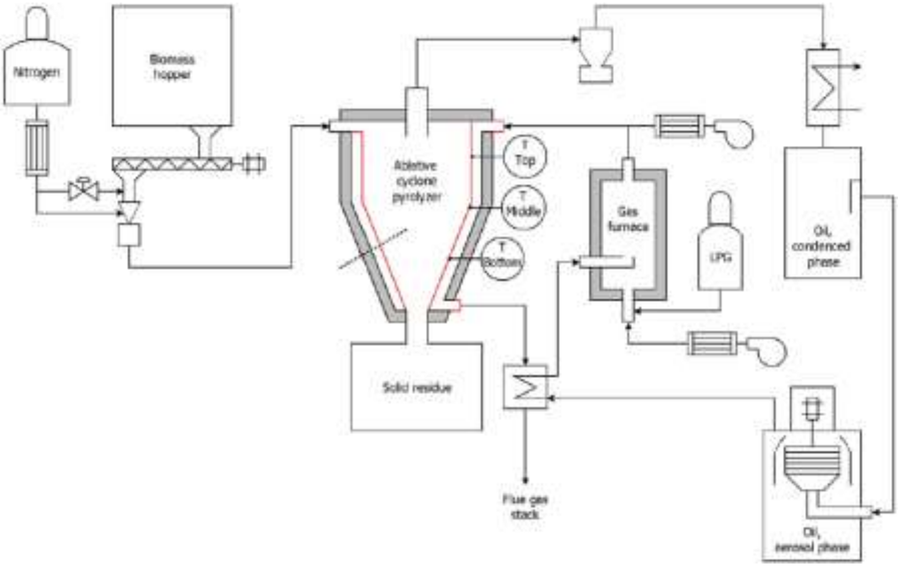


Figure 13. A schematic of the bio-oil plant at SP ETC.

The hydrogen needs for today (0.2 MW_{th}) and the future (4 MW_{th}) equal the carrier gas flow requirements of the bio-oil plants (Table 4). In other words; the hydrogen need is equal to the carrier gas need. The calculated hydrogen needs in Table 4 does not take into account the amount of hydrogen consumed in the process. Again, the hydrogen need given here is a first estimate which will need to be adjusted through a more detailed analysis.

Table 4. Hydrogen need (today and future) for direct use in a bio-oil plant (unit: (n)m^3 h^{-1}).

Technology	Today	Future
Bio-oil plant	45	900

6.2.2.4 Direct use of hydrogen in a fuel cell bus

Today, Piteå municipality´s bus fleet consists of 13 buses, plus 4 school buses which all currently run on conventional diesel fuel. The municipality is now seeking fuel alternatives for moving towards a more sustainable local bus fleet [2]. For example, funding opportunities have been investigated for financing a local fuel cell bus and a hydrogen filling station (as a part of a multifuel tank station) with the aim of investigating the performance of the bus in cold conditions. A fuel cell bus would require ~440 (n) m^3 of hydrogen per day [2]. This daily hydrogen demand is equal to 55 (n)m^3 h^{-1} assuming 8 hour of driving. However, the hourly hydrogen demand is only calculated for comparison with the other hydrogen demands from the biorefinery plants and is not direcly applicable to direct use in a fuel cell bus. While the other demands equate to a constant hydrogen flow for a continuous process, the fuel cell bus require hydrogen to be produced and then compressed and stored for filling.

6.2.3 Summary of local hydrogen demands

Table 5 summarises estimated current and future hydrogen demands described in prevailing sections in this report. Table 5 also lists the corresponding electrolyzer power consumption for hydrogen production calculated from the estimated hydrogen demands and a electrolysis power consumption of 5 kWh/(n)m^3 (in practice varying in the range of 4-7 kWh/(n)m^3, see Table 1).

Today, the only existing renewable hydrogen demand in the region is the listed hydrogen demand of the slurry hydrocracker (SHC), while the others are hydrogen demands based on various far-reaching plans or future scenarios under consideration and/or discussion. Note that today's hydrogen demand for the PEBG listed in Table 5 refers to the hydrogen demand of the 1 MW_{th} pilot scale gasifier at operated by SP ETC. Likewise the PEBG, the black liquor gasifier system is herein also listed as "today" and the given hydrogen demand of the plant assumes normal operation mode. This herein given status classification is motivated by the fact that the plant has been mothbolled and efforts are being made to reassume its operation (Section 6.2.1). Moreover, the hydrogen demand for the bio-oil plant listed under "today" refers to the demand for catalytic pyrolysis using the 0.2 MW bio-oil plant at SP ETC. Note that there is no hydrogen demand in the bio-oil plant that is currently on place at SP ETC. Furthermore, the establishment of a hydrogen filling station in Piteå is today still under discussion and any decision on how to proceed is not to be expected before the end of 2016. The hydrogen demand cited in Table 5 therefore corresponds to the hydrogen demand for operating the single fuel cell bus presently under consideration. Finally, listed "future" hydrogen demands for the PEBG, black liquor gasifier, and bio-oil concept, respectively, refer to the estimated demands of commercialized technologies, i.e. a move from pilot scale to full scale operation. Future demand for the SHC refers to the demand of a demonstration scale SHC given that is currently not being envisioned for Piteå.

Table 5. Summary of estimated plausible current and future hydrogen demands identified for local in Piteå and corresponding power consumption needed for its production through AEC/PEM-electrolysis. The calculations assume an electrolyzer power consumption of 5 kW_e/(n)m^3 H_2.

Local demands	Estimated hydrogen demand ((n)m^3 h^{-1})	Corresponding power consumption for electrolysis (MW)
Direct hydrogen use in a slurry hydrocracker (SHC)	Today: 1 Future: 10	n/a 0.05
Addition of hydrogen to synthesis gas produced from solid biomass (PEBG concept)	Today: 52 Future: 26 000	0.3 130
Use of hydrogen for production of bio-oil using catalytic pyrolysis	Today: 45 Future: 900	0.2 4.5
Addition of hydrogen to synthesis gas produced from black liquor gasification (LTU Green Fuels concept)	Today: 67 Future: 6 700	0.3 33.5
Direct use of hydrogen for operation of one fuel cell buss	55	0.3

6.2.4 Regional hydrogen needs

The regional hydrogen needs identified in this work refer to future plausible needs of two completely different industries located in Norrbotten county. One is possible hydrogen needs of SSAB´s steel production in Luleå, the other one is possible hydrogen needs of the regional biogas industry.

6.2.4.1 Hydrogen as a reduction agent during steel production as SSABs steel plant in Luleå

SSAB has recently announced that they will reduce their use of fossil fuels in their steel production plants [3]. One of those plants is situated in Luleå and as part of the steel production process, iron ore reduction is needed. In order to reduce the dependence on fossil fuels in this reduction step, new technologies based on renewables are now under investigation. One such technology is to use renewable hydrogen as a reduction agent. Assuming that the same energy content of hydrogen would be needed as for direct natural gas reduction, the SSAB site in Luleå could potentially in the future become in the need of as much as 5 – 10 TWh H_2 per year depending on production rate and process efficiency [46].

Another possibility for renewable hydrogen at the site is to combine the hydrogen with the surplus of blast furnace gas containing large amonuts of carbon dioxide and carbon monoxide and produce various electrofuels by the same way as e.g. LTU Green Fuels [1]. As mentioned in Ch. 4, this is also a process that soon will be implemented and evaluated in pilot-scale in the newly launched EU-project *FreSME*.The advantage of such a process compared to the hydrogen reduction process mentioned above would be that this is a well-known technology that could be applied more or less directly in large-scale. The principal disadvantage would be that the blast furnace gas is of fossil orgin and that the fuel produced would not be considered as fully renewable.

6.2.4.2 Addition of hydrogen to increase efficiency in biogas production plants

Likewise it can be advantagous to add hydrogen into various thermochemical processes, there could also be a great potential to take use of renewable hydrogen in biogas and/or a land fill plant.

Biogas or landfill gas, produced through anerobic digestion, mainly consists of methane (40-70 vol%) and carbon dioxide (30-60 vol%). The gas can be used directly for heat and power production and/or be upgraded into biomethane and used as a replacer to natural gas, e.g.vehicle gas. Today, gas upgrading is in general carried out by removing carbon dioxide and other impurities through water or amine scrubbing. The upgrading process is however expensive [47] and often a too large investment for minor to medium scale biogas plants to tackle, especially for plants located off-grid. A technical option for fully or at least partly up-grading the raw biogas could be to add hydrogen to the biogas process. In this way, the added hydrogen reacts with the CO_2 excess and extra methane is formed according to:

$$CO_2 + 4\ H_2 \leftrightarrows CH_4 + 2\ H_2O \qquad \text{[Eq. 3]}$$

Methanisation may be of interest to consider for both those who have and have not conventional gas up-grading in place since it opens up for increased biogas production yield (up to the double) from a given amount of biogas substrate. Methanisation can take place either inside the digester (*in-situ* biological process) or downstream the digester (*ex-situ* through biological or thermochemical process)[12]. The different path ways attract much attention today and are under investigation in different pilot and demonstration plants in for example Germany and Denmark [6]. Their respective status and technoeconomical suitability to be combined with Swedish biogas plants are also under investigation in an *f3*- funded knowledge synthesis [8], and will therefore not be further discussed herein. *What instead is focus and interest in this project is 1) to highlight the possibility of* *up-grading thorugh hydrogen addition, 2) to investigate whether this could be of interest to implement for any of the existing biogas or land fill plants in Norrbotten county and 3) in particular, if so, what amounts of hydrogen, in rough terms, then would be needed?*

Today, the biogas production in Norrbotten county mounts ~36-37 GWh/yr. There are in total nine biogas plants, out of which four are land fill plants. The different existing biogas plants, some characteristics and their locations are listed in Table 6. As can be seen, the majority of the biogas plants are small, and there are today only two plants (i.e. Uddeboverket in Luleå and Svedjan in Boden), where the biogas is up-graded into biomethane **c**orresponding to a total regional biomethane production of somewhat over 3 GWh/yr (2015), i.e. close to 10 % of the total regional biogas production. In comparison to the national average for biogas up-grading (ca 63 % 2015, [48]), 10 % is indeed very low, but the regional interest for biomethane production is increasing and there is analysis pointing at a regional biomethane market potential as large as 36 GWh/yr by 2030, i.e. the same amount as the total regional biogas production of today [49]. To our knowledge, Uddeboverket, owned by Luleå municipality, is for example planning to successively expand their newly launched biomethane production to in the future up-grade all their biogas into biomethane. Simultanously, they are expanding their raw biogas production by investing around 65 MSEK 2016/17 in an additional digester and a new public vehicle gas filling station is also under planning. The aim of Luleå municipality is to have a fossile free public vehicle fleet by 2018 [50]. There is also an interest to implement biogas up-grading at Alviksgården. A final example showing this interest is Piteå Biogas AB in Piteå who is planning for 25 GWh/yr biomethane production [51]. It should be noted however that the outcome of these different plans are today all, to different degrees, uncertain as a consequence of the difficulty to obtain any profitability for the gas [2, 50].

As it is difficult today to motivate for conventional gas up-grading at the majority of the biogas plants in Norrbotten county (specific CAPEX ~ 2-10 kkr/kW_{metan} [52]), it is today most probably also difficult to afford up-grading by hydrogen addition through thermochemical or biological methanation [8], where the hydrogen is produced through electrolysis in small-scale adjacent to the plant (10-20 kkr/kW_e, Table 1, to be noted that this cost is excl. additional costs for methanisation). This situation could however be different for some of the regional biogas plants in the future depending on the outlook of the regional electricity and biogas markets, the development of the electrolyzers´cost, the size of the biogas plant, what the biogas is used for and the location of the biogas plant, etc. The location, besides the markets, is herein out of this respect believed to be a very crucial parameter. If for example the biogas plant in the future could take use of low cost renewable hydrogen produced in large-scale at an adjacent industrial site, such as a larger biorefinery in Piteå or at SSAB in Luleå, it would then most probably also be profitable to inject some hydrogen into the plant. Based on this reasoning, it could therefore be of especial interest to look more carfully into the biogas plants in Luleå and Piteå and estimate their potential future hydrogen demands. In this very rough estimation, it has been assumed that the biogas consists of solely methane and carbon dioxide (average methane concentration is given in parenthesis next to the given production capacity in Table 6), and that hydrogen is added at 4 times the average quantity of CO_2 for reaching a hypothetical CO_2-conversion of 100 %. As seen in Table 6, this would in total correpond to a relatively small hydrogen demand, i.e. up to 14 GWh/yr, assuming continous operation all year long. If also Skellefteå biogas plant is included, which is the largest biogas plant in Norrland (located in Västerbotten county, but a part of SE1) and only 80 km from Piteå, this hydrogen demand would become almost the double.

Table 6. Biogas production plants in Norrbotten county and Skellefteå (located in Västerbotten, but included in SE1). [1][ref. 50] [2][ref. 48] [3][ref. 1], [4][ref. 53]. The number given in the column "Uses", within the parenthesis, relates to the percentage of the total given biogas production. In the hydrogen estimations (column 6), no account has been taken of the amount already up-graded biogas.

Municipality	Name of plant, Owner	Type	Biogas production (GWh/yr)	Uses	Estimated hydrogen supply for gas-upgrading (GWh/yr)
Luleå	Uddeboverket, Luleå municipality	Sewage treatment	15[1] (77 vol % methane)	vehicle gas , power, heat , flared	~ 6
Luleå	Alviksgården	Agricultural	10[2] (66 % methane)	power, heat	~ 6
Luleå	Sunderby, Luleå municipality	Landfill	0,2 (40 -50 % methane)[1]	flared	-
Piteå	Sandholmen, Pireva	Sewage treatment	3[3] (62 % methane)	power, heat, flared	~ 2
Piteå	Bredvidbergets, Pireva	Landfill	0,2[3]	flared	
Boden	Brändkläppen, Boden municipality	Landfil	0,2[3]	heat	
Boden	Svedjan, Boden municipality	Co-digestion	7[4]	vehicle gas, heat	
Kalix	Kalix municipality	Landfil	0,2[3]	heat	
Haparanda	Bottenviken sewage treatment	Sewage treatment	1[3]	heat	
Skellefteå (Västerbotten)	Skellefteå municipality	Co-digestion	8[1] (62 % methane)	vehicle gas, heat, flared	~12

7 AVAILABLE ELECTRICITY MARKETS TO ACT ON?

Adding up the estimated local power consumed for producing the hydrogen gas demand of today in Table 5, one obtain a total power need of around 1 MW or 8 GWh/year assuming that hydrogen is produced 8000 h/yr. In relation to the current regional power situation (regional power excess of 12 TWh/yr, Ch. 6.1), this is minor demand that will have no significant impact on the market. Eventually, if the electrolysis process is also coupled to a gas-to-power unit (e.g. fuel cell stack), it could be of interest to consider acting on the regional frequency market (20 GWh/yr corresponds to approx. 2 MW, the minimum bid-size is 0,1 MW) and in this way, get the ability to earn an income for hydrogen not utilized. This assumes however that the requested endurance (1 h) and activation time (up to a few minutes) also can be met. The compensation for acting on the regulating power market (FCR-N, normal reserve) is today at about the same level as the electricity cost [18].

Furthermore, if we instead assume that all “future” hydrogen needs listed in Table 5 also become realized, the total power consumption would be around 170 MW; i.e. a power magnitude that is sufficiently large for considering also acting on the spot market (minimum bid-size is 10 MW for SE1, activation time 15 minutes, endurance 1 h [18].

Finally, if also SSAB's future hydrogen need (5-10 TWh/yr H_2 corresponding to a power consumption of 1000-2000 MW assuming 8000 h operation/yr) would become a reality, the whole electricity market of SE1 would change as SSAB in that case would become a major player for the regional energy balance, calling for significant more renewable power installations and strengthening of the regional power grid.

8 TECHNO-ECONOMICAL INDATA FOR P2G/P2L

This section lists the capital costs associated with P2G/P2L systems. All costs are summarized in Table 7. The investment cost of electrolysis is in the order of ≤10 000 SEK/kWe for AEC electrolyzers and ≥20 000 SEK/kWe for PEM electrolyzers (Table 1). The most relevant source of power for electrolysis in the Piteå-Luleå-Norrbotten area is wind and the capital cost of a wind turbine is 11-30 MSEK per MW [54]. None of the current and future hydrogen demands in the area require the electrolyzer to have a short start/stop time and therefore the cheaper AEC technology can be used. However, when using an intermittent power source such as wind, hydrogen storage will most likely be nessecary to enable hydrogen overproduction which is directed to compression and storage during periods of surplus wind to be used during periods of wind shortfall. The capital cost investment for hydrogen storage depends on the volume needed and the pressure at which the hydrogen needs to be stored. According to a recent technological and economic review of renewable P2G [55], hydrogen storage costs vary between 46 000 and 53 000 SEK m^{-3} of storage. Compressors for 200 and 700 bar costs 1 and 4 MSEK respectively [16]. Capital cost investment of a P2G/P2L plant can therefore be significantly reduced by minising storage needs. Another way of reducing cost associated with P2G/P2L is to minimize the need for transportation. A pipeline for hydrogen transport costs 1.7-5.1 MSEK per km depending on pipeline diameter [56]. Such expenses can be minimized by placing electrolyzers close to where the hydrogen is needed. Also, several hydrogen demands should ideally be met by the same electrolyzer.

Regarding direct use of hydrogen in fuel cell busses, a hydrogen refuelling station costs 10-15 MSEK [57] and a fuel cell bus costs 9-10 MSEK [58]. Altogether, the total capital cost of a hydrogen refueling station with one bus would therefore be in the order of 19-25 MSEK [57, 58].

Table 7. Capital costs for major components associated with a P2G/P2L system. As a hydrogen filling station for FC-buses are also under consideration in Piteå, cost estimates for hydrogen filling stations and fuel cell buses are also included in the table.

Component	Capital Cost
Wind turbine	11-30 MSEK per MW
AEC electrolysis	≤10 000 SEK/kWe
PEM electrolysis	≥20 000 SEK/kWe
Hydrogen compressor (200/ 700 bar)	1 MSEK (200 bar@25 kg H_2/day)/ 4 MSEK (700 bar)
Hydrogen storage (30-200 bar)	46 000-53 000 SEK per m^3
Hydrogen pipeline	1.7- 5.1 MSEK per km
Hydrogen filling station	10-15 MSEK
Fuel cell bus	9-10 MSEK

9 SUGGESTIONS FOR A P2G/P2L-SYSTEM IN PITEÅ

The Piteå/Luleå/Norrbotten area is characterized by large electricity production compared to the use, large biomass resources and extensive expertise in the production of biofuels and bio-oil. This makes the area a suitable location for demonstrating Power-to-gas/Power-to-Liquid (P2G/P2L) and the best utilization of P2G/P2L in the area is as a source of renewable hydrogen for a future biorefinery infrastructure. Biofuels and bio-oil could be produced in the area on an industrial scale using biomass resources and renewable electricity. This could be achieved by

- scaling up today´s biorefinery plants from pilot scale to commercial scale and by
- using wind power to produce hydrogen which is used to increase efficiency of the plants.

Currently, more wind power is being planned and there is an interest in P2G/P2L at the municipality level. Also, today´s pilot scale biorefinery plants are on the same site, i.e. Industrigatan 1 in Piteå. This makes it possible to take the first steps towards the envisioned industrial scale biorefinery (Section 6.2.1) by installing a P2G/P2L system at Industrigatan 1 to demonstrate the technology. As described in Section 6.2.2 of this report, there are three ways in which hydrogen can be used at Industrigatan 1, (i) doping of synthesis gas from entrained flow gasification, (ii) use as a carrier gas for bio-oil production through catalytic pyrolysis and, (iii) direct use in a slurry hydrocracker. There are also possibilities that a hydrogen filling station will be commissioned in order to supply a fuel cell buss. Ideally, both the filling station and the Piteå Sciende Park site would share one electrolyzer. Installing a P2G/P2L system at Industrigatan 1 would connect four separate pilot plants thus resulting in a complete pilot scale biorefinery infrastructure. A part from using the hydrogen produced by the electrolyzer in the pilot plants, the oxygen stream, which is also produced by the electrolyzer, could be used as oxidizing media in the entrained flow gasifiers to improve efficiency. Also, waste heat from the pilot plants could preferably be used to heat the electrolyzer. To demonstrate the utilization of such synergies will be an important objective of the pilot scale biorefinery. Efficient use of waste heat could become more important in the future for the efficiency of the biorefinery concept as SOEC electrolyzers become commercially available. The use of SOEC electrolysis would significantly increase the efficiency of hydrogen production (up to 10-15%, see Table 1) but will simultaneously require more heat as the SOEC electrolyzer operates at a much higher temperature than the AEC or PEM electrolyzer (600-1000 °C vs. 50-90 °C, see Table 1). By adding a wind turbine to the pilot scale biorefinery, the remaining features of an industrial scale biorefinery could also be demonstrated. This includes (but is not limited to) directions of electricity and hydrogen flows in reponse to changes in wind conditions and frequency and spot market prices. The suggested pilot scale bio-refinery infrastructure is shown in Figure 14.

This infrastructure would be capable of demonstrating biofuel and bio-oil production from raw biomass to finished product using renewable electricity. This will be done by installing an electrolyzer on site and connecting hydrogen gas lines to both gasifiers (the PEBG and the black liquor gasifier), the bio-oil plant and the SHC. Note that the hydrogen demand of the pilot scale SHC is insignificant compared with the other plants and does not need an electrolyzer for hydrogen production. It will instead be connected to the hydrogen gas line simply to make more efficient use of the hydrogen infrastructure. By adding a wind turbine and a filling station, further features of a full scale biorefinery could be demonstrated.

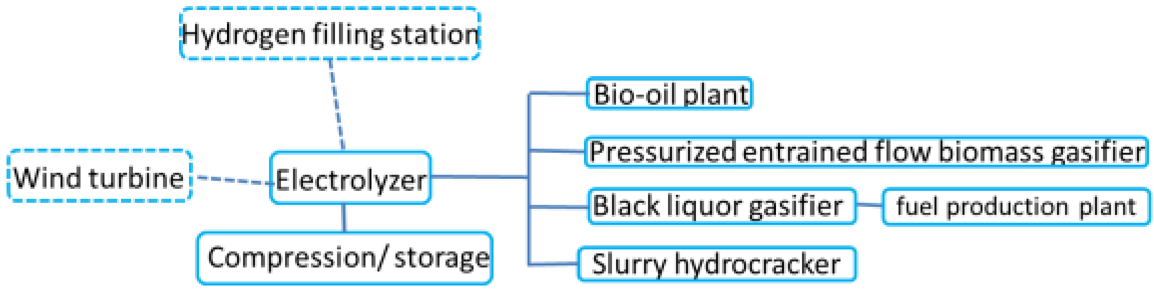


Figure 14. Schematic of the suggested use of P2G/P2L in Piteå to supply a pilot scale biorefinery infrastructure (and possibly also a hydrogen filling station) with renewable hydrogen. Possibly self-sufficient through a wind turbine.

The electrolyzer for the pilot-scale biorefinery infrastructure will need to supply a continuous hydrogen flow to the black liquor gasifier as it is commissioned to operate continuously for 8000 h per year. As a result, a PEM electrolyzer, capable of short startup times is not nessecary and the cheaper AEC electroyzer can be used. The other components of the biorefinery operate for 2-3 days per week during campains which lasts for 2-3 weeks and are carried out around 5 times per year. They seldom operate simultaneously. Hence additional hydrogen use will be intermittent. A full scale biorefinery including a P2G/P2L system would have all components running continuously which means that the hydrogen supply for the refinery will also need to be continuous. This presents challenges with regard to making use of intermittent power sources such as wind. Solutions involve, (i) improved transfer capacity within the power grid and, (ii) hydrogen compression and storage. A detailed investigation of these challenges and of their solutions is needed. The electricity demand for hydrogen production during operating of the black liquor gasifier is 0.3 MW (Table 5). The electricity demands for hydrogen production for the PEBG and the bio-oil plant are 0.3 and 0.2 MW respectively meaning that a 0.8 MW electrolyzer capacity will be needed if all plants would run simultaneously. The cost of a 0.8 MW AEC electrolyzer is an estimated 8 MSEK.

Adding a wind turbine at the pilot scale biorefinery for self-sufficiency with regard to power for electrolysis would most likely incur installment of a system producing excess power. As note above, the capital cost of a wind turbine is 11-30 MSEK per MW [53]. Most wind turbines commissioned in 2016 had a capacity of 3-5 MW and the wind turbine trend is towards larger turbines with higher capacity as this reduces the capital cost per MW. Excess power can be used for production of hydrogen for energy storage or be traded on the regulating power and/or spot market (Chapter 7); hence installment of excess power would not incur an economic penalty. Instead it would provide the opportunity to use the pilot scale biorefinery to demonstrate the above mentioned features which will be important for the envisioned future industrial scale biorefinery in the Piteå-Luleå-Norrbotten area.

Adding a hydrogen filling station to the pilot scale biorefinery would make more efficient use of the electrolyzer. The 0.8 MW electrolyzer discussed above could also supply a fuel cell bus requiring 440 (n)m^3 of hydrogen per day assuming that the electrolyzer produces hydrogen for compression and storage at the filling station during times when hydrogen is not needed for the PEBG and and the bio-oil plant. Note that it is assumed that the black liquor gasifier operates continuously, using 0.3 MW while the PEBG and bio-oil plant will only be run intermittently. Hydrogen for the fuel cell bus could for example be produced overnight and stored, ready for refueling in the morning. The cost of a hydrogen filling station listed in Chapter 7 of this report includes an electrolyzer and compression and storage. The above discussed scenary would reduce costs for the filling station as it would not need its own electrolyzer. Ideally, the filling station should be located adjacent to the pilot scale biorefinery. However, another option would be to install a hydrogen pipeline which costs 1.7-5.1 MSEK per km depending on pipeline diameter [55]. For this application, it is assumed that a small pipeline will be sufficient and so the cost for a pipeline between the pilot scale biorefinery and the hydrogen filling station would likely cost around 2 MSEK per km.

10 CONCLUSIONS

This study has identified, analysed and suggested different roles and possibilities for P2G/P2L in the Piteå-Luleå-Norrbotten area with respect to the regional electricity market and hydrogen demands. The starting point of the analysis is the pilot-scale biorefinery infrastructure in Piteå which is connected to an envisioned future regional industrial scale biorefinery in the scale of hundreds MW_{th} biomass input. The analysis considered both current conditions and plausible future scenarios with regard to technical and economic aspects.

SE1 is today a net producer of electricity (regional power excess of 12 TWh/yr) and future plans point to an extensively increased amount of available renewable intermittent power in the region during the coming 10-20 years (≥ +10 TWh/yr). Consequently, it is herein stated that large scale energy storage in hydrogen and various biofuels/biochemicals through P2G/P2L will most probably, among other storage alternatives, become of high interest in the area.

As a first step towards demonstrating the value of the P2G/P2L-technology in the region, it is suggested to supply the pilot scale biorefinery infrastructure in Piteå, possibly also a nearby future municipal hydrogen filling station, with renewable hydrogen. The pilot scale biorefinery would consist of a bio-oil plant, a slurry hydrocracker and two types of oxygen fed pressurized entrained flow biomass gasifiers for biofuel/biochemical production, whose process efficiencies all would greatly benefit from hydrogen supply. The analysis indicated that an alkaline typ electrolyzer (using the most mature and less expensive electrolysis technology) in the size of ~1 MW_e shall, at least in the very first stage, be the electrolyzer of choice, possibly self-sufficient through a wind turbine of a few MW size. Further on, it would be of interest to make use of waste heat from the biorefinery processes and also to demonstrate the integration with the less mature but significantly more efficient solid oxide electrolysis technology. Another synergy of interest to examine is the possibility to use the oxygen produced by the electrolysis as oxidant medium in the gasifiers to simultaneously reduce the cost and increase the overall efficiency. As the different biorefinery processes at full scale would run continuously, the operation profile of the pilot scale system shall aim to be the same. This in turn presents a critical challenge with regard to making use of low cost intermittent power for the hydrogen supply, calling for transfer capacities within the power grid and installation and use of hydrogen compression and storage. Another parameter that could be used to tackle the energy balance to look into and demonstrate with the suggested demonstration unit is the possibility to trade on the regulating power and/or spot market.

In addition to the hydrogen needs of the biorefinery infrastructure and the hydrogen filling station in Piteå, the interest, values and plausible future need of renewable hydrogen of the regional steel (5-10 TWh/yr) and biogas industry (up to 30 GWh/yr) were presented and shortly discussed. It is clear that if the steel industry´s plausible hydrogen need would be realized, the entire regional electricity market would change. Most likely this would also result in the commisioning of an infrastructure for renewable hydrogen in the region, which other regional industries, such as biogas plants, in need of hydrogen can benefit from.

11 APPENDIX: CALCULATIONS OF HYDROGEN DEMAND FOR DOPING OF SYNTHESIS GAS

11.1 PEBG

Synthesis gas flow: 75 kg per hour

Table A1. Synthesis gas composition during operation of the PEBG (mol%), Reference: [29].

CO_2	16.7
CH_4	1.9
N_2	18.1
H_2	22.8
CO	39.9
C_2H_4	0.1
C_2H_2	0.2

Note that this synthesis gas composition is not representative of gasifier operation aimed to producing a synthesis gas for downstream upgrading (e.g. biofuel production), but instead for demonstration of synthesis gas production in more general terms. To produce synthesis gas for downstream upgrading, the fuel load would be increased. This would result in a N_2 composition lower than 1 mol% with retained H_2:CO ratio.

11.2 BLACK LIQUOR GASIFIER

Synthesis gas flow: 780 (n)m^3 synthesis gas per hour.

Table A2. Synthesis gas compostion during operation of the black liquor gasifier (vol%), Reference: [59].

CO_2	30.8
CH_4	0.9
N_2	1.5
H_2S	1.6
H_2O	0.1
H_2	40.7
CO	24.4

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