LOCATIONAL STUDY – POWER TO GAS

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Locational study – Power to gas

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Summary

The task was to identify a suitable location for a demonstration plant for Power to gas in Sweden. The following three municipalities participated in the study; Gotland, Falkenberg and Piteå. They have in common large scale plans to expand wind power and aim for increased use of biofuels. Otherwise, the conditions in their energy systems differ regarding the infrastructure and local energy balances, illuminating the concept of Power to gas from different perspectives.

In a large scale expansion of wind power, its share of the electricity production can become so large locally, that all the electricity cannot be consumed due to limitations in the electricity network. Power to gas is a way to store electricity in form of gas. The fundamental component is an electrolyzer, in which water is split into hydrogen and oxygen using electricity. Electrolyzers are available in various designs and in different development stages, with regard to the potentials of dynamic operation and to follow a diversified electricity production. The technology development in the area is growing fast since the manufacturers of electrolyzers have identified a new market in Power to gas.

The hydrogen can be used directly in an industrial process or as fuel in fuel cell cars. The hydrogen can also be fed into the natural gas pipeline in small quantities. Another alternative is to proceed to the next process, where hydrogen reacts with carbon dioxide to form methane. Methanation can be done through various processes. The easiest way is to inject the hydrogen directly into a digestion plant for biogas. The hydrogen then reacts with the carbon dioxide, leading to a higher concentration of methane in the biogas. That is an example of biological methanation

Another alternative is to let hydrogen gas and carbon dioxide react in a separate methanation reactor, called a Sabatier reactor. It requires a pure carbon dioxide stream, presence of a catalyst and stable reaction conditions. With today's technology it is an expensive and complicated solution.

Within the study, three main tracks for Power to gas have been identified: 1) An electrolyzer solely for hydrogen production; 2) An electrolyzer in combination with biologic methanation in a biogas plant; 3) An electrolyzer in combination with a Sabatier reactor for catalytic thermal methanation.

For each municipality the following questions have been answered in this study:

- What are the socioeconomic benefits with Power to gas in Sweden?
- What should the demonstration plant produce, hydrogen or methane?
- In what way can the demonstration plant contribute to more renewable electricity?
- What production capacity is reasonable to aim for?
- When is it reasonable for the plant to be commissioned?

The conditions for each municipality are described below.

Gotland

Gotland aims at being self-sufficient in renewable and recycled energy by 2025. The goal is to be achieved by export of locally produced wind power balancing the residual use of fossil energy. To succeed, the locally generated electricity has to be twice as large as the total electricity consumption. This means that today's wind power production must increase from 0.4 TWh to 1.8 TWh, which is a great challenge for the electrical power system. The production of renewable fuels must also increase to achieve the target.

A demonstration plant for Power to gas on Gotland should follow the main track 2, i.e. to place an electrolyzer adjacent to Brogas biogas plant in Visby. It may, according to estimates from the Royal Institute of Technology (KTH) increase the supply of methane from 2.2 to 2.4 million Nm^3/ year, i.e. by about 10%. The electrolyzer should have a conventional design i.e. an alkaline electrolyzer, and have an installed capacity of 2 MW_e. The demonstration plant could be in place in 2016, according to Region Gotland.

In a long term perspective, by 2025, a plant according to the main track 3 can be located in Slite adjacent to the Cementa factory. That requires both technical development for the electrolyzers and installation of carbon capture at the Cementa factory. The parent company of Cementa, Heidelberg Cement, conducts research and development in the area, and Cementa welcomes the opportunity to develop the concept in Slite.

In a short term perspective, a demonstration plant doesn´t contribute to more wind power. Gotland is an island and the challenges are greater than on the mainland at a large-scale expansion of wind power. Power to gas can thereby facilitate an increased wind power capacity since Power to gas can use excess electricity in the power system.

The project should be managed as a collaborative project with the key players Region Gotland, Gotlands Energy (GEAB), Cementa, Biogas Gotland and Uppsala University Campus Gotland.

Falkenberg in Halland

Falkenberg has access to natural gas infrastructure, unlike Gotland and Piteå. It has paved the way for biogas as vehicle fuel. Halland has great potential for wind power and the municipalities in the region were early to invest in the technology. There are no immediate constrains in transmission capacity for a continued expansion of wind power. Southern Sweden is additionally a deficit area of electricity, so more production capacity may be needed.

Halland has many similarities with Denmark and Germany, with regard to investment in wind power and access to an infrastructure for natural gas. In the neighboring countries Power to gas is seen as a solution for developing wind power, and to gain more renewable fuels at the same time. Falkenberg is facing the same challenges.

In the short term, the best alternative for a Power to gas demonstration plant is to install an electrolyzer in connection with a planned hydrogen filling station along the European road E6 i.e. to follow the main track 1. Initially, the capacity of the electrolyzer will be too large, since the number of hydrogen cars are intended to increase over time. In that case, possible surpluses of hydrogen can be fed into the natural gas network, to a volume at a maximum of 2%. A suitable size of the electrolyzer is 630 kW, which corresponds to a production of 10 kg H_2/h. The electrolyzer delivers the produced hydrogen the storage at the filling station. Falkenberg intends to build a filling station with a capacity of 150 kg H_2/day. It is expected to be commissioned in 2016.

In the short run, the socio-economic benefit is that the electrolyzer provides renewable hydrogen that otherwise would be purchased from external suppliers. It also contributes to a completely new component in the energy system, creating new opportunities for more renewable energy.

Another important aspect is the development of a new area of technology which can contribute to a stronger labor market. By investing in new energy technologies needed in the energy system, it can also pave the way for new business opportunities.

The project should be managed as a collaborative project with the key players Falkenberg Energy, E.on, Swedegas and Falkenberg Biogas.

Piteå in Norrbotten

There is a large oversupply of electricity in Norrbotten, compared to the consumption. The production is primarily based on hydropower, but there is also a great potential for wind power. Today, there are no restrictions in the electricity network for the expansion of wind power, but at a large-scale deployment, the transfer capacity southward must be strengthened.

There is great expertise in research and development of biofuels in the region, and hence a unique expertise and structure to operate this type of project. To take advantage of this, a demonstration plant for Power to gas is suggested to be located adjacent to the existing facilities at SP ETC and LTU Green Fuels. Since their focus is on producing liquid fuels, it will be a demonstration plant for “power to liquids”. This technique also requires hydrogen, why a Power to gas facility is still needed.

Since it is a research facility with great competence in place, a Polymer Electrolyte Membrane/Proton Exchange Membrane (PEM) electrolyzer can be selected. It can handle a more dynamic operation, but is still under development. The electrolyzer could be in place by 2016.

In the long term, a similar facility could be built on a larger scale at SSAB in Luleå. SSAB has not participated in this study, so whether there is any interest in this we do not know.

Sammanfattning

Uppdraget var att identifiera en lämplig lokalisering för en demonstrationsanläggning för power to gas i Sverige. Följande tre kommuner har deltagit i studien; Gotland, Falkenberg och Piteå. Gemensamt för dessa är storskaliga planer på att bygga ut vindkraft och målsättningar om en ökad användning av biodrivmedel. I övrigt skiljer sig förutsättningarna åt, vilket gör att konceptet power to gas kan belysas ur olika perspektiv.

Vid en storskalig utbyggnad av vindkraft, kan dess andel av elproduktionen lokalt bli så stor att all el inte kan tas tillvara p.g.a. begräsningar i överföringskapacitet. Power to gas är ett sätt att lagra el i form av gas. Den mest centrala komponenten är en elektrolysör, i vilken vatten spjälkas upp i väte och syre med hjälp av el. Elektrolysörerna finns i olika utföranden, och i olika utvecklingsstadier vad avser möjligheterna att kunna gå i dynamisk drift för att följa en varierad elproduktion. Teknikutvecklingen på området går snabbt eftersom tillverkarna av elektrolysörer har identifierat en ny marknad i power to gas.

Vätgasen kan användas direkt, i en industriell process eller som drivmedel i bränslecellsbilar. Vätgasen kan också i låga halter matas in i en naturgasledning. Ett annat alternativ är gå vidare i ett nästa förädlingssteg, där vätgasen reagerar med koldioxid och bildar metan. Metaniseringen kan ske på olika sätt. Det enklaste är att mata in vätgasen direkt i en rötningsanläggning för biogas. Vätgasen reagerar då med koldioxiden i rötgasen, vilket leder till att metanhalten i biogasen blir högre. Det är ett exempel på biologisk metanisering.

Ett annat alternativ är att vätgas och koldioxid reagerar i en separat reaktor, sk. Sabatierreaktor. Den kräver en ren koldioxidström och stabila förhållanden. Med dagens teknik är det en dyr och komplicerad lösning.

Inom studien har 3 huvudspår för power to gas identifierats: 1) endast en elektrolysör för produktion av vätgas; 2) en elektrolysör i kombination med biologisk metanisering i en biogasanläggning; 3) en elektrolysör i kombination med en Sabatierreaktor för katalytisk metanisering.

För respektive ort ska studien besvara följande frågeställningar:

- Vilka är de samhällsekonomiska nyttorna med en svensk power to gasanläggning och var bör den vara belägen för att tydligast visa på dessa nyttor?
- Vad bör demonstrationsanläggningen producera, vätgas eller metan?
- På vilket sätt kan demonstrationsanläggningen bidra till mer förnybar el?
- Vilken produktionskapacitet bör man sikta på?
- När det är rimligt att den kan komma tillstånd?

Nedan beskrivs kortfattat förutsättningarna på respektive ort.

Gotland

Gotland har som mål att vara självförsörjande på förnybar och återvunnen energi 2025. Målet ska uppnås genom att export av gotländsk vindkraft balanserar den resterande användningen av fossil energi. För att det ska vara möjligt måste den lokalt producerade elen vara dubbelt så stor som den totala elanvändningen. Det innebär att dagens vindkraftsproduktion ska öka från ca 0,4 TWh till 1,8 TWh. Det är en stor utmaning för det tekniska systemet. Även produktionen av förnybara drivmedel måste öka för att uppnå målen.

En demonstrationsanläggning för power to gas på Gotland bör följa huvudspår 2, d.v.s. att förlägga en elektrolysör till Brogas biogasanläggning i Visby. Det kan enligt beräkningar från KTH höja utbudet av metan från 2,2 till 2,4 miljoner Nm^3/år, d.v.s. med ca 10%. Elektrolysören bör ha ett konventionellt utförande, d.v.s. en alkalisk elektrolysör, och ha en eleffekt på 2 MW. Demonstrationsanläggningen skulle kunna finnas på plats redan 2016, enligt Region Gotland.

På längre sikt, till 2025, kan en anläggning enligt huvudspår 3 förläggas i Slite i anslutning till Cementas fabrik. Det förutsätter både en teknikutveckling för elektrolysörerna och att det finns koldioxidavskiljning vid Cementas fabrik. Cementas moderbolag, Heidelberg Cement, bedriver forskning och utveckling inom området, och Cementa ser positivt på möjligheten att utveckla konceptet i Slite.

På kort sikt bidrar inte demonstrationsanläggningen till mer vindkraft. Gotland en ö och utmaningarna är större än på fastlandet vid en storskalig utbyggnad av vindkraften. Power to gas skulle därför kunna bidra till att mer installerad effekt i systemet, utan att någon elenergi behöver spillas bort.

Projektet bör drivas som ett samverkansprojekt med nyckelaktörerna Region Gotland, Gotlands energi, (GEAB), Cementa, Biogas Gotland och Uppsala universitet campus Gotland.

Falkenberg

Falkenberg har tillgång till en naturgasinfrastruktur till skillnad från Gotland och Piteå. Det har bland annat banat väg för biogas som fordonsgas. Halland har goda förutsättningar för vindkraft och satsade tidigt på att bygga ut vindkraften. Det finns inga omedelbara begränsningar i elnätet för en fortsatt utbyggnad av vindkraft. Södra Sverige är dessutom ett underskottsområde så mer elproduktionskapacitet kan behövas.

Halland har stora likheter med Danmark och Tyskland, vad avser satsningen på vindkraft och tillgången till en infrastruktur för naturgas. I grannländerna ses power to gas som en lösning för utveckla vindkraften vidare och samtidigt få fram mer förnybara bränslen. Falkenberg står inför samma utmaningar.

På kort sikt är de bästa förutsättningarna för power to gas att anlägga en elektrolysör i anslutning till en planerad vätgasmack utmed E6:an, d.v.s. att följa huvudspår 1. Initialt kommer elektrolysören ha en för stor kapacitet, eftersom antalet vätgasbilar planeras öka över tid. Eventuella överskott på vätgas kan så i stället matas in i naturgasnätet, till en volymsandel på max 2%. En lämplig storleksordning på elektrolysören är 630 kW el, vilken kan producera 10 kg H_2/h. Elektrolysören ska arbeta mot ett lager i tankstationen. Falkenberg avser bygga en tankstation som ska kunna leverera 150 kg H_2/dygn. Vätgasmacken beräknas kunna tas i drift 2016.

Kortsiktigt är den samhällsekonomiska nyttan att Falkenberg får in en helt ny komponent i sitt energisystem, som binder samman planerna på en fortsatt utbyggnad av vindkraft och satsningen på ett nytt förnybart drivmedel. Ur Falkenbergs perspektiv ser man det också som en kompetensuppbyggnad inom ett nytt teknikområde, som kan differentiera näringslivet och gynna arbetsmarknaden.

Det finns flera biogasanläggningar i Falkenberg. På sikt kan power to gas även bidra till att öka metanproduktionen i dessa.

Projektet bör drivas som ett samverkansprojekt med nyckelaktörerna Falkenberg Energi, E.on., Swedegas och Falkenberg Biogas.

Piteå

Norrbotten har stora överskott i elproduktionen relativt användningen. Potentialen är stor för vindkraft och det planeras också för stora vindkraftsparker. Idag utgör elnätet i Norrbotten ingen begränsning för utbyggnaden av vindkraft, men vid en storskalig utbyggnad måste överföringskapaciteten söderut förstärkas.

I regionen finns det stor kompetens kring forskning och utveckling av biodrivmedel, vilket gör att det finns en struktur för att driva den här typen av projekt. En demonstrationsanläggning för power to gas kan därför förläggas i direkt anslutning till befintliga forskningsanläggningar hos SP ETC och LTU Green Fuels. Eftersom de fokuserar på att ta fram flytande drivmedel, så går projektet här under ”power to liquids”, men det innebär ändå produktion av vätgas genom en elektrolysör. Vätgasen används sen i sin tur för produktion av DME eller metanol.

Nyttan med att komplettera befintliga anläggningar med en elektrolysör är att tillförsel av väte gör att upp till 50% fler gröna kolatomer ur bioråvaran kan tas tillvara för framställning av förnybara drivmedel.

Eftersom det är en forskningsanläggning med stor kompetens på plats, kan en PEM-elektrolysör väljas. Den klarar en mer dynamisk drift, men är fortfarande under utveckling. Elektrolysören skulle kunna finnas på plats 2016.

På längre sikt skulle en motsvarande anläggning kunna byggas i större skala hos SSAB i Luleå. SSAB har dock inte deltagit i denna studie, så huruvida det finns något intresse för detta vet vi inte.

1 Background

The aim of this project is to identify a suitable location for a first Power to gas demonstration plant in Sweden. The technology is pre-commercial and is already in use in many different places on the European Continent. The objective is to assess the possibilities for the technology in a Swedish context rather than to demonstrate the technology itself. It is also to identify the factors of importance to achieve maximum environmental, energy and social benefit with current technology.

The project analyses current preconditions at three different locations, Falkenberg in Halland, Gotland and Piteå in Norrbotten county. These sites have been selected on the grounds that they can provide the Power to gas technique system integration, but that the characteristics in their energy systems are otherwise different.

The analysis is based mainly on literature reviews and communication with various stakeholders in each location. A key activity has been organization of local workshops, with a broad representation of different energy actors at the location, including local politicians and officials from the County Clerk. At these workshops, different options for Power to gas has been identified and discussed for each location.

The assignment is performed by M.Sc., Lic.Eng. Karin Byman.

1.1 Comments to the design and implementation

Power to gas is a very complex system solution and it is not possible to provide a completely fair analysis within the frame of this project. The technology is immature at the system level for this type of applications and it is not commercial today. There are therefore no commercial or industrial applications in the relevant scale to refer to. Before a demonstration facility can be launched, this pre-feasibility study requires to be complemented by a deeper analysis.

This report is structured as follows:

- Various technology and system solutions in brief.
- Important technical aspects, but no specifics concerning technical design, such as type of reactor or electrolyzer.
- Important prerequisites for the design of the system solution, but no details, such as temperatures and flows, are specified.
- Economic quantities, but without detailed financial calculations.
- General information about prerequisites for the different are discussed, but there are not enough data to give details on different solutions.
- The mission is primarily a pre study for a demonstration plant, in order to assess the applicability of a new technical system, rather than to make an analysis of the technology as such.

The project also involves a master's thesis conducted by chemistry students at The Royal Institute of Technology (KTH). They have carried out detailed analyses and calculations applied on Gotland's energy system. Calculations and data in the master’s thesis have been used in parts of this report.

2 Introduction to Power to gas

The need to store electricity will increase with an increasing share of renewable and weather dependent electricity generation. Thus, storage of electricity and a well-functioning infrastructure is of strategic importance for Sweden in order to meet our ambitious national energy and climate targets (Ref 1).

Power to gas is one of several methods for capturing surplus electricity and is a complement to batteries, storage in district heating systems, pumped power storages and flywheels. In the design of our future energy systems, there will be no single solution that suits all. Local preconditions and available infrastructure determines what method should be applied.

Power to gas means that electricity is converted to an energy gas. The first and most important process is the electrolysis where hydrogen is extracted from water by means of electricity. Hydrogen can either be used directly or be further processed into methane. Hydrogen is currently used primarily in industrial processes, and is not established in the market as an energy gas. However, the development of hydrogen cars is at high pace and both Hyundai and Toyota manufactures fuel cell vehicles powered by hydrogen (Ref 2). Smaller amounts of hydrogen can also be fed directly into a natural gas pipeline. Oxygen is also a product of the process, but in fairly modest volumes.

Methane is the main component of natural gas and biogas, which are used in industries, vehicles, electricity and heat production, and in households. In order to make methane from hydrogen, carbon dioxide is required. The origin of the carbon dioxide is not relevant for the chemical process. The carbon dioxide may be derived from a biological process, such as the digestion process for biogas, or separated from flue gases from combustion. High-tempered heat that can be utilized for example in a district heating system is developed from the production of methane.

Power to gas links the electricity system with systems for gas and heat, thereby enabling efficient utilization of all available energy resources. The system is illustrated in the figure below.

A more technical review of Power to gas is presented in the following chapters. The individual steps are more complicated than as illustrated above. The whole concept of electricity to methane, based on recycling of separated carbon dioxide, is currently very expensive and complicated. Regular flows, precise pressures and temperatures are required for an optimal function of the process. This lack of flexibility contradicts the idea of taking advantage of intermittent electricity generation. There is however intense technology development to increase the flexibility. There are currently 40 demonstration plants for Power to gas in Europe. Manufacturers of electrolyzers and other important components expect a future big market for Power to gas following the rollout of solar, wind and wave energy. The gas infrastructure also develops towards operators bringing in more renewable gas into their systems.

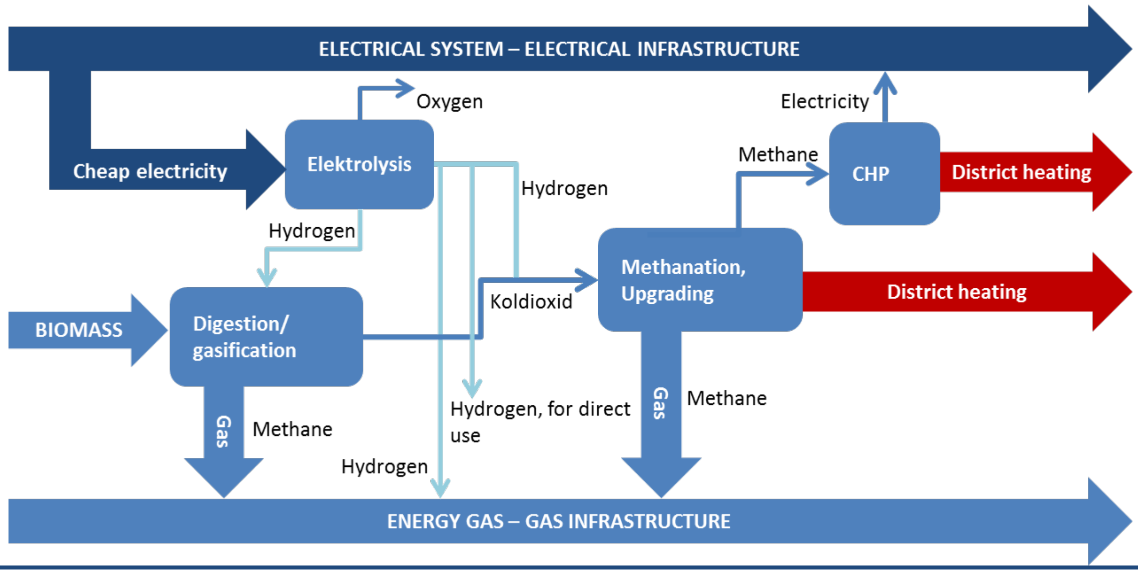


Figure 1 Illustration of Power to gas. The hydrogen can either be used directly, for example in a fuel cell, be fed into the gas infrastructure or react with carbon dioxide to methane.

3 Technical overview

In this chapter, commercially available Power to gas technologies are presented along with technologies that are in a pre-commercial phase or at the research stage. Possibly upcoming technologies and techniques for other fuels or for further processing to produce other fuels are only mentioned briefly with regard to the hydrogen-to-methane process step (methanation).

3.1 The concept of Power to gas

Power to gas means that the energy carrier electricity is transformed into chemically bound energy in the form of gas. There are different system layouts, but the first stage is always an electrolysis process in which electricity is used to split up water (H_2O) into oxygen (O_2) and hydrogen (H_2). The process is endothermic, i.e. it requires energy. Hydrogen can be used directly for energy purposes or be further processed into methane (CH_4). This latter step is a methanation process where hydrogen reacts with carbon dioxide (CO_2) and forms methane (CH_4) and water (H_2O). The reaction is exothermic, i.e. it develops heat. The carbon dioxide may be of different origin, e.g. from a biogas plant, or an industry. Technically, the carbon dioxide can be of either renewable or fossil origin.

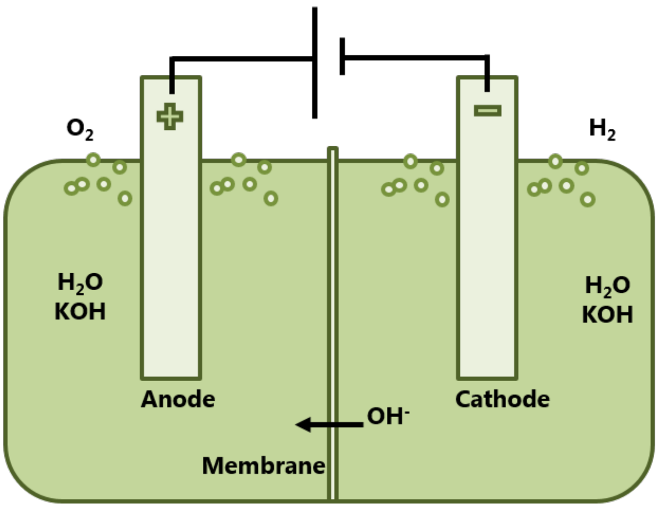
The two process steps can simplified be illustrated with the following formula:

Electrolysis: $2\ H_2O \rightarrow 2\ H_2 + O_2$

Methanation: $CO_2 + 4\ H_2 \leftrightarrow CH_4 + 2\ H_2O$ + heat

3.1.1 Electrolysis

Electrolysis involves an electrochemical process where electric energy induces a chemical reaction. The principle for electrolysis of water is well known. Electrolysis is mainly used in industries today.



Electrolysis process

An electric field is created between two electrodes.

At the negative electrode (cathode) a reduction occurs - hydrogen gas develops, and at the positive electrode (anode), an oxidation occurs (oxygen develops).

One mole of oxygen and two moles of hydrogen are produced from two moles of water:

$2\ H_2O \rightarrow 2\ H_2 + O_2$

Figure 2 Illustration of a liquid alkaline electrolysis.

There are three different techniques for electrolysis of water in different development stages; alkaline electrolysis, electrolysis PEM *(Proton Exchange Membrane/Polymer Electrolyte Membrane)* Electrolysis, and SOEC electrolysis *(The Solid Oxide Electrolysis Cell).* Common for these techniques is their main components; electrodes, electrolyte, and a membrane. Alkaline electrolysis is the simplest technique, and the basis for development of PEM and SOEC electrolysis.

The overall efficiency of the electrolysis depends largely on the materials used (e.g. the materials' electrical resistance) and on at which temperature and pressure the electrolysis is performed. High temperatures facilitates the decomposition of water, which means that higher temperatures provide higher efficiencies, but this in turn places greater demands on the materials and workmanship of the electrolyzer. (Ref 3).

3.1.2 Alkaline electrolysis

The alkaline electrolysis is the most wide spread technology for water electrolysis. It is a mature and robust technology, with relatively low costs. It also exists in large units, up to the order of MW. The downside is that it has a relatively low efficiency if compared to the other techniques, about 50-70% (Ref 3) and that it cannot be operated in reverse. That is, it is not possible to produce electricity from hydrogen, which is a possibility for the other two types of electrolysis.

Alkaline electrolysis takes place at relatively low temperatures between 70-80 °C. The electrolyte is a highly caustic liquid consisting of potassium hydroxide (KOH) dissolved in water (20-30%). The anode and cathode materials are usually made of nickel plated steel and steel, respectively. The electrolyte is corrosive and electrodes must be replaced or re-activated after 2 to 5 years.

The technique has so far been developed for continuous stable operation and is currently not flexible enough to capture a varying electricity supply. According to the manufacturer Hydrogenics, however, the alkaline electrolyzer has the potential to operate with a more varying electricity supply. Within a few years, it is expected that alkaline electrolyzers are developed and can be adjusted within a range of 5-100% of total capacity within seconds. The time from a cold start to operation can be shortened from about one hour to 10 minutes, according Hydrogenics (Ref 4).

In figure 3, the cost structure for and electrolysis device is shown. The capital cost is in EUR/kW_{H2}, and the operational costs in EUR/kW_{H2},year. The capital cost is a trend curve based on data from different sources. The operational costs are evaluated yearly to approximately 4% of the total investment (Ref 4).

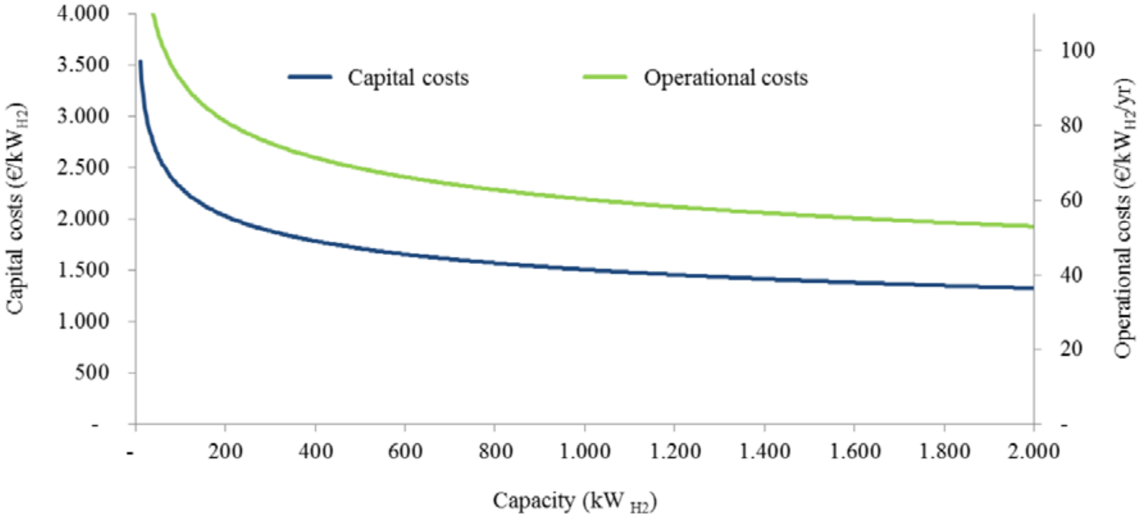


Figure 3 Capital and operational costs for an alkaline electrolyzer (EUR2011); DNV 2013.

3.1.3 PEM-electrolysis

PEM electrolysis is a further development of the alkaline electrolysis principle. In a PEM, the electrodes are in direct contact with a solid electrolyte, in this case consisting of an ionic conductive polymer, which together are forming a so called MEA (membrane electrode assembly). In comparison to alkaline electrolysis, this MEA-concept renders a higher efficiency, 67 to 82% (Ref 4). The electrodes are affected by thermal and mechanical stress, although they are not degraded in the same way as from acid/alkaline attacks of an alkaline electrolysis. (Ref 3).

The PEM electrolyzer is better suited for a dynamic operation than the alkaline. The PEM electrolysis is reversible, i.e. it can be used for either electrolysis or electricity generation. PEM has approximately the same operation temperature as the alkaline, about 80°C (Ref 5).

PEM electrolysis is still in the research and development stage, but there are smaller units that are commercially available, up to 50 kWe.

Valuable characteristics from a Power to gas perspective are fast response time and high energy density. Since technological development is rapid, one can expect that a PEM electrolyzer in MW-scale will be commercially available within a few years (Ref 4).

A demonstration plant for Power to gas in Frankfurt is currently testing a PEM electrolyzer. The goal is to demonstrate its ability to comply with varying electricity generation from wind power, or electricity price variations. It has an installed power of 300 kW_{th}, and can produce 60 Nm^3/h. The produced hydrogen is fed into Frankfurt's gas distribution system, with a volume share of 2%. So far, the electrolyzer has managed to react within milliseconds when in operation. From a warm start, it can adapt within minutes and from a cold start within 15 minutes (Ref 6).

Figure 4 The picture shows the PEM-electrolyzer in Frankfurt. It is tested for a dynamic operation following a varying electricity production. The hydrogen is fed into the gas infrastructure in Frankfurt.

3.1.4 SOEC-electrolysis (Solid oxide electrolysis)

SOEC-electrolyzers are based on ceramic materials allowing for very high operating temperatures of 700-1000°C. It reduces the need for electricity in the production of hydrogen and can provide efficiencies of up to 90%. The system requires access to high temperatures. Development of the SOEC technology stems from situations were abundant waste heat is available, for example at a nuclear power plant. Furthermore, focus has been on technology for continuous operation, which is not appropriate from a Power to gas perspective. The ramp-up time from a cold start to operation can amount to hours and from the stand-by mode to operation mode in the order of 15 minutes (Ref 4). The high operating temperature also provides a possibility to integrate the electrolysis with the production of fuels such as methanol or DME (dimethyl ether). The technology is still immature and in the research and development stage.

3.1.5 Summary electrolysis

Short ramp-up time and flexibility are the main sought for characteristics of an electrolysis process for Power to gas applications. It is an advantage if the process can be reversed and if it can be operated in a wide load range.

For alkaline electrolyzers it takes "minutes" to go from cold start to operating mode and the efficiency is then at 20-40% of maximum capacity, which is low. According to one manufacturer however (Hydrogenics), the technology is developing towards meeting the requirements for more flexible operation.

In operation, the efficiency for alkaline electrolysis ranges between 50% and 70%, which is lower than for PEM electrolyzers, 70-80%. Furthermore, alkaline electrolysis cannot be reversed, which is possible for PEM technology. PEM electrolyzers can thus be used either for electrolysis or electricity generation, depending on the price of electricity.

PEM electrolyzers have a higher energy efficiency and production rate than alkaline electrolyzers. Potentially, PEM can perform very fast ramp-up and shut-down within a part load range of 5-100%. PEM electrolyzers are also more efficient and compact than alkaline electrolyzers.

Disadvantages of PEM electrolyzers are the technical life time of electrodes and electrolyte, which today is about a third of an alkaline electrolyzer, and that the material cost is considerably higher.

Currently, the cost of a PEM electrolyzer (of size 50 kW) is between 2000 and 10,000 EUR/kWe (Ref 4). With larger units, capital costs and operating costs are expected to decrease.

Electrolyzer	Advantage	Disadvantage
Alkaline electrolyzer	Commercially available.	Low partial load range.
	Mature technology	Limited dynamic operation.
	Larger scale (MW)	Reversed operation is not possible.
PEM electrolyzer	Wide load range	Still under development.
	Quick response time	Small scale.
	Reversed operation is possible.	Expensive.

3.2 Methanation

The next step in a Power to gas plant, from hydrogen (H_2) to methane (CH_4), is called methanation. Methanation can be done through various processes, which are divided into catalytic (thermo-chemical) or biological processes. The catalytic process is based on mature technology, while the biological is in the research and development stage.

The reaction takes place according to the following formula and is exothermic, i.e. it emits energy. Enthalpy (H) denotes the systems (internal) energy. Delta H (ΔH) represents how the energy level has changed in the system in kJ/mole.

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \ (\Delta H = -165 \text{ kJ/mole})$$

The reaction is called the Sabatier reaction, after the Frenchman Paul Sabatier, who discovered the process about 100 years ago.

The Sabatier reaction takes place in two steps; the first step is endothermic and requires energy, while step two emits energy. The process thus requires certain start-up or activation energy. Using a catalyst reduces the need for activation energy.

Step 1: $CO2 + H2 \leftrightarrow CO + H20 \ (\Delta H = +41 \text{ kJ/mole})$

Step 2: $CO + 3H2 \leftrightarrow CH4 + 2H20 \ (\Delta H = -206 \text{ kJ/mole})$

The reactions are reversible and usually used to produce hydrogen from methane (natural gas) through methane steam reforming.

3.2.1 Biological methanation

The biological methanation can be seen as part of a biogas process. The decomposition of biological materials (substrates) goes through several stages, and methanation takes place in the final phases of the process. Methane formation is effected by means of various microorganisms (methanogen Achaea) by conversion of carbon dioxide and hydrogen or acetic acid (CH_3COOH) to methane.

With an extra supply of hydrogen to a biogas process, the methane content may increase from 50% to 75%, according to the company MicrobEnergy that owns two demonstration plants of Power to gas in Schwandorf in Germany (Ref 3). In one plant the hydrogen is fed from the hydrogen electrolyzer directly into an existing biogas plant which uses substrate in the form of corn and hay. The Power to gas plant has an output of 120 kW_e, which corresponds to a hydrogen flow to the reactor of about 70 kW. The output of methane can increase through improved technology. In laboratories, higher levels of methane have been achieved.

The second facility is a reactor for biological methanation of carbon dioxide and hydrogen. The cell has an output of 55 kW_e. The temperature in the reactor is between 40-65 °C and operates at atmospheric pressure. The plant must be heat supplied in order to sustain the operation temperature.

According to another study (Ref 7) and calculations by students at the Royal Institute of Technology (Ref 5) the supply of 20% hydrogen in a biogas reactor increases methane production by 22%.

The supply of hydrogen must be carefully controlled so that the biogas process is not adversely affected. If the share of hydrogen is too high, it can have the opposite effect.

The biological processes operate at temperatures around 20-40 °C (mesophilic) or 45-60 °C (thermophilic), which means that the biological methanation takes place at a considerably lower temperature than the thermo-catalytic methanation process.

Development of bio-methanation is on-going, but remains mostly in pre-commercial or research stages.

P2G-BioCat Project

In Avedore, south of Copenhagen, there is an experimental reactor for biological methanation using microorganisms taken from volcanoes in Island (methanogenic archaea). The facility is run by Energinet and Electrochaea, who developed the process. Hydrogen and carbon dioxide are fed into a bio-reactor, which, assisted by the microorganisms, in turn form methane and heat. The process takes place at 60-65 °C. The hydrogen is produced in an alkaline electrolyzer at 1 MW_e, from Hydrogenics. The carbon dioxide is collected from a biogas plant nearby and purified. The methane produced is fed into the natural gas system at a pressure of 3 bars. The oxygen and heat from the process is also utilized. The pilot plant will be in operation until December 2015.

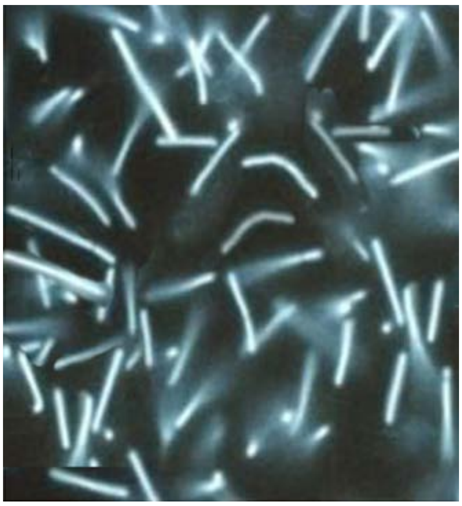


Figure 5 Biological methanation in Denmark.

3.2.2 Catalytic or chemical methanation

Catalytic methanation is an established and commercially available technology mainly used in large scale petrochemical processes (>1000 MW). A catalyst is a substance that speeds up a chemical reaction without being consumed. Nickel is commonly used as the catalyst for methanation (Ref 4).

A catalytic methanation may occur in temperature ranges between 300 and 800°C and in pressures up to 20 bars. (Ref 3). The efficiency of between 70-85%, is calculated as the energy content of the effluent gas relative the energy content of input gas. The rest is emitted as high grade heat (15-30%) (Ref 4).

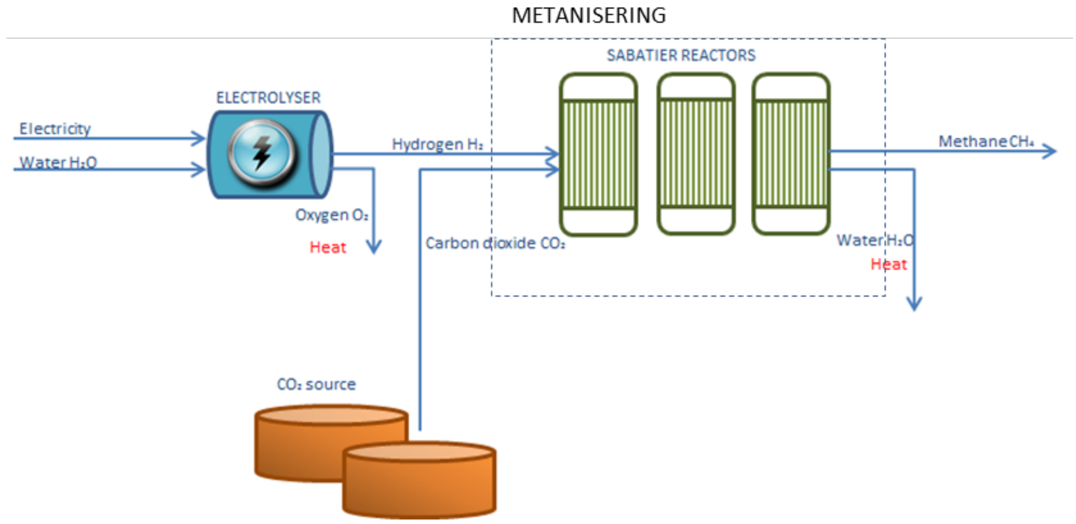


Figure 6 Schematic illustration of the two processes that may be included in a Power to gas pathway.

Below the cost structure of a catalytic methanation is shown (demarcation, se figure above). The capital costs are in EUR/kW_{CH4} and the operational costs are in EUR/kW_{CH4},year. The capital costs are based on facilities and a thermal capacity of <10 MW_{th}. The operational costs are approximated to 10% of the investment per year (Ref 4). When the market develops for small scale methanation, the costs are estimated to be 300-500 EUR/kW.

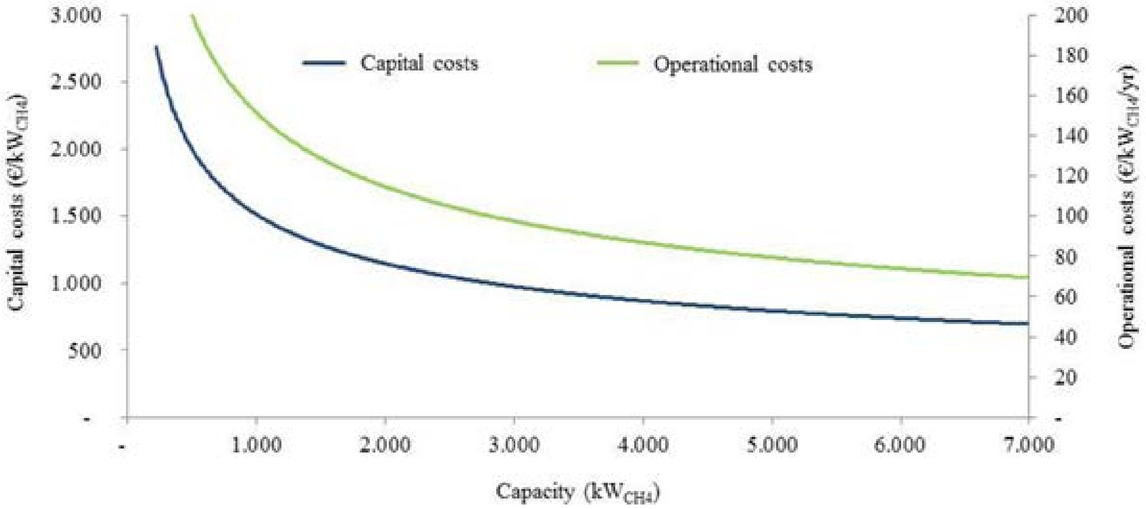


Figure 7 Capital and operational costs of catalytic methanation plants (EUR 2011, DNV KEMA, 2013).

3.3 Access to carbon dioxide

Carbon dioxide is, beside hydrogen, also required for methanation. The carbon dioxide can be of fossil or renewable origin; it can be procured from an existing biogas process or captured from flue gases. Usually one speaks of "carbon capture and storage" (CCS), a reference to carbon capture and storage of CO_2, from flue gases from for example coal-fired power plants. An alternative is CCR (carbon capture and re-use), i.e. reuse of carbon dioxide, for example, by methanation.

Carbon capture can be made from all types of gases containing carbon dioxide regardless of whether it is fossil or biomass-based combustion process or e.g. a chemical process for the production of cement.

As an example can be mentioned Cementa, a concrete producer in Gotland. Cementa has participated in a large research project to capture carbon dioxide from their flue gases. The project is carried out within Cementa's Norwegian sister company Norcem. Several different relevant separation techniques should be evaluated by 2017 (Ref 8).

Carbon capture methodologies are at the research stage and there are no commercial facilities available today.

Carbon dioxide is also formed in the production of biogas. Biogas refers to the raw gas formed during the digestion of biological wastes (e.g. food waste from households, various types of agricultural waste or sewage sludge). The organic waste or raw materials for a biogas process are called substrates. The proportion of methane formed varies between different processes, but is typically about 60%. The remaining gases consist primarily of carbon dioxide i.e. about 40%. The carbon dioxide may either be separated and methanized in a separate process, or hydrogen can be induced into the biogas reactor, and thereby contribute to increased methane production (see Section 3.2.1).

Audi operates a Power to gas plant for the production of hydrogen and methane from renewable wind in Werlte in northern Germany. It is the first facility for Power to gas in an industrial scale. It has a capacity of 6 MW and produces 6 million m^3 of synthetic methane per year, equivalent to 66 GWh. The gas is called “Audi e-gas” and is offered to buyers of Audi A^3 g-tron. The supplier of the facility is ETOGAS Gmbh.

Figure 8 Audis production av e-gas.

4 Three different system solutions for Power to gas in Sweden

Power to gas is a complex system solution with many different varieties. The main purpose of Power to gas is to effectively exploit and utilize any surplus electricity that may occur when a large-scale expansion of wind power or other renewable electricity that cannot be regularized. Power to gas is by nature not a large-scale solution, since the conditions at the national level may look quite different than at the regional or local level. Also, conditions differ between sites.

There are two main reasons to produce gas from excess electricity. The first is that among the available storage methods for electrical energy, Power to gas can capture the largest energy volume. (See the illustration in the figure below.) The second driver is the challenge of developing renewable fuels that can replace fossil fuels for transportation. Vehicle fuels based on methane (natural gas or bio methane) are established techniques. Hydrogen can also be used directly in fuel cell vehicles, or as an alternative to methane, further processed into liquid fuels such as methanol or DME. (See section 7.6 about Piteå).

The design of a Power to gas solution is governed by the specific local technical conditions, the purpose of the facility (energy storage, biogas production, recycling of carbon dioxide, etc.) and which actors are involved. Examples of actors are energy companies, biogas producers, wind power companies and municipalities.

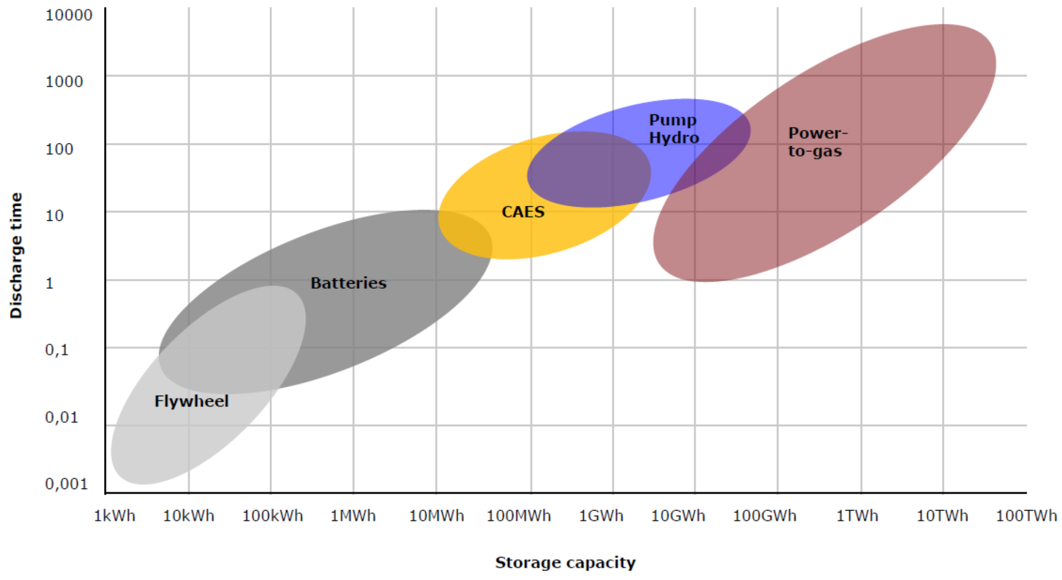


Figure 9 Comparison between different storage techniques for electric energy. Source: Frauenhofer Institute.

4.1 Three possible main tracks for Power to gas

A Power to gas solution can be of many different variants, and based on different technical solutions. In the present work, three main tracks are discussed for each concerned location.

These are:

1. An electrolyzer that can follow the variations in wind production and convert electricity into hydrogen.
2. An electrolyzer combined with the production of biogas. The hydrogen produced in the electrolyzer, is fed into a biogas plant and contributes to increase the production of bio-methane. The electrolyzer either follows the wind energy production, or is customized for the need of hydrogen in the biogas process.
3. An electrolyzer in combination with thermos-catalytic methanation. The hydrogen produced in the electrolyzer, is further fed into a (methanation) Sabatier reactor, in which hydrogen reacts with carbon dioxide to form methane. The carbon dioxide comes from an external source.

The following describes the various options in more detail.

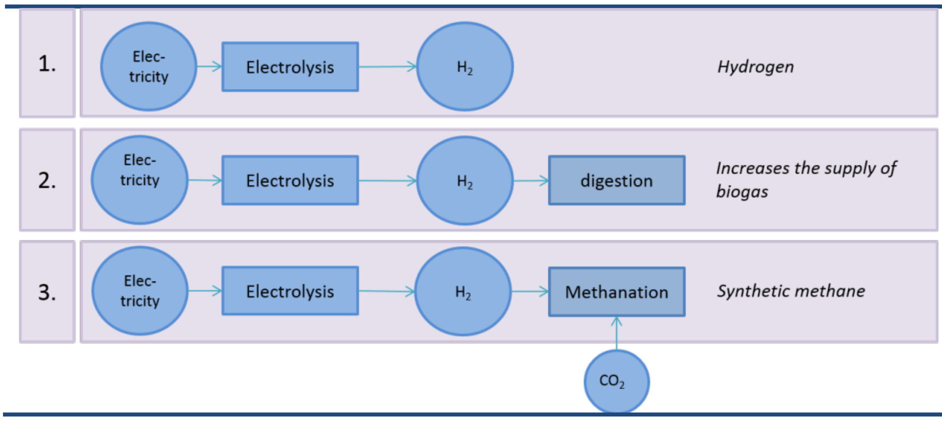


Figure 10 Illustration of the three possible tracks for a Power to gas solution

4.2 An electrolyzer for hydrogen production

The electrolyzer is the main component in a Power to gas solution, and the simplest Power to gas solution therefore consists of an electrolyzer only. Important characteristics of the electrolyzer are a fast response time; from a cold start to the operative position and a dynamic operation within as broad power range as possible. For a demonstration plant for Power to gas in Sweden, there are basically two types of electrolyzers to choose from, alkaline or PEM.

Power to gas is a method for storing electrical energy in periods of very low or negative electricity prices. In an optimal design the electrolyzer follows electricity price, or wind power's variability. This requires a PEM electrolyzer which is yet at the research stage. The alkaline electrolyzer is also in a development stage and it is expected in a few years be able to go into more dynamic operation. However, we are not there yet.

An alternative to flexible operation on the level of seconds, may be that the system works in batches, and is in operation during periods (days) based on forecasted low electricity prices. Then it is possible to use commercial technology, i.e. alkaline electrolyzer.

If there is an infrastructure for natural gas in the area, hydrogen could be fed into the natural gas system. In a demonstration plant for Power to gas in Frankfurt (see section 3.1.3) hydrogen gas is fed into the natural gas network with a volume share of 2% (Ref 6). For this solution, it is mainly the price of electricity and the plant utilization rate over the year that determines the profitability.

In theory, it is the expected surplus of electricity that governs the dimensioning and size of the facility. In practice however, for a demonstration plant, the investment cost is crucial for the sizing of the plant.

In some places there are plans for hydrogen vehicles' filling stations. An electrolyzer can be placed adjacent to such a filling station. If the price ratio of hydrogen towards electricity is more advantageous and provides more operation hours over the year, and it is profitable to use the hydrogen as a fuel, the demand of hydrogen governs how the plant is designed and operated rather than the availability of surplus electricity.

Table 1 An illustration of selection criteria when choosing electrolyzer.

The purpose of a demonstration plant:	Selection of electrolysis:
Demonstrate the possibilities to follow variation and to take advantage of the energy in the power peaks.	Use PEM; it can follow the variability of wind production, and if the price is favorable, run in reversed operation mode for re-production of electricity from hydrogen. This also requires: • Ability to store hydrogen. • Very large fluctuations in electricity prices. Alternatively, the hydrogen gas can be fed into the existing gas infrastructure.
Address the surplus of electricity in periods of low electricity prices and that hydrogen gas can be fed into the existing energy gas network, or be distributed via a filling station.	Use an alkaline electrolyzer. This requires: • The operation is planned based on forecasted electricity price levels and the plant runs continuously during a set period.

4.3 Increased production of bio-methane by feeding hydrogen to the biogas process

It is not always possible to find a market for hydrogen. Methane, however, is an established energy gas, with several alternative areas of application in industry, vehicle operation and in households. Methane (natural gas) is also used for electricity generation.

The next Power to gas solution therefore includes a methanation step, where methane production takes place in an existing biogas process. The hydrogen gas produced in the electrolysis is then fed into the biogas reactor. As noted in section 3.2.1, this means that the methane content can increase from 50% to 75%, although the figures differ between different sources.

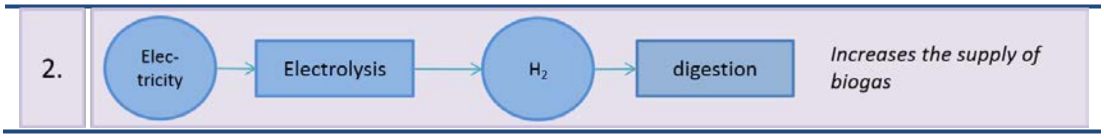


Figure 11 Illustration of main track no 2, where the hydrogen is fed into a digestion plant to increase the share of methane in the produced biogas.

This system solution is in this case, compared to alternative 1), more complex, since the hydrogen production should be adjusted to the biogas process. Hydrogen will not have to be induced continuously, but the proportion of hydrogen gas must not exceed a certain level, since that will have an opposite effect.

The system solution can be complemented with a storage, either a battery to store electricity when this price is too low or a hydrogen storage for periods when the production of hydrogen gas exceeds the capacity of the plant.

Storing cheap electricity in a battery is not an option, since the efficiency of reusing electricity from a battery in the form of electricity is significantly higher than using already stored electricity for hydrogen production.

In order to use biogas as a fuel for vehicles, it must be upgraded. This is accomplished in the subsequent process steps where biogas is purified from carbon dioxide, water vapor and other gaseous components so that the methane concentration amounts to 96-99%. If the methane content can be raised already in the biogas reactor by the addition of hydrogen, it reduces the need for subsequent purification steps and lowers the cost of upgrading.

In the case that biogas will not be upgraded, this hydrogen addition is still favorable since the energy content of the biogas will be higher with a higher methane content.

The relationship between the electricity price and the price of methane, determines the profitability of the plant. A very important parameter is the systems' utilization factor over the year.

The dimensioning of the plant is governed by the capacity of the biogas plant to make use of hydrogen gas, including a possible storage.

4.4 The electrolyzer in combination with catalytic methanation

The third system solution for Power to gas is the most complex and involves several different types of processes. In this combination, commonly referred to as the Sabatier reactor, the hydrogen gas reacts with a separate stream of carbon dioxide. The carbon dioxide is separated from flue gas or raw biogas.

This is a more integrated system solution and therefore more complex than the prevailing alternatives because the flows of hydrogen and carbon dioxide must be adjusted to each other. This may require some form of interim storage for either hydrogen or carbon dioxide.

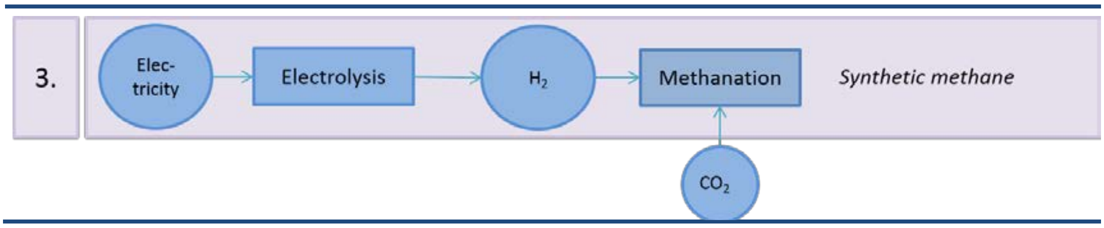


Figure 12 Illustration of main track no 3, where the hydrogen reacts with carbon dioxide in a separate methanation reactor.

The plant works optimally with a uniform gas supply. At the intermediate storage, the alternatives are either to close down the reactor completely between the operational times, or to keep the plant warm waiting for enough hydrogen. Letting the facility work under various operations and in the prolongation follow the production from the wind turbines, is not effective.

The produced methane is of high quality and can be used to power vehicles, or fed into an existing natural gas infrastructure. Since it is methane, there are virtually no limits to how much can be inserted.

The profitability of the plant is determined by the relationship between the electricity price and the price of methane. However, capital costs are significantly higher because investment in carbon dioxide capturing and transport are also required in the Sabatier concept. Some form of interim gas storage is probably also required. The plant factor, or the utilization rate, therefore has a major impact on profitability.

The design is based on the expected profitability of the entire system. A demonstration plant based on the above concept, should consider that it is just a demonstration and research facility, i.e. a small scale facility. Moreover, since it is the system solution that needs be tested, each component should rather be based on proven technology.

5 Gotland

With an area of 3,000 tsqm, Gotland is Sweden's largest island. Out of a total population of 57,000 people, 24,000 live in Visby, the only city on the island. Being an island with good wind conditions and approximately 1500 hours of sunshine per year, Gotland has good prerequisites for renewable energy, such as solar energy, wind power and but also for biofuels. There are many cottages on Gotland that are only used during the summer, and the population on Gotland increases significantly during the summer. Thanks to the latter, the difference of the electricity consumption between summer and winter is to some extent levelled out.

Gotland has one heavy industry, Cementa, i.e. a cement production industry. Cementa is situated in Slite on the north eastern part of Gotland. The rest of Gotland's business is dominated by tourism and farming.

5.1 Energy supply and usage of today

The total energy consumption in Gotland was 3.9 TWh in 2012. The energy usage divided by different sectors is shown in the pie chart below. The industry uses approximately 60% of the total energy consumption on Gotland, and Cementa's consumption is a large part of this.

In 2013, the total usage of electricity was 947 GWh, of which 384 GWh was produced locally by wind power and the rest was imported from the Swedish mainland.

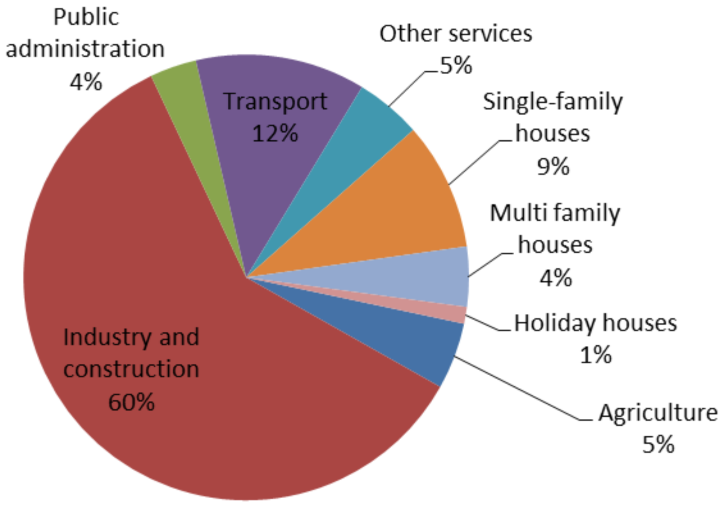


Figure 13 Energy consumption in Gotland, in total 3.9 TWh 2012, distributed by different sectors. Source: Statistics Sweden.

5.2 Energy and climate goals

Gotland's overall vision is to be self-sufficient in renewable and recycled energy in 2025, including the large demand from the industry. There's a sub target to this goal for 2020: To supply enough renewable energy to cover its own households and commercial uses, except for Cementa. These goals are depending on export of wind power balancing the remaining use of fossil fuels (Ref 9). This means that the locally produced electricity needs to be twice the amount of the total local demand. Today, wind power produces about 40% of the electricity demand.

Region Gotland also aims at reducing the carbon dioxide emissions with 45% from 1990 to 2020. In 1990, 970 tons of carbon dioxide was emitted, and in 2012 the emissions were reduced by 33%, resulting in 660 tons of carbon dioxide. Cementa's emissions are not included in these measures, since they are included in the European Union Emissions Trading System (EU ETS). Cementa´s target is to become carbon dioxide neutral by 2030. (Ref 8).

5.3 Development of the electricity market

There are great possibilities for wind power on Gotland. The wind power produced electricity was 384 GWh in 2013, corresponding to 40% of Gotland's total electricity demand. Today the production exceeds Gotland's demand momentarily. The installed wind power capacity amounts to 170 MW. There are limitations concerning the installed capacity of variable electricity. Both the network on Gotland and the transmission capacity to the mainland, limits the possible amount of locally produced electricity, to 195 MW. This mainly affects the installations of wind power, but also the installation of solar power.

Wind power can never be the only type of electricity generation in a network. There is a need for balancing the varying electricity production from the wind turbines. On Gotland, the balancing consists of the two direct current cables, connecting Gotland's energy system with the mainland's balancing hydropower stations. The DC-cables have both a capacity of 160 MW. There is also a backup system on Gotland, based on diesel generators and gas turbines.

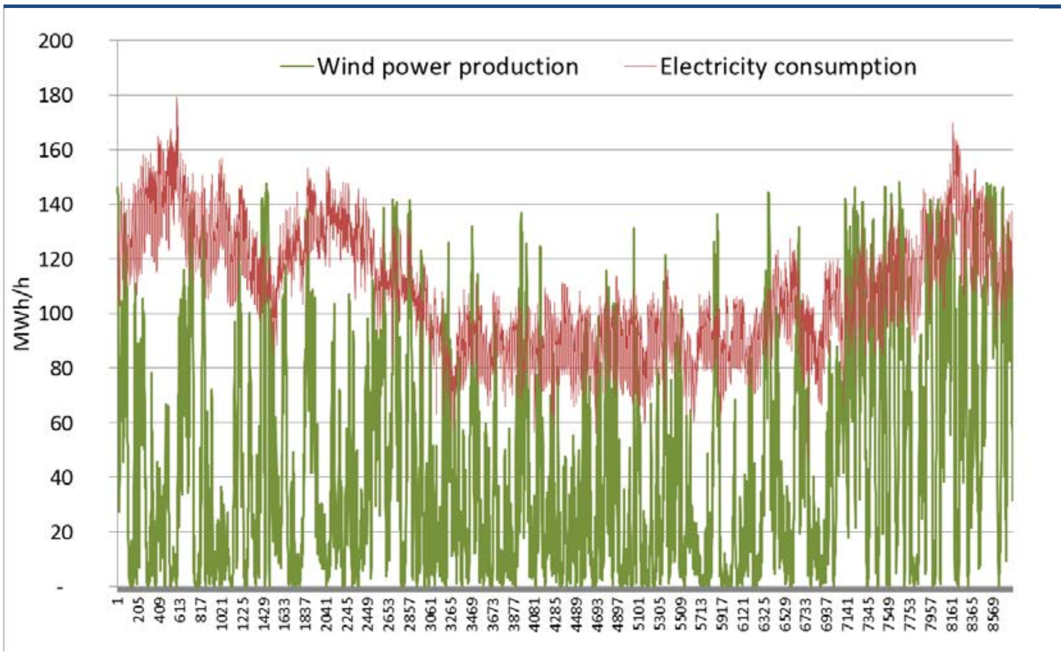


Figure 14 Wind power production and use of electricity per hour on Gotland, 2013. The wind power corresponds to 40% of Gotland's electricity use today. Momentarily the wind power production can exceed the demand of the island. Source: Gotland Energy AB, processed by ÅF.

According to The Energy plan for 2020 by Region Gotland, the goal is an installed wind power capacity of 650-700 MW by 2020, and by then also to be prepared for an installation up to 1000 MW wind power. The production goal of 2020 is 1.8 TWh, which corresponds to five times the production of today. To ensure that this expansion is possible, more electricity transmitting cables to the mainland are necessary. There is also a visionary goal, to increase the yearly production of electricity on Gotland to 2.7 TWh. The interest in solar power is increasing, and today, there are about 40 separate solar power systems, with a peak power of 230 kW.

Svenska Kraftnät, the owner of the Swedish national electrical network, has decided to increase the transmission capacity between Gotland and the mainland by 500 MW, with the purpose to increase Gotland's production of wind power electricity. With an even bigger expansion another 300-500 MW is required. Reinforcements in the local electricity distribution network are also a necessity and thereby investments in this sector. There is e.g. a bottle neck in the network limiting the production south of Hemse, a village on Gotland. Large investments and reinforcements in GEAB's network will be needed and the cost for this will most likely be placed on the new production units south of Hemse.

The graph below illustrates how a large expansion of wind power will affect the production versus the consumption of electricity. The present electricity production from wind power (2013) with its variations are up scaled to a total of 1.8 TWh, while the consumption is still on the same levels as 2013. The power peaks that exceed the consumption are equivalent to about 1 TWh. Today (2014) there is no fixed plan to where these wind turbines are to be placed. Most likely power peaks will be too large to be fully transferred fully to the mainland, and need to be taken care of locally.

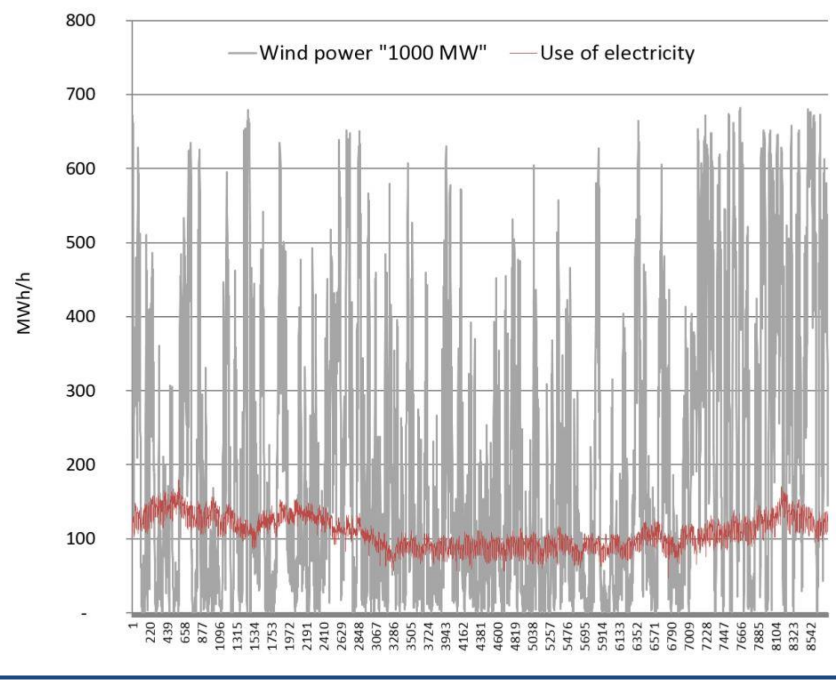


Figure 15 Illustration of a planned wind power production, with an installed power of 1000 MW and an electricity production of about 1.8 TWh. The excess energy, the hours where the wind power production exceeds the use of electricity, is about 1 TWh. Source: Gotlands Energy AB, processed by ÅF.

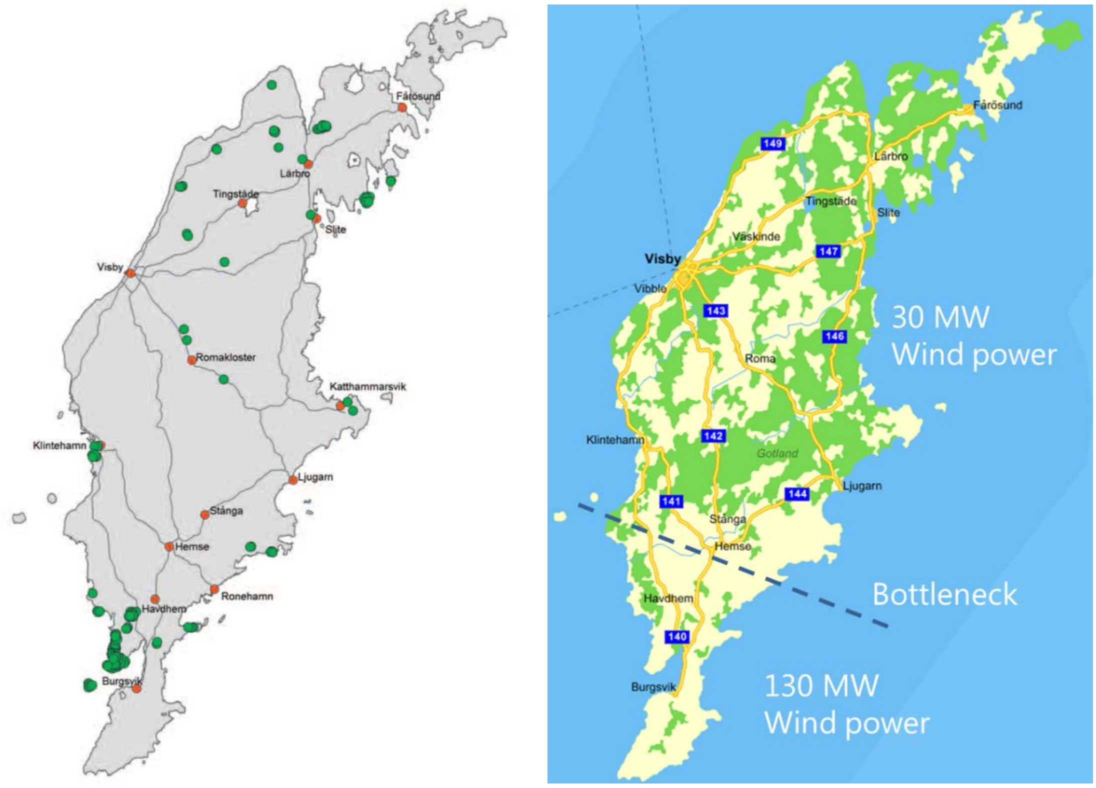


Figure 16 Current wind turbines on Gotland (green dots). Out of the national risk interest areas for wind power, identified in the general plan for Gotland, 2010-2025, most are situated north of Hemse. One is situated in Näsudden, south of Hemse. Source: "Översiktsplan Gotland 2010-2025".

5.4 Development of the biogas market

Today 25 GWh of biogas is produced on Gotland. The main part is used as raw biogas for production of steam, used by Arla for milk drying. Approximately 2 GWh is upgraded to vehicle fuel gas. The energy content in the fuel gas is equivalent to 220,000 liter of petrol.

There is a planned expansion of the biogas production up to 45 GWh per year, and a target of 100 GWh in 2020, of which 30 GWh is to be upgraded to vehicle fuel gas. In 2030, the goal is to have a yearly production of 300 GWh of fuel gas, i.e. 10 times the amount in 2020. That would cover half of the demand of the transportation sector on Gotland.

The current potential for production of biogas on Gotland, with today's cost levels and technical conditions, is approximately between 150 and 200 GWh per year (Ref 10). This biogas potential can increase if energy crops are used more widely, that is, if the prices fall and/or if the methane exchange from the substrates can increase through the insertion of hydrogen.

To ensure the development and increase the biogas production on Gotland, Region Gotland has already entered a business agreement about the volumes of biogas that is to be purchased over the years to come. The procured supplier is Biogas Gotland. The agreement creates a solid foundation for expanding the production and the subsequent enhancement of the infrastructure needed for the futures use of biogas as a vehicle fuel on Gotland.

There are two producers of biogas on Gotland: Region Gotland, with an anaerobic digestion plant close to the up-grading plant in Visby, and Brogas, North West of Visby.

By the up-grading plant in Visby there is an anaerobic digestion plant producing 3-4 GWh of biogas per year from sludge. The capacity of the plant is larger than this and used to produce up to 10 GWh of biogas yearly, but the main part of the production has been moved to the Brogas plant. The produced gas is used for heating of buildings and all excess biogas is transferred via a gas pipeline to the district heating system, owned by GEAB (Ref 11).

Brogas was the largest producer of biogas on Gotland in 2014. The facility is at full capacity producing about 20 GWh of biogas per year and is planning an expansion up to 40 GWh. There is a limitation in the volumes of organic waste the facility is allowed to handle, 95,000 tons per year (Ref 12). The biogas plant in Bro uses the residues from farming and food industries as substrate. Most of the gas is used for drying of milk, production of steam and only a smaller part, about 2 GWh is upgraded to vehicle gas.

The upgrading process takes place at Biogas Gotland's facility on Lundbygatan in Visby. During the upgrading process the methane content is increased from 60% to at least 97%. The raw biogas, with the 60% content of methane, arrives from Brogas via an 8 km long pipeline. At the facility there is also a fuelling station for buses, light trucks and cars. The vehicle gas on Gotland contains 100% bio methane. There are three filing stations on Gotland, see map in the figure below.

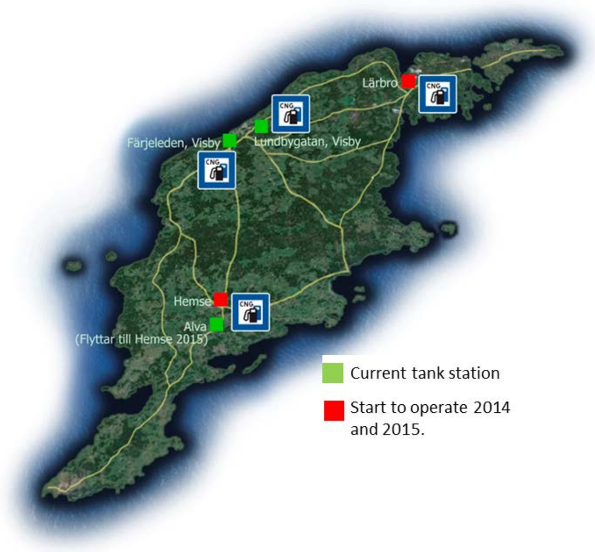


Figure 17 Filling stations for biogas on Gotland, present and the ones planned to open during 2014-2015. Source: Biogas Gotland; www.biogasgotland.se

5.5 Access to carbon dioxide?

Cementa is Sweden's largest building material company and part of the international group Heidelberg cement. Cementa has three cement factories in Sweden: in Slite on Gotland, in Skövde and in Degerfors, respectively. The Slite facility is one of Europe's most modern and energy efficient cement facilities. 225 people work there and contribute to the 2.0 million tons of cement produced every year. The excess heat from the process is used for producing electricity and district heating, used on Gotland.

The cement process is very energy demanding. The main raw material is limestone, grinded and burned into so called cement clinker. The burning process requires very substantial temperatures, around 1450 °C. The process has large carbon dioxide emissions, both from combustion of fossil fuels and also from the thermo-chemical process (calcination) where limestone is transformed into cement.

Cementa has highly set goals and run several projects to minimize their emissions of carbon dioxide. Energy efficiency measures, replacing fossil fuels with recycled fuels (waste), and new types of cement that has less impact on the climate, are some examples of how they are working to reduce their CO_2-emissions. Cementa's Norwegian sister company, Norcem, is running research and development projects to separate carbon dioxide from the flue gas. Several separating technologies are tested and examined in parallel until 2017. The most favourable techniques will be suitable and available not only for Norcem, but also for Cementa. The Slite factory emits 1,6 million tons of carbon dioxide every year[1].

Figure 18 Cementa is Gotland's largest industry.

5.6 Power to gas on Gotland

Gotland has extensive plans to continue the expansion of wind power, which demands large investments both in the local network and in the transmission capacity to the mainland. Wind power is a very volatile power source and the larger the share of wind power is, the higher are the requirements on the rest of the energy system to handle the production variations. Since Gotland is an island, the challenges are larger there than on the mainland.

It is difficult to determine how large the excess energy will be from the wind turbines, since the distribution network will develop along with the expansion of wind power. A simple calculation example can demonstrate one possible scenario. Today (2014) the installed wind power on Gotland is 170 MW. If it expands to 250 MW, without any reinforcements in the local network or transferring capacity to the mainland, and with the same consumption pattern as today, there will be a surplus of about 100 GWh per year. This is more than what can be taken care of with a Power to gas solution, based on today's technology and the costs of electrolysis.

[1] Calculated on a production of 2.0 million tons of cement per year, and 850 kg CO2/ton cement.

Two of the three main tracks for Power to gas are suitable for Gotland: The second one; electrolyzer in combination with biogas, and the third one; electrolyzer in combination with catalytic methanation. The first one is the simplest solution, but it needs a demand for hydrogen. During this project, no such demand could be identified.

Master students in Chemistry at KTH (The Royal Institute of Technology), have done a separate study on Gotland, within this project. Data and some of the conclusions come partly from this sub-project.

5.6.1 Supplement of Brogas biogas plant with electricity electrolysis device

A suitable solution for Power to gas on Gotland is to have the electrolysis process connected to Brogas' biogas plant. Today (2014) Brogas is producing 22 GWh of biogas per year and are planning to expand their production to 40 GWh per year. Region Gotland has ambitious goals to use 100% renewable energy in 2020, which means large investments in biogas. This goal will increase the demand for biogas.

It is difficult to quantify the amount of excess electricity that might come from the expansion of wind turbines locally. Reinforcements in the network, electricity demand, consumption patterns, within which time frame the system is analyzed, and if the expansion plans of the wind power takes into account the possibility to store electricity, are all affecting how much electricity the network will be able to handle.

A biogas process works optimally at stable conditions, without large fluctuations. The purpose of the demonstrational Power to gas plant should in this case be to investigate how the input of hydrogen can increase the amount of methane in the final product, and not how an electrolysis process can increase the installed wind power.

This also means that well tested equipment should be used primarily i.e. an alkaline electrolysis process. The size will be determined by the capacity of the biogas plant and with respect to the economy of the project, i.e. the price of a commercial electrolysis process.

KTH-students have made general calculations about how much the methane content is increasing when hydrogen is added to the biogas process. Without the added hydrogen the methane content is about 58% and the carbon dioxide content is 38%. With an optimal amount of added hydrogen, 20% of the total amount of substrates, the methane content is increased to 71% and the carbon dioxide content is decreased to 15%. Based on a yearly production of 3.8 Nm^3 the production of biogas can increase from 2.2 to 2.7 Nm^3 per year.

This optimization of the biogas process demands 2.0 MNm^3 of hydrogen per year and an electrolysis device of 4-5 MWe, depending on how it's used over the year. With E.on's facility in Falkenhagen as a role model, a more proper capacity is 2 MWe. The smaller option will increase today's biogas production to 2.4 MNm^3 of methane per year.

One way to ensure the future of the project is to start small, with an electrolysis device and build a bigger system later.

Table 2 Values for different parameters in Brogas' biogas plant with today's conditions and with 20% added hydrogen. Source: KTH 2014, processed by ÅF.

Brogas	Today's production	Production with 20% added hydrogen (0.2 atm H_2)	Electorlyser, capacity of 1,89 MW
Biogas production, MNm³/year	3.8	3.8	3.8
Added hydrogen, MNm³ H_2/ year	-	2,0	0.81
Methane production, MNm³ CH_4/year	2.2	2.7 (i.e. +0.5)	2.4 (i.e. +0.2)
Methane percentage in the biogas, vol% CH_4	58%	71%	63%
Carbon dioxide percentage in the biogas, vol% CO_2	38	15	-
Hydrogen percentage, vol% H_2	0	10	-
Other gases, H_2S, H_2O,vol%	4	4	-

Assumed conditions (KTH 2014).

Students from The Royal Institute of Technology in Stockholm (KTH) have calculated fluxes and use of electricity. E.on's facility in Falkenhagen, outside Frankfurt in Germany has been used as an industrial model. They use an electrolyzer of 2 MWe, using electricity from a nearby wind park. In practice, it has a total electrical power of 1.87 MW in a total of 6 electrolyzers from Hydrogenics. The facility produces 360 Nm^3 of hydrogen per hour in total (6x60 Nm^3/h).

The students have used an alkaline electrolyzer from Hydrogenice, HySTAT 120-10, with a power of 630 kW per unit. Three units give 1.89 MW, which can produce 360 Nm^3 per hour. The students have also made calculations with an electrolyzer with 9 separate units, equivalent to 5.67 MW_e, which constitutes the upper limit for the available techniques today.

ÅF has provided input of a hypothetical excess electricity of 250 MW wind power. This gives a full load time of 2248 hours, respectively 2132 hours for the electrolyzer. The reason for the small differences is that the excess electricity is much larger than the installed power. The electrolyzer is either operating at 100% or not at all, due to this large difference in installed wind power and power of the electrolyzer.

Technical data about the electrolyzer (Hydrogenics HySTAT 120-10):

	Per unit	3 units	9 units	Unit
Electrical power	630	1 890	5,670	kW_e
Full load time (based on assumptions)		2 248	2,132	h/year
Electrical demand (ÅF)		4.2	12.1	*GWh/year*
Dry weight	14.5	43.5	130.5	ton
Dimensions	6.10*2.44*2.90	-	-	m
Hydrogen production	120	360	1,080	Nm^3 H_2 per h
Oxygen production	60	180	540	Nm^3 O_2 per h
Water demand	240	720	2,160	l/h
For the biological methanation in the biogas process following data is valid:				
Electrical power, MW	Hydrogen production MNm^3 H_2/year	Methane production MNm^3 CH4/year	Hydrogen demand in the biogas reactor for optimal methane production. MNm^3 H_2/ year	
1.89	0.81	0.18	2.0	
5.67	2.4	0.5	2.0	

Table 3 Assumed conditions for production of hydrogen adjacent to Brogas' biogas production plant on Gotland. Source: KTH 2014

5.6.2 Building a plant adjacent to Cementa

The third and most complex Power to gas solution is to combine hydrogen production through electrolysis with a separate stream of carbon dioxide. This needs access to pure carbon dioxide.

Cementa is currently researching efficient methods to separate carbon dioxide from the rest of the flue gas from their concrete production. The plant in Slite emits about 1,6 million tonnes of carbon dioxide per year, and the carbon dioxide is thereby not a limiting factor in building a Power to gas plant, but the cost of separating it from the various flue gas is.

The students from KTH (Ref 5) have also investigated a Sabatier reactor operating in different conditions. A full-scale plant would include an electrolysis device, carbon capture, intermediate storage, a unit for separating steam from the methane and a heat exchanger. The process occurs under high pressure, which is why a compressor is required. The excess heat can be used if connected to e.g. the district heating system, and the oxygen can be utilized in Cementa´s process.

Available data is too uncertain to give a realistic picture of the conditions in Slite. There will be several years until Cementa has installed carbon capture in their facilities.

Since wind power is unpredictable, the production of hydrogen will vary a lot when the electrolysis device is determined by the production of electricity in the wind turbines. This varying operation is a good reason to build the facility small-scale, as a research project, and not as a demonstrational project for the industry. The simplified calculations made by the student on KTH show that the facility will be very expensive and hard to realize.

In a longer perspective, beyond 2020, the technological development may have changed the prerequisites. Both Cementa and Region Gotland are interested, and regard it as possible to materialize a facility in Slite by 2025.

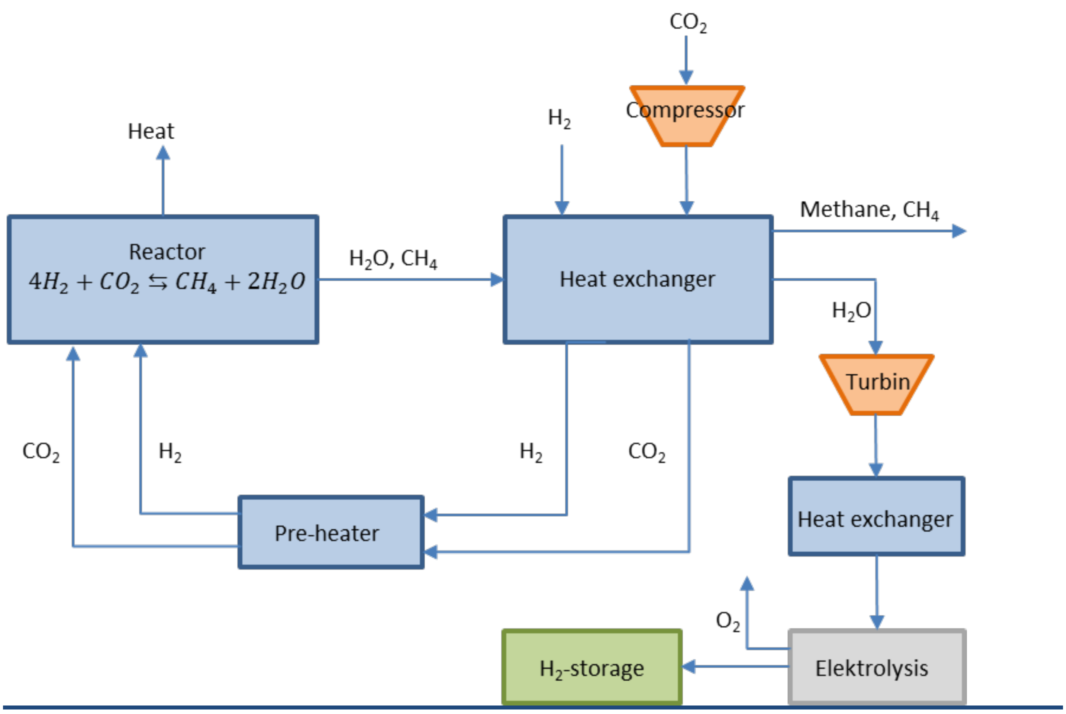


Figure 19 Illustration of the different processes in the Power to gas alternative 3 for Gotland. KTH 2014, processed by ÅF.

5.7 Conclusions Gotland

Gotland aims at being self-sufficient in renewable and recycled energy by 2025. The biggest industry, Cementa, is replacing fossil fuels with waste that is suitable for their process, for example old tires. The goal will be achieved through the export of locally produced wind power that will balance the residual use of fossil energy. For this to be possible, the locally generated electricity has to be twice as large as the total electricity consumption. This means that today's wind power production need to increase from about 0.4 TWh to 1.8 TWh, which will entail a great challenge for the technical system. Beside more cables to the mainland, the local network needs to be reinforced and the electricity consumption must be more flexible.

Since Gotland is an island with certain conditions, a Power to gas facility could demonstrate how the local energy systems can be integrated, to offload the local electricity network and to contribute to more renewable fuels.

5.7.1 A Power to gas demonstration plant on Gotland

In the short run, the best choice for Power to gas on Gotland is to use an electrolysis device adjacent to Brogas' biogas plant in Visby. The produced hydrogen is fed directly to the biogas plant, and helps to increase the share of methane in the final biogas.

In the longer term, a plant in a larger scale, based on catalytic methanation, can be located in Slite adjacent to Cementa´s factory. Cementa aims at being carbon-neutral. Carbon capture and storage is one part of this, but the carbon dioxide can also be reused, to form methane. The oxygen produced in the electrolyzer can be used in Cementa´s process.

5.7.2 Socio-economic benefits

In the short run, the socio-economic benefit for Gotland is that the bio methane production can increase by 0.2 MNm^3 per year, i.e. from 2.2 to 2.4 MNm^3 of methane.

In the longer run, Power to gas can contribute to Gotland´s ambitious goals for renewable energy, both the further development of wind power and biogas, but also to become climate neutral and base the whole energy supply on renewable energy. Since it also includes Cementa´s usage of energy and climate goals, it may have a positive effect on the labor market on the island.

5.7.3 Hydrogen or methane?

The demonstrational plant will primarily produce hydrogen, which in a second step will be used to increase the production of bio methane. The facility will demonstrate the possibility to increase the methane exchange from the same amount of substrates through the addition of hydrogen to the process.

5.7.4 In what ways can Power to gas contribute to more renewable electricity?

In the margin, the electrolysis device can unburden the electrical system at a high production of wind power electricity. The demonstrational plant will not by itself generate more wind turbines or solar cells on Gotland. In the present report a conventional solution is suggested with an alkaline electrolysis device. It is not suitable for operating under varying conditions. However, the technology is being developed to make a dynamic operation possible.

In the longer term, within 5 to10 years, electrolyzers with dynamic operation will probably be available in the market. This means that they may play a much larger role in balancing the electricity system than is currently possible. The demand for hydrogen may increase, partly as suggested above, in more biogas plants, but also of Cementa. It is also possible that the hydrogen can be used directly in cars or buses powered by fuel cells.

5.7.5 Dimensioning – how large should the facility be?

The electrolysis device should at this stage be a conventional model and be based on well tested techniques. A suitable size is 2 MW of electricity.

5.7.6 Timetable

A demonstration plant with an electrolyzer in Visby could be in place in 2016. A larger plant, according to the main track 3, in Slite, is estimated to be possible to about 2025 according to Region Gotland and Cementa.

5.7.7 The way forward

The Power to gas concept includes several technology steps and different types of players. In the short term, it is not a commercially driven energy solution, but a demonstration plant for knowledge creation and development of technology.

Therefore it should be a collaborative project with representatives of both public and private actors, such as Region Gotland, Cementa, Gotland Energy and Biogas Gotland. Since it is a demonstration facility, the academy should be represented, for example Uppsala University, campus Gotland.

6 Falkenberg in Halland

Falkenberg is situated in the county of Halland on the west coast of Sweden. In Halland there are six municipalities and apart from Falkenberg there are Varberg, Kungsbacka, Hylte, Halmstad and Laholm. The industries are mainly agricultural, but there is also food industry and heavy industry in pulp, paper and foundries. Falkenberg with surroundings also have a great tourism business.

6.1 Energy supply and usage of today

The total use of energy in Halland was 14,300 GWh in 2012, where 5,300 GWh was used as electricity and 900 GWh as district heating. The rest origins from different fuels e.g. natural gas. The Swedish pipeline for natural gas runs through Halland, from Laholm in the southern parts to Varberg in the north. Access to the pipeline is a potential possibility for biogas producers, and in the future maybe also for hydrogen producers. The energy use of Falkenberg was 1.3 TWh in 2012, which corresponds to approximately 9% of the total energy usage of the county.

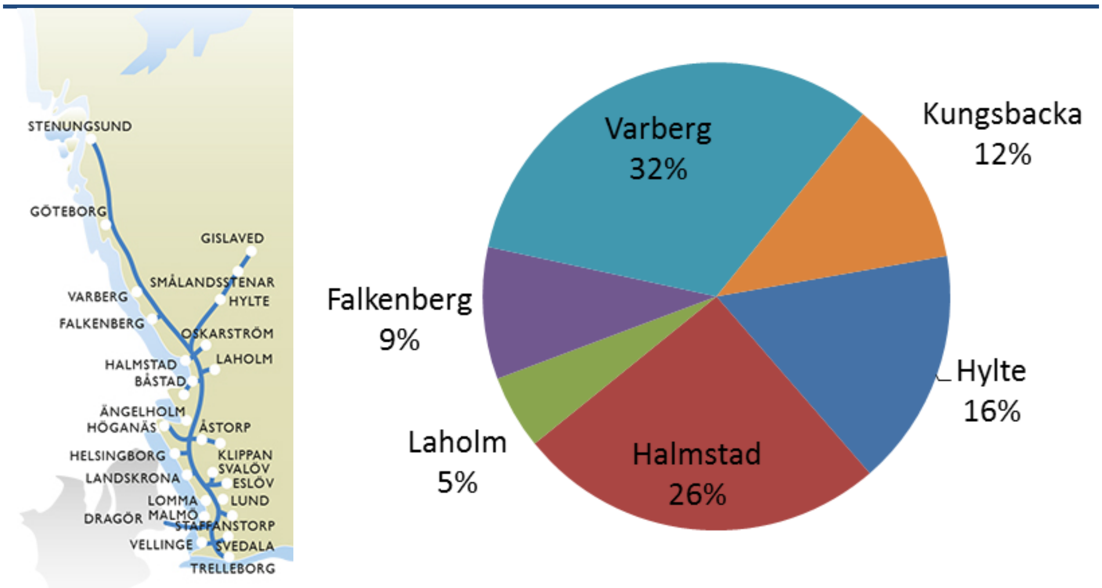


Figure 20 Energy usage of Halland was 14.3 TWh in 2012, where 1.3 TWh was used in Falkenberg. Source: Statistics Sweden's statistical database, 2014.

6.2 Energy and climate goals

Halland has no specific environmental targets for the county, but the national goals are applied to Halland, including the milestones for Halland set by the government in April 2012 (Ref 13).

The municipality of Falkenberg has a vision to grow for a sustainable future. The use of energy should be efficient and renewable energy is given priority over fossil fuels. These two strategies are of outmost importance for achieving sustainability.

Falkenberg's municipality has set the following goals to maintain a sustainable development:

- The inhabitants of Falkenberg are prepared to make active choices in their everyday life to contribute to a sustainable development.
- The need for transportation by car will decrease.
- The amount of public transportation will increase by 50% until 2015.

- The use of energy in buildings will decrease by 10% until 2015.
- The production of renewable energy will increase by 50% until 2015.
- In 2020 as latest, the amount of produced renewable energy will match the amount of consumed energy in the entire municipality.
- The availability of renewable fuels will increase.

(Ref 14)

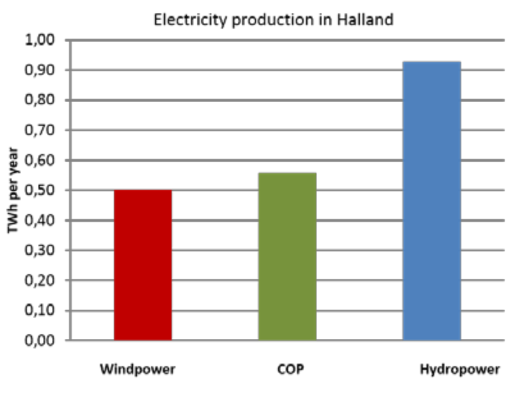
6.3 Development of the electricity market

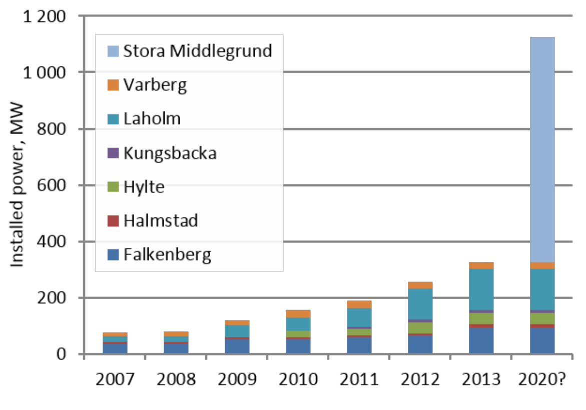
The production of electricity was 26.9 TWh in 2012, including the nuclear power in Ringhals. Ringhals is seen as a national source of energy and is not normally included in the electricity production of Halland. The production of electricity was 2.0 TWh in Halland in 2012, the nuclear power set apart, of which wind power stood for 25% and hydropower for 47%. Just short of one third of the power generated is from combined heat and power plants for district heating or the industry. Examples of producers of electricity are e.g. the pulp factory Södra Cells in Varberg's municipality, the paper factory of Stora Enso in Hylte and the heat plant of Kristinehed in Halmstad's municipality.

There are plenty of smaller hydropower plants in Halland. Statkraft and E.on own the largest hydropower plants, where the largest one is Karsefors in Laholm's municipality. The installed power in Karsefors is 31.4 MW and the production is 130 GWh per year normally. Other hydropower stakeholders are Halland' s Hydropower Association and Varberg Energy, (Ref 15, Ref 16).

Halland has good conditions for wind power and invested at an early stage. The total installed power is 327 MW and there were 220 wind turbines in the county in 2013. Laholm is the municipality with the largest amount of wind turbines, with 101, secondly comes Falkenberg with 61 wind turbines and an installed power of 93 MW (Ref 17).

The largest present wind power project in Halland is the sea based wind power park "Stora Middelgrund". It contains 110 wind turbines with a planned total installed power of 800 MW. The yearly production of electricity is approximated to 3 TWh. The project is yet to be started but have secured every needed permit to start building the park. Compared to todays installed power of 327 MW, this means a triple of the power to 1,127 MW. This size corresponds to one of the larger nuclear reactors in Ringhals.





Electricity production in Halland, excluding the nuclear power.

Installed wind power in Halland, 2007-2013 and an indication of the size of Stora Middelgrund.

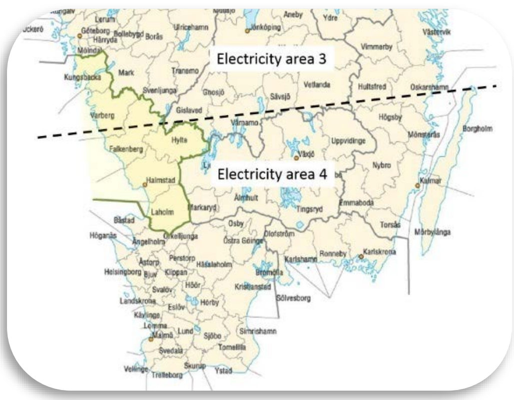
Figure 21 The total electricity use in Halland was 26.9 TWh in 2012, including the nuclear power plant Ringhals. Without the nuclear power the electricity usage was about 2 TWh. Source: SCB, The Swedish Energy Agency.

6.3.1 Limitations in the network?

Sweden is divided into 4 different electricity areas, and northern Halland is part of area number 3, whereas southern Halland, with Falkenberg, is part of area number 4. In this study, focus lies on Falkenberg, and therefore electricity area 4. Area 4 is a deficit area, where use of electricity is larger than the production. It is also the area with the lowest installed power in relation to its consumption. The total installed power in the area, available for production is 2,400 MW, and there is an extra back-up resource of 1,600 MW. The maximum power withdrawal in the area is 4,800 MW. Normally the electricity deficit is about 18 TWh (Ref 18).

The plans to expand the installed wind power at sea, sets high demands on the rest of the energy system, and the electrical network in particular. Apart from Stora Middelgrund, there are also plans to build large wind parks in the Baltic Sea, on “Södra Midsjöbanken” and in “Hanöbukten”. E.on runs the project on Södra Midsjöbanken and plans for an installed power of 2,100 MW. In Hanöbukten, Blekinge Offshore AB plans for 2,500 MW wind power. These three projects combined contribute with an installed wind power of 5,400 MW in electricity area 4, compared to the 1,400 MW of today (Ref 19).

In the figure 20, the wind power production per hour in electricity area 4 is demonstrated. In the background the consumption is shown, sorted from large to small consumption. The figure shows that already with today’s installed power, there are times when the produced wind electricity exceeds the consumption. Today, the surplus electricity is ”exported”, but if the planned sea-based wind power farms are materialized, a Power to gas storage solution might be needed, especially since a similar development is going on in Denmark and Germany.



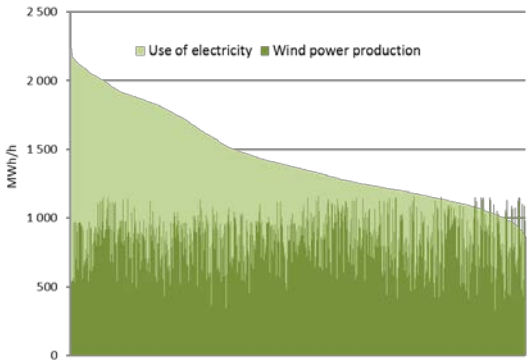


Figure 22 Falkenberg and southern Halland are situated in electricity area 4. This is a deficit area where electricity usage exceeds the production. The diagram on the right shows the wind power production per hour in 2013, relative to the electricity usage. Source: Svenska Kraftnät, www.svk.se

6.4 Development of the biogas market

Halland has a long tradition of using biogas. The first biogas facility was built in Laholm in the early 1990s as a reaction to the eutrophication in Laholmsbukten. Today, there are 13 different biogas production facilities in Halland.

The biogas production stands for 85 GWh per year (2011), which corresponds to 7% of Sweden's total biogas production. 50 GWh, or 60%, of the produced biogas in Halland is upgraded to vehicle gas and the rest is used for heat and electricity. The amount upgraded to vehicle gas is relatively high, compared to the rest of Sweden (44% in 2011 and 54% in 2012) and the reason for this is the possibility to use the natural gas pipeline (Ref 20).

There are 4 biogas plants in Falkenberg (2011):

Table 4 Current biogas facilities in Falkenberg 2011. Source: BioMil 2012.

NAME	OWNER	TYPE	USAGE GAS	PRODUCTION (GWh)
Carlsbergs industry facility	Falkenberg Vatten & Renhållning AB	Industry	Electricity/heat	5.2 GWh
Gödastorp	Falkenberg Biogas AB	Codigestion	The natural gas network	35 GWh (capacity 40 GWh)
Smedjeholm sewage treatment plant	Falkenberg Vatten & Renhållning AB	Sewage	Electricity/heat	4.0 GWh
Hede	Nils Toversson	Agriculture	Electricity/heat	2.1 GWh

The co-digestion plant in Gödastorp stands for 76% of the biogas production in Falkenberg. They produced 35 GWh in 2011, but have a yearly capacity of 40 GWh. The biogas is upgraded and fed into the natural gas distribution network. At times, the capacity of the natural gas network is a limiting factor for the biogas production.

In Laholm, there is also a co-digestion plant where the upgraded biogas is fed into the natural gas network. The plant produced around 13 GWh per year (2011), and the total capacity is 25 GWh per year.

There are plans for another 10 new biogas plants, mostly in Falkenberg and Halmstad. In Halmstad there are also plans to build a large co-digestion plant with a capacity of 45 GWh per year. Göteborg Energy and E.on gas Sverige are the stakeholders behind these plans (Ref 20).

The access to natural gas has facilitated the development of biogas in the region, by serving as back-up. It has also facilitated the introduction of biogas upgraded to vehicle fuel. There are 6 filling stations in Halland, out of which two are in Falkenberg (Ref 21). One of the stations in Falkenberg is connected to the local gas network. To the other one, which is in Ullared, the biogas is transported by truck from Gödastorp.

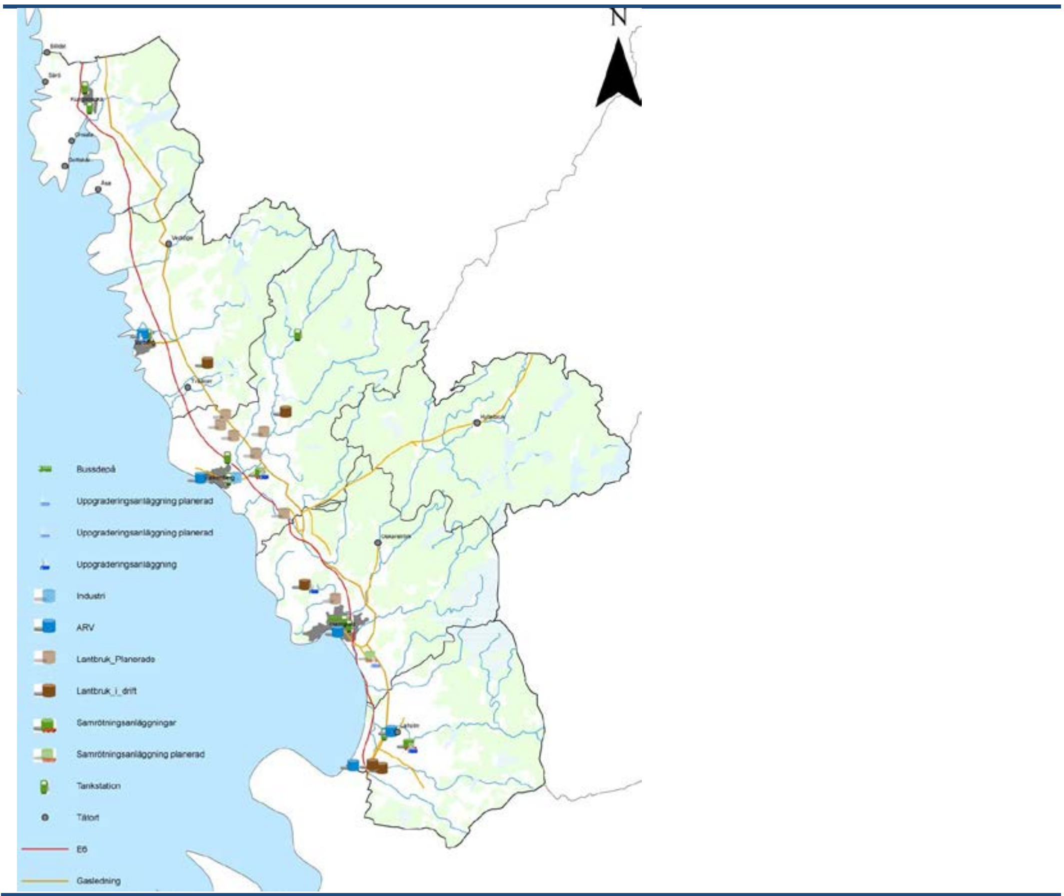


Figure 23 Biogas facilities in Halland 2013. Source: Input to regional biogas strategy in Halland's municipality, BioMil AB, Triventus 2012.

6.5 Access to carbon dioxide?

In Halland, no source of pure carbon dioxide has been identified. In the long run, some of the industries can start separating carbon dioxide from their flue gas, but there are no such plans today (2014). The available carbon dioxide for a Power to gas project in Falkenberg with surroundings is therefore mostly at the biogas plants.

6.6 Power to gas in Halland with focus on Falkenberg

There are three different main tracks identified as possible for a demonstrational plant for Power to gas in Sweden. They are described in chapter 4.

Halland is a region with many wind turbines and there are plans for expanding this industry, mostly off shore. Today there are no obvious technical limitations in the electrical grid preventing the establishment of more wind power in Halland, different from the situation on Gotland.

Falkenberg and the southern parts of Halland are in the electrical area number 4. That is from an energy perspective a deficit area, but it is also a region with a large percentages volatile and weather dependent energy, being close to Denmark and northern Germany. Both in Denmark and Germany, Power to gas is seen as a way to handle large amounts of wind power and solar energy through storage of the excess energy in the natural gas network. Halland has in that sense, similarities with Denmark.

The conditions in Falkenberg suits main track 1; with an electrolysis process for producing hydrogen, and the main track 2; which means an increased production of methane through adding hydrogen to a biogas process. These two alternatives are presented below.

6.6.1 The hydrogen idea

Main track 1 assumes that there is a direct deposition of hydrogen, in a hydrogen filling station, in an industrial process or that there is a natural gas infrastructure to add the hydrogen to. The hydrogen idea has thereby two possible outcomes in Falkenberg, feeding hydrogen to the natural gas network or distribution of hydrogen to a hydrogen filling station.

Figure 24 Falkenberg wants to build a filling station for hydrogen. The picture shows the South Korean Hyundai fuel cell car ix35 Fuel Cell. There are already 3 cars like this in Sweden, tested by Region Skåne, supplied with hydrogen from a hydrogen filling station in Malmö.

6.6.2 Filling station for hydrogen

Falkenberg Energy has far reached plans to build a hydrogen filling station along the highway E6. This project is part of a larger EU-project containing 29 filling stations in Europe, where the Swedish contribution is the filling station in Falkenberg. The application was submitted during November 2014, and it was approved in February 2015. According to the application, Falkenberg Energy will build a station with a production capacity of 150 kg hydrogen per day. Falkenberg Energy will also be in charge of the filling station i.e. buy hydrogen and run the filling station. No hydrogen supplier has been determined yet today. The project is considering buying an electrolysis device as well, but there needs to be a backup, like hydrogen transported to the filling station by trucks.

The project is foreseen to run for 5 years and initially 3 fuel cell cars will be purchased, but eventually there may be as many as 10 hydrogen driven cars in Falkenberg.

The Swedish Hydrogen Association has examined different alternatives for how to get hydrogen to the filling station. It can be brought in by trucks, produced on site through electrolysis processes, or produced by reforming natural gas or biogas, where the third option with reforming was omitted due to the high costs of the technical equipment. It is too expensive for this kind of small scale production facility. The board of the project has decided to start with delivering the gas to the station by trucks, and replace it with an electrolysis device as soon as possible (Ref 22).

The profitability of the station depends on the number of vehicles needing hydrogen and their driving range, i.e. the amount fuel sold. The cost of hydrogen, produced or purchased, price of pumps and how long the station is planned to be open are also factors affecting the profitability. The project is assumed to last for 5 years, and the average numbers of cars is assumed to be 6.4 during this period of time. In an EU financed project, the maximum price of hydrogen is limited to 100 SEK/kg hydrogen, equal to 1 SEK per kilometer. This set price is not high enough to make the project profitable (Ref 22).

If the European project with 24 stations is realized, this will mean an increase in hydrogen supply in Falkenberg which in turn can lead to a larger demand and a path to an electrolysis device. According to information from Falkenberg Energy (Ref 23) a filling station of 150 kg hydrogen per day will be built in 2015. A demonstrational plant for Power to gas could benefit from being bought at the same time and coordinated with the hydrogen filling station.

The dimensions of the electrolysis device is determined by the dimension of the hydrogen production. Initially, the demand for hydrogen is determined by the hydrogen need of 4 vehicles bought by the municipality, and by external clients.

The purpose of the hydrogen station is mainly for fuel gas and not to follow the variations of wind power production, and therefore a commercially available electrolysis device is to be chosen i.e. an alkaline device. It can be in operation during periods when the electricity price is low and when the production costs are lower than the price of purchased hydrogen. The hydrogen can be stored at the filling station between the operation times.

KTH has calculated on key figures for commercially electrolysis devices (Ref 5). An alkaline electrolysis device with an installed power of 630 kW_e produces 120 Nm^3 of hydrogen per hour, which is equivalent to 360 kWh/h. This is just short of 10 kg hydrogen per hour, which should be sufficient for the planned station.

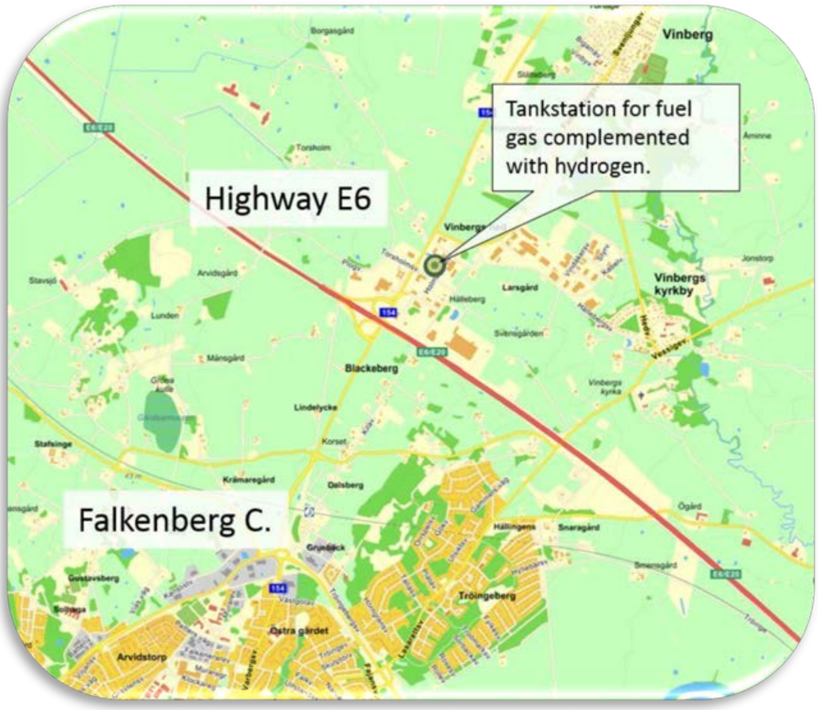


Figure 25 North east of the city center of Falkenberg, along E6, there is already a filling station for vehicle gas. The plan is to add hydrogen to it. Source: Falkenberg Energy.

6.6.3 Feeding the natural gas network

An alternative to building a hydrogen filling station is to feed the produced hydrogen to the natural gas network, either in the distribution or the transmission network. This could also be a complement to a filling station to ensure that any excess hydrogen that cannot be stored still comes to use.

The advantage of the possibility to feed in hydrogen in an existing gas infrastructure is that there is no need for an external intermediate storage, which normally is very costly, and that the production can cease when the electricity price is too high. Thereby the goal with Power to gas is achieved.

If the gas is to be used as vehicle fuel, the volume limit for input is 2%. Combustion processes in industries and power plants, can however handle higher levels of hydrogen. In a demonstration plant for Power to gas in Frankfurt, where the hydrogen is fed directly into the natural gas distribution network, they chose a level of 2%.

Biogas from "Falkenberg Biogas"' plant in Gödastorp is fed into the distributional network, which can affect the possibilities of also adding hydrogen. During the summer when the demand of gas decreases, the biogas production is limited by the demand and the capacity of the network. It might not be room for hydrogen then.

If feeding the distributional network with hydrogen is not possible an alternative might be to inject it into the transmission network instead. The necessary requirements of this solution needs however to be investigated.

6.6.4 The biogas idea

The biogas idea implies that the hydrogen is used to increase the methane exchange in a biogas process, see section 2.

There are four biogas plants in Falkenberg. The largest one is “Falkenberg Biogas” in Gödastorp. It produces 35 GWh upgraded bio-methane per year and all is feed to the local distributional network in Falkenberg. During the summer, when the demand for gas decreases, the production is sometimes limited. Feeding hydrogen to the process would in this case mean an increased production of bio-methane during the periods of low electricity prices. This often occurs during summer, when the reception capacity is limited. An alternative to increase the capacity is to investigate the possibility to feed bio-methane to the transmission network.

In the other facilities the raw biogas is used for heat and electricity production. Adding hydrogen to the process increases the percentages of methane in the biogas, which means more “green” carbon atoms are utilized and the energy density of the biogas increases. If a filling station for hydrogen is not an option, a suitable way of using the hydrogen is a Power to gas project to feed the hydrogen to a biogas production process.

6.7 Conclusions Falkenberg

Based on good wind conditions, Falkenberg and the Region of Halland have a long tradition of the development of wind power, and have also further plans for expansion. There are no immediate constraints in the electricity network for more wind. Besides, Falkenberg is located in a deficit area, where the demand for electricity is much higher than the production. The installed wind capacity in the “electricity area 4” is currently 1400 MW. If current plans for new offshore wind farms are materialized, it adds further 5400 MW wind power to the region. Similar investments are made in Denmark and Germany. In neighboring countries Power to gas is seen as a measure to deal with future excess wind power. As in Denmark and Germany, there is a natural gas infrastructure in Halland. The conditions are relatively equal, and similar solutions could be applied.

6.7.1 A Power to gas demonstration plant in Falkenberg

In the short run, the best conditions for Power to gas in Falkenberg is to build an electrolyzer in connection to the planned refueling station for hydrogen along the highway E6. Since the number of cars initially is few, and will be expanded over time, the capacity of the electrolyzer is oversized to begin with. Possible excess production of hydrogen can be injected to the natural gas grid.

In the longer run, hydrogen can be used to increase the methane content in biogas production, for example, the biogas plant in Gödastorp. However, this assumes that the gas can be fed into the transmission network for natural gas, since the capacity to receive gas in the distribution network is already limited.

6.7.2 Socio-economic benefits

In the short run, “the socio-economic” benefit is that the electrolyzer provides renewable hydrogen that otherwise would be purchased from external suppliers. It also contributes to a completely new component in the energy system, creating new opportunities for more renewable energy. The gas infrastructure makes it possible to reach a larger market for renewable gas.

Another important aspect is the development of a new area of technology which can contribute to a stronger labor market. Business in Halland is based on agriculture and food industry. By investing in new energy technologies needed in the energy system, it can also pave the way for new business opportunities.

6.7.3 Hydrogen or methane?

In Falkenberg, a demonstrational plant of Power to gas should primarily be used for, and focus on manufacturing hydrogen that can be utilized in fuel cell cars.

6.7.4 In what ways can Power to gas contribute to more renewable electricity?

In Falkenberg and Halland the electricity power grid is capable of handling an increased wind power as a whole, but local limitations in the electricity distribution network are likely. There are large-scale plans to extend the wind power system in Halland and Power to gas can facilitate these plans.

6.7.5 Dimensioning – how large is the facility supposed to be?

The electrolysis device in this context should be conventional and be based on well tested technology. A suitable size is 630 kW electricity, which has a capacity of 10 kg hydrogen per hour. Falkenberg Energy aim to build a filling station with a capacity of 150 kg hydrogen per day.

6.7.6 Timetable

The hydrogen filling station can be in operation during 2016, which means that an electrolyzer also can be in place by then. In the longer run, forward to 2025, there should be prerequisites for using hydrogen to increase biogas production and inject the biogas in the transmission grid for natural gas.

6.7.7 The way forward

The Power to gas concept includes several technology steps and different types of players. In the short term, it is not a commercially driven energy solution, but a demonstration plant for knowledge creation and development of technology. Therefore it should be a collaborative project with representatives of both public and private actors, such as Falkenberg Energy, E.ON, Swedegas and Falkenberg biogas.

7 Piteå in Norrbotten

Characteristics of Norrbotten's energy system are that there are considerable energy resources but the region is also highly energy intensive. A large proportion of heavy industries, a cold climate and vast distances that require a lot transports, result in both high energy consumption and high emissions of carbon dioxide.

The use of energy is about 30 TWh, and the electricity consumption amounted to 7.4 TWh in 2012. (Ref 16). The industry consisting mainly of mining, iron and steel, pulp and paper, account for 75% of the energy consumption in Norrbotten, which is a high share compared to the average on the national level, which is 40%. Household and transport accounts for about 9% each, the service sector accounts for 6% and the agricultural industries for 0.4%.

Norrbotten has a good potential for renewable energy, today in the form of hydropower and biomass from the forest, but there is also a great potential for wind power. Furthermore, there is a great potential for waste heat from industries that can be utilized as district heating.

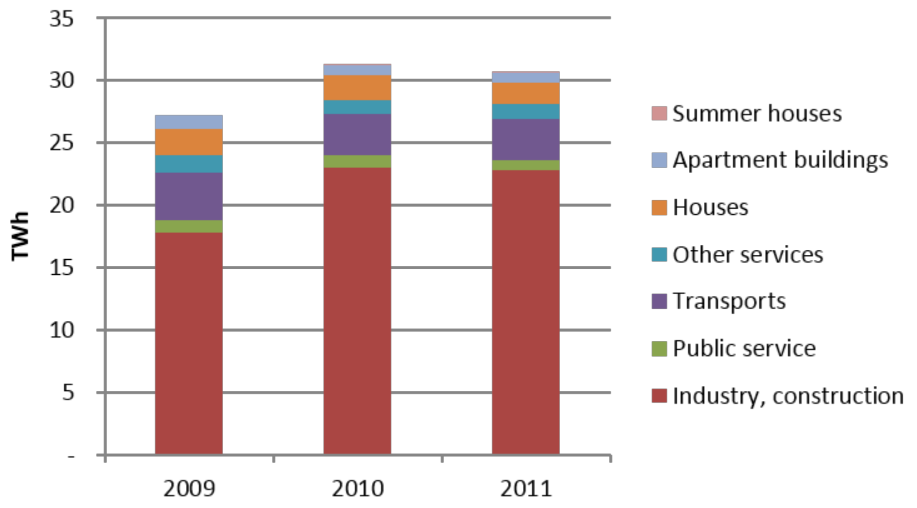


Figure 26 Energy consumption in Norrbotten. The heavy industry account for 75% of the energy consumption. Source: Statistics Sweden's statistical database. www.scb.se

7.1 Energy and climate goals

In order to reduce the impacts on climate change, the region[2] has chosen to focus on three areas for its energy system:

- Sustainable economic growth
- Sustainable transport
- Sustainable urban planning

Collaboration between local authorities, research bodies, basic industries and other businesses is required to achieve these goals.

Norrbotten will continue to develop renewable energy sources such as hydro, wind and bioenergy. Large scale wind farms are planned. Bioenergy initiatives will take advantage of the entire bioenergy range and increase the use of bioenergy.

[2] Länsstyrelsen?

Norrbotten is today a major net supplier of energy, primarily hydroelectric power. One goal is to increase electricity exports further by investment in co-generation and wind power (Ref 24).

Five of Norrbotten's 14 municipalities count for about 90% of the energy use in the region. Luleå and Piteå together account for about 60%, mainly due to heavy industry that is located in these municipalities.

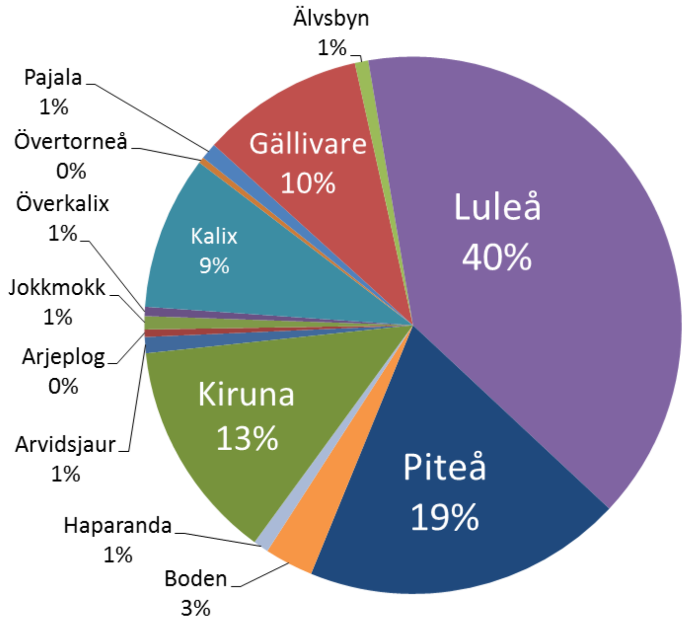


Figure 27 Energy use in Norrbotten per municipality. Luleå and Piteå account for 60% of energy use in the region. Source: Statistics Sweden's statistical database. www.scb.se

7.2 Investment in bio refineries in Norrbotten

In Norrbotten, there are several initiatives to take advantage of, and refine bioenergy resources from the forest through bio refinery techniques. There are three pulp mills and several sawmills in the region. On-going research and development projects are largely based on taking advantage of the sub-streams within the mills and develop methods to refine them to a higher energy value than of today.

There are strong research centers of relevance for the forest industry at Luleå University of Technology and SP Energy Technology Center (SP ETC) in Piteå. There are also several companies that develop new technologies supporting the forest industry to increase the production of non-traditional products.

The region has a value chain based clusters, with Piteå Science Park as coordinator, in order to accelerate the pace, and the commercialization of research.

An example is the Chemrec gasification technology and processing into bio-based fuels (black liquor gasification). In order to conduct applied research and development, Chemrec has established a test plant in Piteå, together with Luleå University of Technology, Energy Technology Centre in Piteå and others. The plant is now being run by LTU Green Fuels.

Another example is SunPine AB, that develops processing of pine oil into biodiesel (pine diesel), which Preem uses in its refinery to produce their "Evolution Diesel" (Ref 24).

SP Energy Technology Centre in Piteå (SP ETC)	*LTU Green Fuels*
SP ETC is a non-profit research organization focusing on thermo-chemical conversion of biomass. Services offered involve incineration, gasification and a bio-refinery. SP ETC is located next to the Smurfit Kappa in Piteå. SP ETC has many years of experience in biomass gasification coveringmany different techniques, such as fluidized beds, cyclones, fixed bed, and downstream gasification. Special attention should be given to SP ETC's work on gasification of black liquor, a by-product of pulp production in the world's only pressurized Chemrec carburetor. Black Liquor Gasification is a key technology for a pulp mill based bio-refinery. (Ref 25)	LTU Green Fuels operates, and is responsible for projects related to one of the world's most advanced pilot plants for gasification of different kinds of products to synthesis gas and green fuels.

7.3 Development of the electricity market

Sweden is divided into four electricity areas. Piteå and Luleå are situated in area 1, in the north. Area 1 covers the whole of Norrbotten County but also parts of Västerbotten County (see map below). Electricity consumption is highest in the cities of Luleå, Piteå, Kalix, Haparanda and Skellefteå. It is also high in Kiruna, where much of the mining industry is located. A large proportion of heavy, electricity-intensive industries results in a fairly even electricity consumption throughout the year.

Electricity production in the area is mainly from hydroelectric power. The main hydropower plants are located in the Lule River and in Skellefteå River. The installed capacity of hydropower is 5,300 MW and in a normal year production amounts to 18 TWh. Installed capacity of wind power is 200 MW (2011) and in co-generation plants, including industrial back-pressure, 300 MW.

Norrland produces substantially more electricity than what is used. In a normal year, approximately 10 TWh of electricity is transmitted to southern Sweden. Transmission is via four 400 kV lines with a maximum transmission capacity of 3,300 MW (2013). There are also power exchanges with Norway and Finland through four alternating current connections (Ref 18).

Hydropower production is expected to increase by 1-3 TWh in the future due to increased rainfall as a consequence of climate change. Electricity consumption, however, is expected to decrease. This will lead to an even greater surplus in the region (Ref 26).

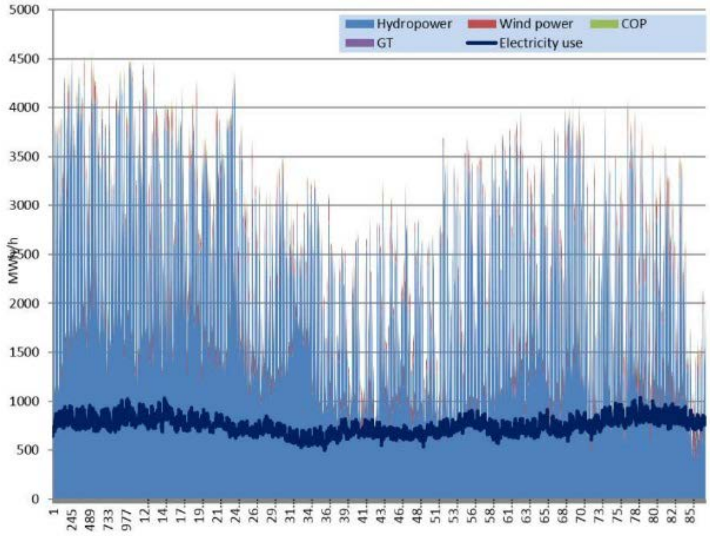


Figure 28 **Left:** Sweden is divided into four price areas. Norrbotten County covers largely price range 1. Source: Swedish National Network; Edited by ÅF. www.svk.se. **Right:** Sweden is divided into four bidding areas. Piteå is located in the electricity area 1 (SE1 or EO1), in northern Sweden. EO1 is a net producer of electricity. Electricity use in EO1 is shown in the dark curve. Source: hourly values for 2013, Swedish electricity networks; www.svk.se.

7.4 Interest in wind power in northern Sweden

There are 151 wind power plants in operation at 11 different sites in Norrbotten. There is a considerable interest to expand the wind power further.

One of the largest wind power projects is Markbygden outside Piteå. The entire establishment includes 1,100 wind turbines, with a maximum overall height of 200 m and within an area of 450 km^2. The implementation process will take about ten years. The total installed power is estimated to become between 2,500-4,000 MW. The project's first phase includes 314 wind turbines with an installed capacity of about 1,000 MW. The annual electricity production from the first phase is estimated to be about 2.8 TWh.

A total of 15-20 TWh of wind power is planned in the region, out of which investment in Markbygden caters for 8-12 TWh (Ref 24).

The southbound transfer capacity must be strengthened in order to realize the wind energy projects, since Norrbotten is already a net electricity producer. A challenge in this context is that the lead times for obtaining permits for new power lines is significantly longer than the lead times for the construction and commissioning of the wind turbines. Swedish Kraftnät is currently investigating the possibilities for increasing the capacity between northern and southern Sweden with an additional cable, in the order of 400 kV (Ref 18).

Investments in transmission capacity is further required both within the region and to surrounding regions. Moreover, investments in new production capacity in Norway and Finland also contributes to the increased need for transmission capacity from northern Sweden and southward.

Figure 1 Markbygden Vind AB has applied for permission to construct and operate 1,100 wind turbines in Markbygden, in the western parts of Piteå. The map shows phase 1, which comprises of 314 wind turbines with a total output of about 2.8 TWh per year. Source: Svevind.se November 2014.

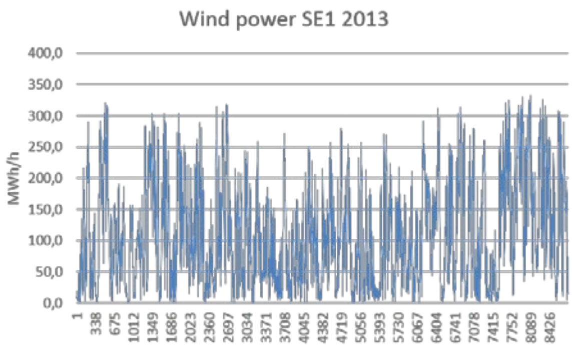


Figure 2 Wind Power Production per hour in electricity area 1, 2013. Source: hour values for electricity area 1, 2013, Svenska Kraftnät; www.svk.se.

Figure 29 **Left:** Markbygden Vind AB has applied for permission to construct and operate 1,100 wind turbines in Markbygden, in the western parts of Piteå. The map shows phase 1, which comprises of 314 wind turbines with a total output of about 2.8 TWh per year. Source: Svevind.se 2014. **Right:** Wind Power Production per hour in electricity area 1, 2013. Source: hour values for electricity area 1, 2013, Svenska Kraftnät; www.svk.se.

7.5 The gas market

There is no infrastructure for natural gas or other energy gases in Norrbotten. Several possibilities of establishing terminals for receiving liquefied natural gas (LNG) in the ports of Luleå, Piteå or Tornio in Finland have been investigated in order to gain access to natural gas. Natural gas is demanded by both LKAB and SSAB. The gas can replace coal and thereby contribute to reducing carbon emissions. Natural gas is also needed as a back-up in the establishment of a biogas infrastructure.

7.5.1 Development of the biogas market

A total of more than 30 GWh biogas per year is produced in Norrbotten, out of which about 22 GWh in Luleå and 5 GWh in Piteå. Another 25 GWh per year is planned for in Piteå. Behind the investment stands Piteå Biogas AB.

There is one filling station for biogas in Norrbotten, located in Boden. LNG (liquefied natural gas) is transported by truck from Norway and used as a back-up for biogas. Moreover, discussions to open filling stations for biogas in Luleå and Piteå are ongoing. There are also advanced plans for a filling station in Umeå, which can facilitate the development of biogas as vehicle fuel along the northern coast. (Ref 27)

Table 5 Daily production of biogas in Piteå, Luleå and Boden. Source: The future of renewable energy gases in the Both-nia region. Umeå University, 2014.

KOMMUN	ÄGARE	TYP	PRODUKTION 2012 (GWh)
Luleå	Luleå municipality	Sewage treatment	8.6
Luleå	Luleå municipality	Landfill	5.8
Luleå	Alviksgården	Agriculture	7.8
Piteå	Pireva	Sewage treatment	3.0
Piteå	Pireva	Landfill	1.6
Boden	Boden municipality	Landfill	0.2
Boden	Boden municipality	Codigestion	2.9
Kalix	Kalix municipality	Landfill	0.2
Haparanda	Bottenviken's purification plant	Sewage treatment	1.1
In total, Norrbotten			31.2

7.5.2 Luleå invests in fuel gas

Luleå has a facility for the production of biogas at the Uddebo sewage treatment plant. In total, about 150 Nm^3 biogas per hour is produced. So far, the gas is used for heating the Uddebo facility and excess gas is flared away.

Luleå Municipality has decided that the biogas should be upgraded to vehicle fuel gas to be used in the municipality's own vehicles and buses. The project was planned for completion in the autumn 2014. Initially, the biogas should be used in the 260 municipal vehicles and the 12 Luleå Lokaltrafik city buses. Instead of flaring away excess gas, electricity and heat could be produced in the plant (Ref 28).

7.5.3 Alviksgården outside Luleå

Alviksgården is located in Norrbotten, outside Luleå. Since 1975, there is a livestock production of 16 000 slaughter pigs here. The bulk of the feedstuff is grown on the farm. Previously, residual waste from the farm was sold to a company for disposal. It was an expensive solution. Therefore, they have instead chosen to build a biogas plant that could treat both pig manure and slaughterhouse waste. The plant was commissioned in 2000, and was then Sweden's first large-scale biogas plant.

The biogas plant consists of two reactors with a total volume of 2,300 m^3. The reactors digest 50 tons of pig manure and 5 tons of slaughterhouse waste per day. Slaughterhouse waste is also received from surrounding slaughterhouses. The manure is pumped directly into the reactors, while the slaughterhouse waste is first pulverized in a mill before it is pumped into the reactor. The process is a fully mixed one-step process and takes place at about 55°C.

The facility generates approximately 9,600 MWh of biogas per year. The gas is purified from sulphur and water vapor and is used for heating water. The hot water goes to a 60 m^3 storage filling that supplies the entire farm with hot water. The rest of the biogas is utilized for the production of electricity using a 16-cylinder, 35-liter gas engine generating 4,300 MWh of electricity per year. The electricity is sold to Luleå energy, of which about 60% are bought back to the farm's own use (Ref 29).

7.5.4 Biogas in Boden

Boden has a plant for the production of vehicle fuel at the Svedjan sewage treatment plant. The plant was commissioned in 2003, and was upgraded with a complementary plant in 2007. Vehicle fuel gas is used in 90 of the municipal vehicles, 10 local buses, 3 waste collection vehicles and nearly 100 private cars. With 11 SEK/Nm^3, Boden has Sweden's lowest price of biogas for vehicles. It equals a petrol price of 10 SEK/l. In order to ensure availability, the plant used liquefied natural gas (LNG) from Norway as back-up. (Boden Municipality 2015)

7.5.5 Piteå Biogas AB

Piteå Biogas is a private company formed by 17 agricultural enterprises seeking to establish a biogas plant in Piteå municipality for the production of biogas and manure. The biogas plant will treat organic material in the form of slurry and other digestible substrate from some twenty farms in Piteå municipality. The goal is to produce 25 GWh and 80,000 tons of manure.

The biogas will be upgraded and used as vehicle fuel gas. Investments in the production facilities will amount to about 50 million SEK, including the upgrading.

Figure 30 Piteå Biogas is planning a plant for the production of 25 GWh per year. Source: Piteå Biogas AB.

7.6 Power to gas in Piteå

As shown in the previous section, there are three main tracks identified for Power to gas. In Piteå and its vicinity, there are prerequisites for all three options. There are outlets for hydrogen, there are biogas plants that theoretically can be upgraded by an extra supply of hydrogen gas and there is also heavy industry, mainly SSAB in Luleå, which could separate a pure carbon dioxide stream for the production of synthetic methane.

Norrbotten is an electricity surplus area. There are large reserves of hydroelectric power that can control the wind power, but overall it can also periodically lead to reduced electricity prices. A large-scale expansion of wind power in northern Sweden, and possibly also in northern Norway and Finland, increases the likelihood of periods of lower electricity prices as well as periods with insufficient transfer capacity of the regional power network. The Power to gas concept can relieve the network, while contributing to the increased use of renewable fuels.

There are prosperous opportunities to build a demonstration plant for Power to gas in Piteå. The heavy process industry, combined with Luleå University of Technology has substantially contributed to the development of research in the energy field. This means that there is already a lot of expertise and structures in place in the region to pursue this type of project. Much of the knowledge is concentrated in SP Energy Technology Centre and LTU Green Fuels in Piteå.

At the workshop, it emerged that a pilot plant can be suitable to be built at SP ETC's plant in Piteå, while a large-scale plant can be connected to SSAB's site in Luleå.

CBG filling stations are under development and there is an investment in biogas/CNG in the region. Therefore, there are many motives for developing a Power to gas solution that contributes to an increased supply of methane. There are also arguments to stop at hydrogen and to use it to increase the production of methanol or DME in Luleå Green Fuels plant in Piteå.

A demonstration project that is based on a catalytic methanation of hydrogen and carbon dioxide is in itself an expensive and complicated solution. There are no incentives to increase production further since there is already a large surplus of various more or less energetic process gases within the SSAB area in Luleå. Main track 3 is therefore not an option in Norrbotten in the short term.

Hydrogen could however be used to increase the methane content in the biogas process, and thus reduce any subsequent processing steps. At the work shop held in Piteå, it was revealed that there is no immediate need for that option. However, there is considerable interest in installing an electrolyzer at SP ETC's pilot plant in Piteå.

7.6.1 Hydrogen for an efficient production of methanol and DME

At the work-shop in Piteå on November 25, 2014, it was concluded that the best location for a demonstration plant for Power to gas, or rather power to liquids, is at the LTU Green Fuel demonstration plant in Piteå.

In the gasification plant, syngas is produced by gasification of liquid biomass (black liquor or pyrolysis oil) or solid biomass (wood powder). The syngas is purified and upgraded in order to be used for the production of methanol or dimethyl ether (DME), which is a liquid fuel. The syngas consists of carbon monoxide (CO) and hydrogen (H2).

In order to obtain an optimal ratio of H2/CO of the syngas, with respect to the downstream synthesis steps into methanol/DME, a so called water gas shift reactor is included in the process. Water vapor is added into this reactor, which converts parts of the carbon monoxide to carbon dioxide ($CO + H_2O \leftrightarrow CO_2 + H_2$). The aim is to increase the content of hydrogen. The carbon dioxide formed is separated from the synthesis gas. The process involves a loss of energy, partly because the process is exothermic, i.e. releases heat, partly because carbon is removed by separation of the carbon dioxide. Since the purpose of the whole gasification plant is to produce renewable fuels, every "green" carbon atom that is removed from the process is considered a loss. If the hydrogen can be supplied to the synthesis gas from an external source, the need for a water shift reactor would decrease.

A “Power to gas/liquids” application in Piteå could therefore be to supplement the gasification plant with an electrolyzer that produces hydrogen when there is a surplus of electricity in the region. During spring runoff, autumn rain, or when wind power is developed, there may be production peaks that could otherwise not be utilized.

According to estimates presented by Professor Richard Gebart at the meeting (Ref 30), the efficiency of the process could increase by 50%, calculated on the energy content in the produced product, compared to the input of biomass.

Since the conditions for Power to gas varies with electricity generation and electricity price, the electrolyzer cannot generate hydrogen continuously. Therefore the water shift reactor must run in conjunction with the electrolyzer. By complementing with an electrolyzer, no electricity would have to be lost, but instead used to generate a green fuel by increasing the efficiency of an existing process.

What speaks for the localization at LTU Green Fuels, is that there is an established research and demonstration facility with access to the knowledge and skills, as well as the infrastructure necessary to manage a Power to gas solution. The investment will therefore be lower than if it had been a totally new investment.

7.6.2 Constructing a large-scale plant at SSAB in Luleå

Another option is to place the entire plant on SSAB's site in Luleå. SSAB has ample surplus of blast furnace gas, containing carbon dioxide and carbon monoxide.

The blast furnace gas at SSAB could be used for the production of synthesis gas, in the same way as in the case of LTU Green Fuels. It could become a large-scale facility. Here, however, major investments would be required in addition to the electrolyzer, in the form of a water shift reactor in a much bigger size than in Piteå, and other necessary equipment.

The advantage is that it could become a large-scale facility. The disadvantage is that it requires larger investments. In addition, the gas is of fossil origin and the fuel that is produced cannot be considered renewable. The blast furnace gas is today used for production of electricity and district heating in Luleå Kraft AB.

SSAB's plant in Luleå - potential source of carbon and location of catalytic methanation.
Steel iron ore is manufactured in SSAB's plant in Luleå. The process is very energy intensive and is based on fossil energy. Residual gases contain carbon dioxide, carbon monoxide and hydrogen. The residual gases are used for production of electricity and heat by Luleå Kraft AB.

The process:
The iron ore is converted into crude iron in a blast furnace using coke. The coke in turn is made through pyrolysis of coal. Both processes generate gases containing carbon and hydrogen. Blast furnace gas is formed through the reduction of iron ore (consisting of about 20% carbon monoxide, 24% carbon dioxide, 3% hydrogen and nitrogen balance (53% N2). Coke gas consists of 66% hydrogen (H2) and 21% methane (CH4). The carbon content of the iron is lowered in an LD converter with oxygen. The gas from the LD converter contains 58% carbon monoxide, 20% carbon dioxide and 18% nitrogen.

Figure 31 SSAB´s industry site in Luleå.

7.6.3 Increased biogas production in Alviksgården

In Piteå biogas is produced at Alviksgården. The gas is not upgraded, but used for electricity and heat generation on the farm. Since the gas is important for the overall economy of the plant, it is interesting to review the prospects for increasing the yield of methane and to be able to produce vehicle fuel gas (Ref 30).

A Power to gas plant in Piteå could induce the hydrogen directly in the digestion process to increase the yield of methane from the process. The existing facility at Alviksgården would be most appropriate for this.

7.7 Conclusions Piteå

There is a large oversupply of electricity in Norrbotten, compared to the consumption. The production is primarily based on hydropower. There is also a great potential for wind power, and several plans for new large wind farms, for example Markbygden outside of Piteå.

Today, there are no restrictions in the electricity network for the expansion of wind power, but at a large-scale deployment, the transfer capacity southward must be strengthened.

There is great expertise in research and development of biofuels in the region, and hence a unique expertise and structure to operate this type of project. To take advantage of this, a demonstration plant for Power to gas should be located adjacent to the existing facilities at SP ETC and LTU Green Fuels. Since they focus is on producing liquid fuels, it will be a demonstration plant for “power to liquids”. But there is still a need for production of hydrogen by an electrolyzer, which is used for the production of DME or methanol.

7.7.1 A Power to gas or liquids demonstration plant in Piteå.

A demonstration plant for Power to gas in Piteå is preferably installed in connection to the LTU Green Fuels plant, for the production of hydrogen, i.e. an electrolyzer. The electrolyzer is operated in parallel to the water shift reactor, which will decrease the loss of “green molecules” by the production of syngas, which in turn is used to produce liquid fuels.

In the longer run, a Power to gas plant could be located in connection to SSAB´s facility in Luleå, with the reservation that SSAB has not participated in this study and hence not given their opinion in the matter.

7.7.2 Socio-economic benefits

The socio-economic (environmental) benefit is that more green carbon atoms can be utilized in the gasification of biomass. If it would be profitable to replace the water shift reactor with an electrolyzer, the utilization of green atoms would increase with 50%, in the production of renewable fuels by gasification of biomass.

7.7.3 Hydrogen or methane?

In the Piteå case, it is interesting to regard a supply of hydrogen gas which can be linked with a water shift reactor. The synthesis gas produced is further processed into liquid fuels, i.e. methanol or DME.

7.7.4 How does Power to gas contribute to more renewable electricity?

There is a lot of renewable electricity in Norrbotten, but still, a Power to gas facility could in the long run relieve electricity transmission constraints and create conditions for more wind power. A demonstration plant is of marginal or no importance for the possibility to increase wind power capacity in the region, in a short time perspective.

7.7.5 Dimensioning – how big should the facility be?

In Piteå at SP ETC and LTU Green Fuels, there are demonstrations of new energy technologies in place today and an established knowledge and expertise to pursue this type of project. It would therefore be possible to test a PEM electrolyzer and regularize it with respect to variations in wind power production or electricity price variations.

PEM electrolyzers are available commercially in the order of 50 MW_e. It is probably possible to install a larger facility if necessary, or to combine several small units.

7.7.6 Timetable

An electrolyzer could be in place during 2016, depending on decisions regarding the total development and possible financing of the research in energy centers in Piteå.

The idea of a long term project in co-operation with SSAB has not yet been discussed, and it is hence not possible to give a preliminary time schedule for it.

7.7.7 The way forward..

The Power to gas concept includes several technology steps and different types of players. In the short term, it is not a commercially driven energy solution, but a demonstration plant for knowledge creation and development of technology.Therefore it should be a collaborative project with representatives of both public and private actors, such as LTU Green Fuels, SP ETC, Luleå Technical University and Piteå Science Park.

8 Conclusions

The task has been to identify a suitable location for a demonstration plant for Power to gas in Sweden, and three municipalities have participated; Gotland, Falkenberg and Piteå. They have many similarities regarding expansion of wind power and biogas, but their energy systems differ in infrastructure and energy balances.

Within the study, three main tracks for Power to gas have been identified: 1) An electrolyzer solely for hydrogen production; 2) An electrolyzer in combination with biologic methanation in a biogas plant; 3) An electrolyzer in combination with a Sabatier reactor for catalytic thermal methanation.

The different tracks have been discussed from the view of different prerequisites in each city. Since the conditions differ, and different solutions are suitable for each city, the study can´t give a clear answer to where a demonstration plant for Power to gas should be located. It is a matter of the engagement of local actors, and if they can persuade involved organizations, The Swedish Energy Agency and EU to finance the project.

Summary and conclusions for each city are given below.

1.1 Gotland

Gotland aims at being self-sufficient in renewable and recycled energy by 2025. The goal is to be achieved by export of locally produced wind power balancing the residual use of fossil energy. To succeed, the locally generated electricity has to be twice as large as the total electricity consumption. This means that today's wind power production must increase from 0.4 TWh to 1.8 TWh, which is a great challenge for the electrical power system. The production of renewable fuels must also increase to achieve the target.

A demonstration plant for Power to gas on Gotland should follow the main track 2, i.e. to place an electrolyzer adjacent to Brogas biogas plant in Visby. It may, according to estimates from the Royal Institute of Technology (KTH) increase the supply of methane from 2.2 to 2.4 million Nm^3/ year, i.e. by about 10%. The electrolyzer should have a conventional design i.e. an alkaline electrolyzer, and have an installed capacity of 2 MW_e. The demonstration plant could be in place in 2016, according to Region Gotland.

In a long term perspective, by 2025, a plant according to the main track 3 can be located in Slite adjacent to the Cementa factory. That requires both technical development for the electrolyzers and installation of carbon capture at the Cementa factory. The parent company of Cementa, Heidelberg Cement, conducts research and development in the area, and Cementa welcomes the opportunity to develop the concept in Slite.

In a short term perspective, a demonstration plant doesn´t contribute to more wind power. Gotland is an island and the challenges are greater than on the mainland at a large-scale expansion of wind power. Power to gas can thereby facilitate an increased wind power capacity since Power to gas can use excess electricity in the power system.

The project should be managed as a collaborative project with the key players Region Gotland, Gotlands Energy (GEAB), Cementa, Biogas Gotland and Uppsala University Campus Gotland.

1.2 Falkenberg in Halland

Falkenberg has access to natural gas infrastructure, unlike Gotland and Piteå. It has paved the way for biogas as vehicle fuel. Halland has great potential for wind power and the municipalities in the region were early to invest in the technology. There are no immediate constrains in transmission capacity for a continued expansion of wind power. Southern Sweden is additionally a deficit area of electricity, so more production capacity may be needed.

Halland has many similarities with Denmark and Germany, with regard to investment in wind power and access to an infrastructure for natural gas. In the neighboring countries Power to gas is seen as a solution for developing wind power, and to gain more renewable fuels at the same time. Falkenberg is facing the same challenges.

In the short term, the best alternative for a Power to gas demonstration plant is to install an electrolyzer in connection with a planned hydrogen filling station along the European road E6 i.e. to follow the main track 1. Initially, the capacity of the electrolyzer will be too large, since the number of hydrogen cars are intended to increase over time. In that case, possible surpluses of hydrogen can be fed into the natural gas network, to a volume at a maximum of 2%. A suitable size of the electrolyzer is 630 kW, which corresponds to a production of 10 kg H_2/h. The electrolyzer delivers the produced hydrogen the storage at the filling station. Falkenberg intends to build a filling station with a capacity of 150 kg H_2/day. It is expected to be commissioned in 2016.

In the short run, the socio-economic benefit is that the electrolyzer provides renewable hydrogen that otherwise would be purchased from external suppliers. It also contributes to a completely new component in the energy system, creating new opportunities for more renewable energy.

Another important aspect is the development of a new area of technology which can contribute to a stronger labor market. By investing in new energy technologies needed in the energy system, it can also pave the way for new business opportunities.

The project should be managed as a collaborative project with the key players Falkenberg Energy, E.on, Swedegas and Falkenberg Biogas.

1.3 Piteå in Norrbotten

There is a large oversupply of electricity in Norrbotten, compared to the consumption. The production is primarily based on hydropower, but there is also a great potential for wind power. Today, there are no restrictions in the electricity network for the expansion of wind power, but at a large-scale deployment, the transfer capacity southward must be strengthened.

There is great expertise in research and development of biofuels in the region, and hence a unique expertise and structure to operate this type of project. To take advantage of this, a demonstration plant for Power to gas is suggested to be located adjacent to the existing facilities at SP ETC and LTU Green Fuels. Since their focus is on producing liquid fuels, it will be a demonstration plant for “power to liquids”. This technique also requires hydrogen, why a Power to gas facility is still needed.

Since it is a research facility with great competence in place, a Polymer Electrolyte Membrane/Proton Exchange Membrane (PEM) electrolyzer can be selected. It can handle a more dynamic operation, but is still under development. The electrolyzer could be in place by 2016.

In the long term, a similar facility could be built on a larger scale at SSAB in Luleå. SSAB has not participated in this study, so whether there is any interest in this we do not know.

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LOCATIONAL STUDY — POWER TO GAS

Power to gas innebär att el kan lagras och även distribueras i form av vätgas eller metan under perioder med låga elpriser. Intresset för tekniken växer och runtom Europa byggs anläggningar för tekniken. Den här rapporten beskriver förutsättningarna för och nyttan av Power to Gas i en svensk kontext med fokus på att analysera bästa lokalisering för en första svensk demonstrationsanläggning.