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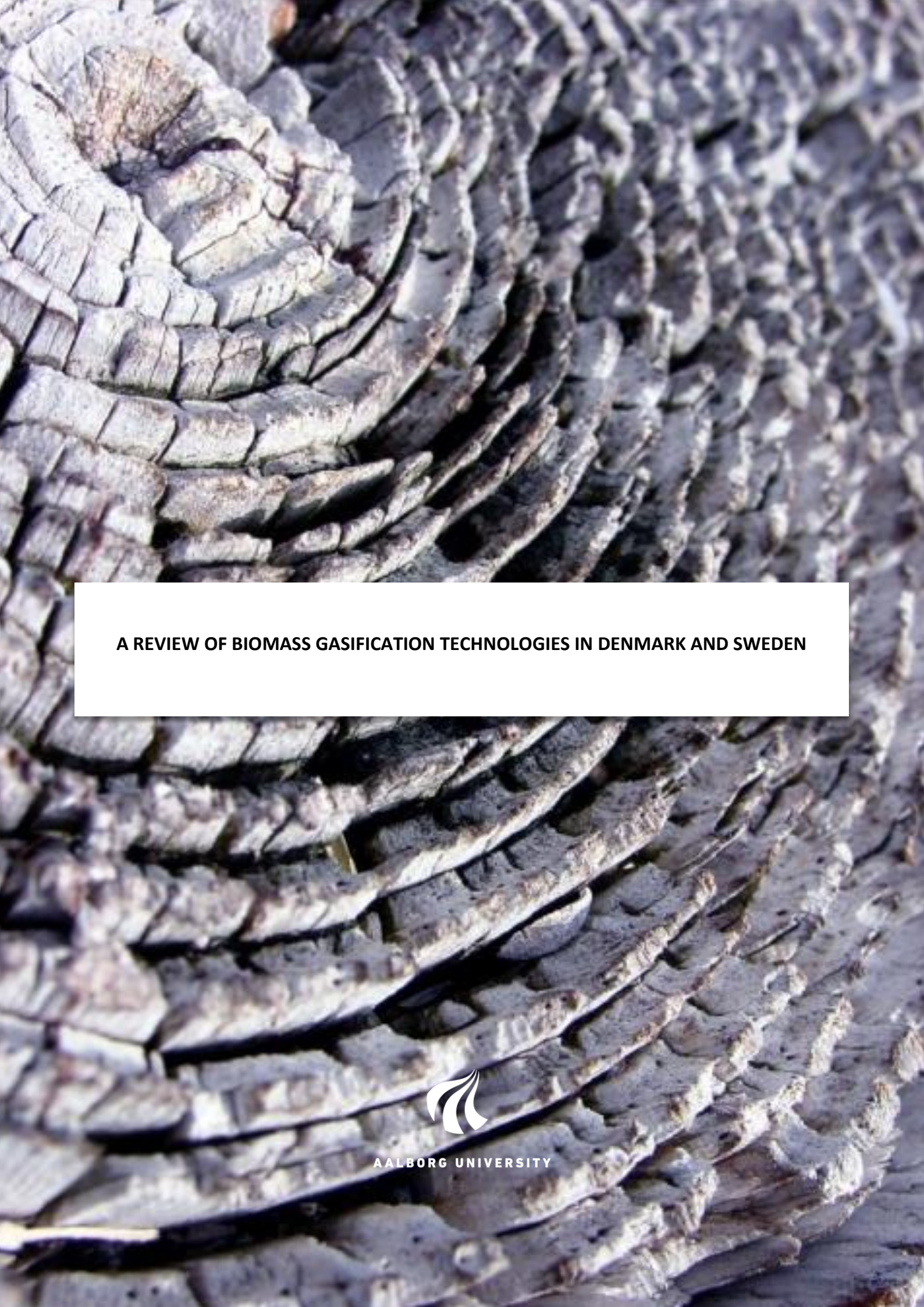

A REVIEW OF BIOMASS GASIFICATION TECHNOLOGIES IN DENMARK AND SWEDEN

AALBORG UNIVERSITY

A review of biomass gasification technologies in Denmark and Sweden

November, 2013

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Abstract

This report provides an overview of existing technologies and projects in Denmark and Sweden with a focus on the Öresund region. Furthermore it presents the research and development of biomass gasification in the region and these two countries. The list of existing gasification plants from laboratory scale projects to big scale plants is given. The report ends with an overview of future gasification projects as well as potential experience exchanges that could occur between the countries.

We regard biomass gasification as one of the key technologies in future renewable energy systems.

This report is prepared as a part of Energi Øresund project

ENERGIÖRESUND

EUROPEISKA UNIONEN
Europeiska regionala utvecklingsfonden

Interreg IVA
ÖRESUND – KATTEGAT – SKAGERRAK

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NOMENCLATURE

Abbreviation	Meaning
BFB	Bubbling fluidized bed
BTL	Biomass to liquid
CCG	Closed coupled gasification
CFB-boiler	Circulating fluidized bed boiler
CFB gasifier	Circulating fluidized bed gasifier
CHEC	Centre for Harmful Emission Control
CHP	Combined heat and power
CIGB	Centre for Indirect Gasification of Biomass
DFB	Dual fluidized bed gasifier
DGC	Danish Gas Technology Centre
DME	Dimethyl ether
DTU	Danish Technical University
DTI	Danish Technological Institute
EGD	E.ON Gasification development
ETC	Energy Technology Centre
EUDP	Energiteknologisk Udviklings- og Demonstrationsprogram *(English: Energy Technology Development and Demonstration Program)*
FBB	Fluidized bubbling bed
HTW gasifier	High Temperature Winkler
IGCC	Integrated gasification combined cycle
LTH	Lund University
VIPP	Vortex Intensive Power Process

1. Introduction

Before the industrial revolution biomass was extensively used as one of the prime energy source. However as the industrial age started the switch from biomass to coal and other fossil fuels occurred. Nowadays, when the sustainability issues are raised along with the climate change and declining abundance of fossil fuel reserves, biomass is gaining more and more attention as an alternative energy source. It is pushed from the policy sides and governmental supports as a clean renewable supplement for fossil fuels with the advantage of not intermittent character as some of the other renewable solutions.

There are many ways to utilize biomass as an energy source so many effort is put to develop different efficient technologies. Biomass gasification is one of the thermal biomass conversion processes. It can be used for producing power and heat or for the production of different fuels with higher energy content than biomass. It can provide gaseous and liquid form of fuel that can be used as a substitute for oil derivatives. Biomass gasification is an emerging commercial technology evolving out of intensive research and development in the 1970's and 1980's, although its developmental roots go back 180 years ago. Despite the fact that there are plenty of gasifiers around the world, most of them are coal fired while the biomass gasification systems from small to large are commercially available only in last 5 years. However a few countries have embraced the demonstration and commercial biomass gasification plants for heat and power generation, here we focus on Denmark and Sweden. Nonetheless, the first commercial plant for transport fuel production is still not established.

The biomass gasification as one of the key technology to fulfil the goal of sustainable renewable energy systems in the future can increase the needed flexibility in the system that is driven by intermittent energy sources such as wind and solar. This is due to the flexibility that this system could offer regarding the production and short start-up time. Biomass gasification can be used as a platform to produce different products that can be used for power production, fuel production or combined production of these three. Produced gas can be stored in the gas network and help balancing the system. As the today's transport infrastructure is completely relied on heavy fossil fuels, biomass can in future be a hydrocarbon building block in the transport sector for different fuels which can be produced through biomass gasification. However to reach this goal and to guarantee the success of the technology there is a need for investments in research and development so the technology can be commercially viable.

Biomass gasification is a very efficient technology with potential efficiencies of more than 90%. While gasification can utilise dry biomass, the production of biogas favours wet biomass. If biomass gasification and biogas production are paired together after the manure treatment in the biogas plant, then the fibre fraction from the biomass residues can be used in the thermal gasification to avoid the production of ash.

This report begins with an overview of existing technologies and projects in Denmark and Sweden with a focus on the Öresund region, followed by research and development of biomass gasification in the region. The next section presents existing gasification plants from laboratory scale projects to big scale plants. The report will end with an overview of future projects in the region as well as potential experience exchanges that could occur between the countries.

Only projects relating to the development of biomass gasification and existing or future plants are included in the report, meaning that the development of gas cleaning technologies, biomass treatment and some other issues relating to biomass gasification are not part of this report.

2. Gasification in the Öresund region

The region of Öresund is very dynamic and developed region that connects south-eastern Denmark with southernmost part of Sweden. It is a very unique region because it unites two different countries with different legislations, national systems and regulation. Moreover it is a densely populated area consisting of the capital city of Denmark and the third largest Swedish city Malmö. From 2000, the Danish and Swedish part of the Öresund region are connected with the Öresund bridge, which enabled an excellent public transport network and made the region very well connected. The region is also the busiest heavy duty transport area in Scandinavia which calls for alternative transportation fuel to avoid the CO_2 emissions caused by fossil fuel in the transport sector.

In 2010 the region Committee has made the Öresund Regional Development Strategy - ÖRUS [1] which established the goals for 2020. One of the goals is to become a centre for clean-tech solutions and sustainable urban development. There are plenty of development projects that are carried out in the region of which three are directly connected with sustainable urban development and smart cities: Energi Öresund, Urban Transition Öresund and Öresund Smart Cities Hub. The Öresund region strives to become the first carbon neutral region in Europe which makes solid grounds for biomass gasification projects.

Therefore it is very interesting to observe both countries and their development of the same technology and potential collaborations in the future to establish biomass gasification for fuel production and heat and power. Denmark and Sweden are both countries with demonstration and commercial plants for biomass gasification while Sweden is a leader in the biomass gasification to fuel plants. An overview of the gasification technologies in Denmark and Sweden is presented in the IEA Bioenergy Task 33 [2], where it is possible to search through thermal gasification facilities and get their locations on a map (see Figure 1). Many different companies in the countries are working on the development of the technology so in the following subsections they will be described by country.

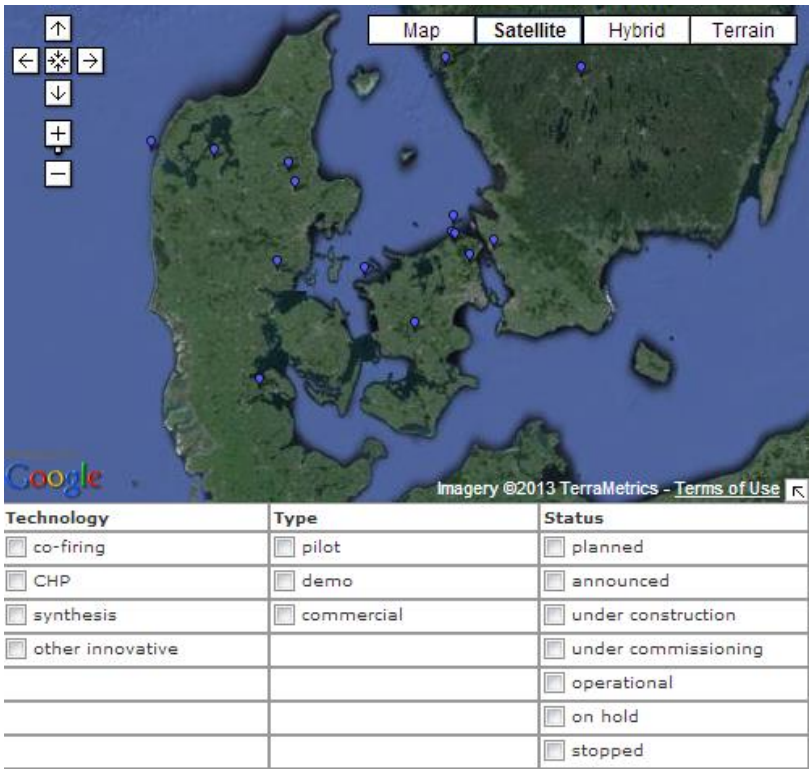

Figure 1. Screen shot of the mapping of thermal gasification facilities [3]

2.1. Gasification technologies in Denmark

The Danish government has set ambitious green targets for the upcoming years by planning for a 100% renewable energy system in 2050. However in 2035 the goal is to have electricity and heating fully covered by renewable energy sources. This created more interest and further investments in biomass gasification technologies and focused the development on fuel production, power and heat production and the general improvements in understanding the process and monitoring of the demonstration plants.

Denmark has a history in gasification development with some guidelines for the development of gasification in the biomass technologies strategy dating from 2003 *"Strategy for research, development and demonstration of biomass technologies for electricity generation and CHP in Denmark" (The Biomass Strategy)* [4]. The implementation and demonstration of the gasification technologies is a priority in Denmark, therefore it can be said that Denmark is advanced in gasification technologies compared to many other countries. As a part of the homonymous project *"Strategy for research, development and demonstration of thermal biomass gasification in Denmark"* [5] a strategy concentrating just on the biomass gasification in Denmark was developed in 2011.

The first gasification project started in 1988, and throughout the 1990s the research was concentrated at DTU, where the CHEC (Combustion and Harmful Emission Control) research group was formed that is still active after 25 years of research. Danish research in gasification is a success. Two developed gasification concepts are internationally recognized: two stage process that can produce tar-free gas and Pyroneer technology that can gasify straw and fertilizer.

Danish thermal gasification technologies cover a wide range of gasifiers, from small scale to large scale CHP plants for district heating. Technologies are also at different levels of development from the research and development stage, pilot and demonstration phase to commercially available technologies with long operating hours. The market for gasification technologies is wide both in Denmark and in other countries, so there are number of stakeholders involved (see Table 2).

During the last few years, after many years concentrating mostly on decentralized heat and power production, interest is redirected towards a wide spectrum of applications such as fuel production, using gasifiers as a balancing agent in the system and combining gasifiers with fuel cells. The new Strategy is therefore concentrating more on the different R&D efforts relating to gasification so the governmental goals can be reached.

Table 1. Danish gasification stakeholders and their area of operation

Stakeholder/Technology group companies	Area of operation	Website
Ammongas A/S	Pilot and demonstration plants	www.ammongas.dk
Babcock&Wilcox Vølund	Demonstration and market introduction	www.volund.dk
BioSynergi Proces ApS	Demonstration plant, developing and marketing	www.biosynergi.dk
Dall Energy A/S	R&D, consultancy on demonstration plants	www.dallenergy.com
Danish Fluid Bed Technology ApS	Consultancy and R&D	-
DONG Energy	R&D, pilot and demonstration plants	www.ltcfb.com , www.pyroneer.com
Haldor Topsøe	R&D, pilot and demonstration plant and market introduction	www.topsoe.com
Organic Fuel Technology	Pilot plant (R&D and demonstration plants are part of the vision)	www.organicfueltechnology.com
TK Energy ApS	Development projects, demonstration plants	www.tke.dk
Weiss A/S	Demonstration plants	www.weiss-as.dk
Skive Fjernvarme I/S	CHP plant operation	www.skivefjernvarme.dk
AAEN Consulting Engineers A/S	Consultancy on demonstration plantt	www.aaenas.dk
Danish Gas Technology Centre	Research and development	www.dgc.dk
Danish Technological Institute	Education, R&D, pilot and demonstration plant	www.teknologisk.dk
FORCE Technology	RD&D, feasibility studies, market studies	www.forcetechnology.com
	Company closure	
EP Engineering ApS (company was ceased in September, 2013)	*Pilot and demonstration plant*	*www.ep-engineering.dk (no longer in business)*
Stirling DK (company went bankrupt in 2013)	*Pilot and demonstration plants, market introduction*	*www.stirling.dk (no longer in business)*

Table 2. Gasification technologies in Denmark, adapted from [6]

Gasifier name	Stakeholder/ Technology owner/ Developer	Type of gasifier	Thermal fuel power MW_{th}	Purpose	Development stage
Alternating Gasifier	Ammongas A/S, Babcock & Wilcox Vølund A/S	Twin bed filter	200+	Fuel production (gas)	Pilot
Vølund Updraft Gasifier	Babcock & Wilcox Vølund A/S	Up-draft	15-200	CHP – IC engine	Commercial
The CHP system of BioSynergy	BioSynergi Proces ApS	Open core down draft	0-15	CHP – IC engine	Demonstration
Staged Down Draft Gasification	Risø DTU, Weiss A/S, Dall Energy, COWI A/S	Multiple steps sown-draft	0-15	CHP – IC engine	Demonstration
Pyroneer A/S	DONG Energy A/S, Risø DTU, Danish Fluid Bed Technology ApS	Low temperature circulating fluid bed	1-200	CHP – co-firing fuel	Demonstration
Tar reforming etc.	Haldor Topsøe		15-200+	Fuel (gas & liquid)	Commercial
Catalytic low temperature pyrtolysis process	Organic Fuel Technology A/S	Catalytic low temperature pyrolysis	1-15	Fuel (liquid)	New/Pilot
Biomass Gasification Gas Engine	Aaen Consulting Engineers, Skive District Heating, Carbona	Circulating fluid bed	15-200	CHP – IC engine	Demonstration
Unknown status of the technologies due to the companies closure					
Close Coupled Gasification (CCG)	*EP Engineering ApS*	*Vibrating grate fluid bed*	*0-1*	*CHP – steam engine*	*Pilot*
Stirling engine with up-draft gasifier	*Stirling DK ApS*	*Up-draft*	*0-1*	*CHP – Stirling engine*	*Commercial*
BlackCarbon	*Stirling DK ApS*	*Pyrolysis*	*0-1*	*CHP – Stirling engine*	*Demonstration*

2.2. Gasification technologies in Sweden

Since the 1970s the use of biomass in Sweden for energy purposes has been increasing and with the goal of at least 50% of final energy provided by renewable energy sources in 2020, it is going to have an important role. From 1990 to 2010 the share of renewable energy sources has raised from 33% to 48% [7]. This was a result of higher usage of biofuels and cleaner production of heat and power, meaning that the bioenergy in Sweden is one of the largest energy sources. Combined heat and power plants for district heating purposes are mainly fuelled with biomass, covering 40% of the total district heating supply in 2010. The main source of bioenergy is forest wood, however there are other resources such as agriculture and sewage treatment. It is expected that in 2020, 23 TWh of bioenergy is going to be used in heating, 7 TW for electricity production and 5 TWh for the transport sector [8].

The largest investments in gasification technologies are through the Swedish Gasification Centre with new finances in the period from 2013 to 2017. Apart from developing gasification technologies for the heat and power sector, a strong emphasis is on fuel production from different sources. The world's first commercial biomass to methanol plant was opened in Sweden in Hagfors. Therefore Sweden is a leader in biomass to fuel production. Moreover there is an on-going project for fuel production from black liquor [9] and future planned projects [10]. Renewable fuel production is supported from the infrastructure side as well. At the end of 2011, approximately 63% of all filling stations in Sweden offered at least one renewable fuel [7].

Sweden is active in publishing gasification data, and as one of the examples the Swedish gas centre has published a gasification database [11]. This gives an overview of biomass gasification plants in the world for computer simulation purposes. It contains 17 gasifiers from around the world including the Swedish and Danish gasifiers.

The developing technology area is wide, from patent applications and laboratory scale developments to existing gasifiers. Some of the technologies that are being developed and used in Sweden are fluidized bed gasifiers (pressured or atmospheric), updraft and downdraft gasifiers, a sand circulation gasifier for oxygen free generation of syngas, indirect gasification and entrained flow. Many stakeholders are involved in this development and research of gasification technologies in Sweden (see Table 3).

Table 3. Swedish gasification stakeholders and their area of operation

Stakeholder/Technology group companies	Area of operation	Website
Chemrec	Demonstration plants and R&D	www.chemrec.se
Meva Innovation AB	R&D and demonstration plants	www.mevagroup.se
Metso Corporation/Metso Power	Demonstration on commercial scale	www.metso.com
Göteborg Energi	Demonstration on commercial scale	www.gobigas.goteborgenergi.se
Malar Energi	Demonstration plant	www.malarenergi.se
Swedish Gasification Center (SFC)	Research, development and training	www.ltu.se/centres/Svenskt-forgasningscentrum-SFC
Cortus Energy AB	Pilot, demonstration plant	www.cortus.se
Energy Technology Center Piteå (ETC)	R&D and demonstration plant	www.etcpitea.se
Växjö Värnamo Biomass Gasification Centre AB	R&D and pilot plant	www.vvbgc.se

3. Biomass gasification R&D in the region

3.1. R&D in Denmark

Research and development is quite active in the region. On the Danish side there are five actors that are involved with gasification technologies: Danish Gas Technology Centre (DGC), Danish Technological Institute (DTI), DTU Chemical Engineering and Biomass gasification group and Force Technology (see Table 4 for overview of their research focus).

The Danish Gas Technology Centre (DGC) is mostly dealing with the utilization of the output gas for the national gas networks and the gasification development is closely connected with bio-SNG production. During recent years they have investigated the possibility of using bio-SNG in the gas grid and its socio-economic and financial aspects [12]. Their new slogan is Sustainable Gas Technology with an increased focus on green energy gases such as biogas, hydrogen and gasified biomass.

The Danish Technological Institute (DTI) has two lab scale projects with pyrolysis and gasification, but their work is also concentrated on the development of new gas cleaning technology. They have a project called "Time to use gasification plants intelligently" that was focused on catalytic decomposition of tar and had the objective to develop test reactors for the existing gasification plants in Denmark (Skive, Harboære and Græsted). Due to their collaboration with developer Haldor Topsøe, it had the potential to commercialise developed technology.

The Department of Chemical Engineering, Centre for Harmful Emission Control (CHEC) and the Biomass Gasification group at the *Danish Technical University (DTU)* are working closely with biomass gasification technologies and their research and development. Their spectrum of activities is wide from the development of the circulating fluidized bed gasification, to the combination of gasification and fuel cells for CHP purposes, and the production of liquid fuels from syngas generated via biomass gasification (mainly focusing on the development of the catalysts). They are also involved in small scale gasification systems for power and heat production and the pre-treatment of the biomass.

FORCE Technology is a national team leader for an IEA BioEnergy Task 33 on thermal biomass gasification. FORCE Technology has participated in several biomass gasification development projects and has developed the Danish "Strategy for research, development and demonstration of thermal biomass gasification in Denmark" for DI Bioenergy with funding from five companies from industry and EUDP, Energinet.dk, DI Bioenergy and FORCE Technology itself. FORCE Technology is a well acknowledged international partner on large RD&D projects on gasification.

Table 4. Main research organisations in Denmark and their research focus

Organisation	Research focus	Website
Danish Gas Technology Center (DGC)	Production of bio-SNG	www.dgc.dk, www.dgc.eu
Danish Technological Institute (DTI)	CHP generation and fuel production	www.dti.dk
Danish Technical University (DTU)	Entrained flow and fluidize bed gasifiers, fuel production, biomass pre-treatment	www.dtu.dk, www.chec.kt.dtu.dk
FORCE Technology	National team leader Task 33 on biomass gasification, RD&D, strategic consultancy, feasibility studies, market studies	www.forcetechnology.com

3.2. R&D in Sweden

Biomass gasification research and development in Sweden is mainly conducted by Swedish universities, institutes and industry that are joined in the Swedish Gasification centre [13]. The Centre is financed by the Swedish Energy Agency, the academy and 25 industrial companies and it was established in 2011 as a platform for biomass gasification research, development and education.

There are three major development directions: direct gasification, indirect gasification and suspension gasification which are divided among Luleå University of Technology, Umeå University, Energy Technology Center, KTH Royal Institute of Technology and Chalmers University of Technology. All three directions are focused on the production of energy and fuels from biomass. The aim with direct gasification technology is to produce fuels from biomass by possibly using pressurized fluidized bed gasification. Indirect gasification enables the production of a dry, nitrogen-free and clean gas from biomass. Suspension gasification or entrained flow gasification is used for the production of fuels like DME and methanol; it uses gasification with pure oxygen instead of air [13].

Apart from the Swedish Gasification Centre, funding for biomass gasification projects and activities was done through the funding agency Energimyndigheten. Two major projects, black liquor gasification in Domsjö and GoBiGas in Gothenburg were financed by the Energumyndigheten. The main actors involved in research and development of biomass gasification in Sweden are:

Bio4Energy is a research program in the Swedish Gasification Centre that gathers three core Swedish Universities in bioenergy research Umeå University, Luleå University of Technology and the Swedish University of Agricultural Sciences. Research collaborations are spread across Swedish academia and other research organisations in Europe, USA, Australia etc. and Swedish industry partners. The idea behind the program is also to create companies related to bioenergy and biotechnology [14].

Luleå Technical University is a coordinator of the Swedish Gasification Centre. Apart from that their research is focused on black liquor gasification activities and close collaboration with the Energy Technology Centre (ETC).

The Energy Technology Centre (ETC) was formed in 1988 in Piteå as a non-profit research organization. It is very active in gasification technologies for black liquor, which include the coordination of the Black Liquor Gasification R&D program. There are three different gasifiers developed in the Centre, the pressurized black liquor demonstration and pilot plant, the VIPP – thermal cyclone gasifier, and PEBG – pressurized entrained flow biomass gasifier.

KTH Royal Institute of Technology and its division for Chemical Technology at the School of chemical science and engineering has conducted research on a Pressurised fluidised-bed reactor with a high-temperature filter and a secondary reactor and Atmospheric fluidised-bed reactor with external heating and two ceramic filters. The research started in the 1970's and continued without interruption until today. The Division of Material Science and technology has worked with high temperature air gasification both updraft and downdraft gasifiers. This technology was sold in 2011 to Boson Energy AB that will continue development for CHP purposes.

Lund University (LTH) was involved in gasification projects and laboratory scale gasifiers from the late 70's until 2000 when all the gasification activities were stopped. During this period a fluidized bed atmospheric gasifier was constructed and operated. LTH was involved in planning the Värnamo plant, which resulted in a test rig with a pressurized internal circulating fluidized bed gasifier. Nowadays they are involved in activities relating to small-scale biomass CHP in the Öresund region as a part of a FP7 project called "GreenSyngas".

Chalmers Technical University is leading the Centre for Indirect Gasification of Biomass (CIGB) as a part of the Swedish Gasification Centre. The University developed the largest gasifier in the world called Chalmers gasifier, which is used in the pilot plant as a part of the Gothenburg Biomass Gasification Project (GoBiGas) for the production biomethane from forest residues.

The Mid-Swedish University, specifically the Bioenergy Gasification group has held different gasification activities. The University is part of the Swedish Gasification Centre and Biofuel Region North. In 2005-2006 they constructed a sand circulation pilot gasifier. Currently, they are focused more on fuel production technologies from biomass.

Table 5. Main research organisation in Sweden and their research focus

Organisation	Research focus	Website
Swedish Gasification Centre	Research and development gasification for energy and fuels	www.ltu.se/centres/Svenskt-forgasningcentrum-SFC
Bio4Energy	Research program	www.bio4energy.se
Luleå Technical University	Research and development of black liquor gasification	www.ltu.se
Energy Technology Centre (ETC)	Black liquor gasification R&D program	www.etcpitea.se/en/
KTH Royal Institute of Technology	Pressurised fluidised bed reactor, atmospheric fluidised bed reactor, high temperature air gasification (updraft, downdraft)	www.kth.se
LTH Lund University	Small scale biomass gasification CHP	www.lth.se
Chalmers Technical University	Centre for indirect gasification	www.chalmers.se
Mid-Swedish University	Sand circulation pilot gasifier, fuel production from biomass	www.miun.se

4. Existing gasification plants

4.1. Overview of Danish gasification plants and pilot projects

The oldest operating gasifier in Denmark is in Harboøre, **Harboøre Varmværk**, dating from December 1993. For the last 12 years it has operated in CHP mode, connected to the district heating covering almost all of the heating demand of the city. The gasifier is 3.5 MW fuel input with 1 MW_{el} and 1.9 MW_{th} output in CHP mode, and it is gasifying wood chips [15]. The gasifier is an updraft moving bed gasifier. The gasifier has more than 120,000 operating hours and it is supported by the Danish Energy Authority [16]. The gasifier connected to the district heating network is in stable operation since 2003; there were some problems during the first ten years with the optimal operation, waste water treatment and the electricity production.

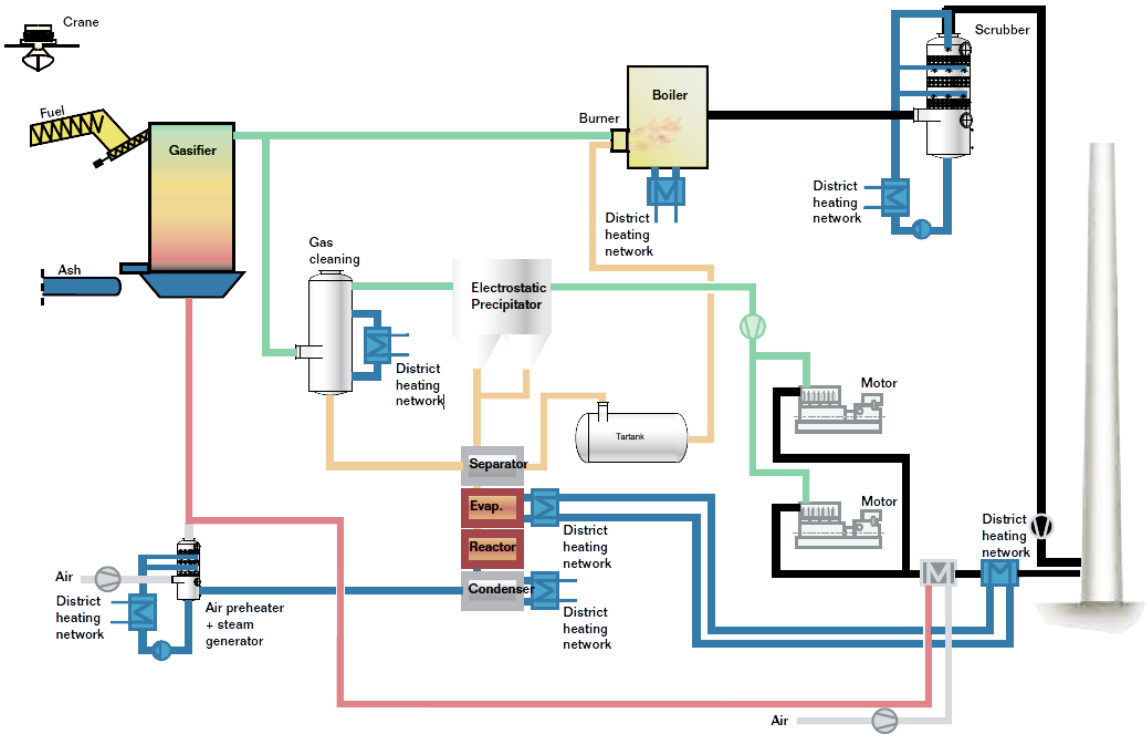

Figure 2. Harboøre district heating plant flow diagram [15]

BioSynergi pilot plant in Græsted is a demonstration plant commissioned in 2003. It has electrical output of 75 kW and thermal output of 165 kW. It is an open core fixed bed wood chip gasifier patented by BioSynergi Proces ApS. It is used as a core for the development process of large scale CHP systems [17]. The plant is not in the operation at the moment. Together with Hillerød Bioforgasning P/S, BioSynergi Proces ApS is constructing a new demonstration plant for combined heat and power in Hillerød. The plant is a staged open core gasifier fuelled with forest wood chips coupled with an IC engine with a CHP capacity of 750 kW_{th} and 300 kW_{el} [18].

Pyroneer is a 6 MW_{th} demonstration gasifier plant fired with straw, manure fibres or local residue. It was commissioned in spring 2011 in Kalundborg near the Asnæs power plant. The capacity is 1.5 tons/hour with a 95% thermal efficiency (based on fuel input and losses) and it operates at lower temperatures than normal gasifiers [19]. The plant is used for co-firing the coal boiler at Asnæs power plant, efficiently replacing fossil fuel with biomass fuel. The project is planned to be expanded with a 50 MW plant in 2015 and it could potentially reach up to 150 MW in the future [20]. Pyroneer has already had 2000 h of

operation, of which 1200-1500h were in full load. It is a completely automatic system that can easily be monitored.

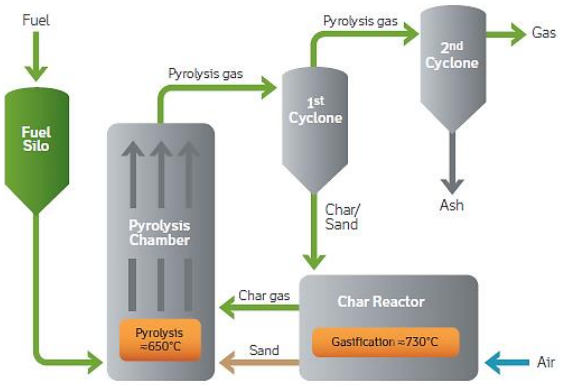

Figure 3. Pyroneer gasifier process flow [21]

Skive Fjernvarme plant was commissioned in 2008 in Skive. It is a Carbona single bubbling fluidized bed (BFB) gasifier that produces gas for combined heat and power (CHP). The maximum fuel input to the plant is 28 MW and it can produce 6 MW_{el} and 11.5 MW_{th} for district heating [22]. The plant is uses either wood pellets or chips. The plant got subsidized by the EU, the US Department of Energy and the Danish Energy Agency [23].

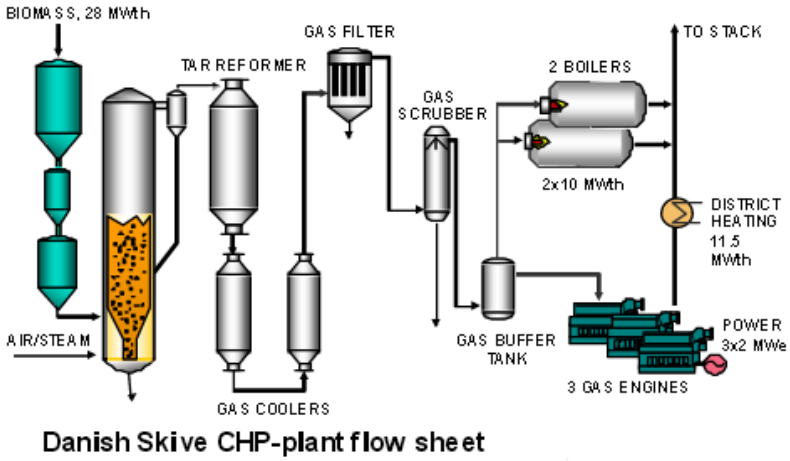

Figure 4. Skive CHP-plant flow [24]

The **Viking plant** at the Danish Technical University was commissioned in 2002 and it is a traditional two stage wood chip gasifier that has separate pyrolysis and char reactors. The gasifier has 75 kW of fuel input, with 17.5 kW_{el} and 39 kW_{th} output [25]. This concept was commercialized by Weiss A/S and up-scaled to three different sizes: a 200 kW input facility in Hadsund, the 500 kW unit in Hillerød connected to the electricity grid and district heating grid and a 100 kW plant which is still not implemented [26].

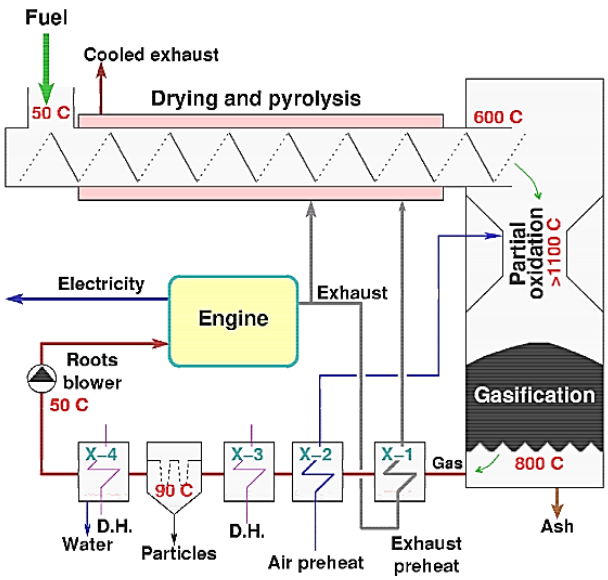

Figure 5. The Viking gasifier [27]

An up-draft gasifier with a Stirling engine, which is owned by Stirling DK, has been installed as a commercial unit at the Technical University of Denmark and started its operation in September 2009. This technology can be scalable to 4 engines with an electric output from 35 -140 kW [28]. The fuel input of wood chips for the gasifier is 200 kW which is approximately 70 kg. The same company has BlackCarbon technology that is based on constant pyrolysis (400 kW unit) and one Stirling engine of 35 kW_e.

Gjøl project was expected to be operating from early summer 2006. It was planned to be a private heat and power station combined with a gasification plant on wood chips. It was dimensioned to produce 0.9 MW_{th} and 0.5 MW_{el}. The cogeneration plant was supposed to supply heat for 325 households. The project was supported by the EU, Danish Energy Agency and Energinet.dk with 9.3 million DKK. However due to some disagreements between the consulting firm and developer, the project was stopped [29].

Close coupled Gasification (CCG) plant at Herlufsholm School and Manor has been financed by the ForskVE program as a development/demonstration project for a small CHP plant, based on gasification and the subsequent combustion of the gas in a steam boiler [30]. The gasifier is a vibrating fluidized bed with 400 kW of boiler capacity.

Stirling DK ApS has installed two commercial units with Stirling engines at the Danish Technical University and in **Barrit**. Both units have the same CHP capacity of 35 kW_{el} and 140 kW_{th}. The gasifiers are updraft gasifiers on wood chips with a capacity of 200 kW [31,32]. The status of these gasifiers is unknown since Stirling DK ApS has gone bankrupt.

Table 6. Biomass gasification plants in Denmark

Gasifier name / Location	Stakeholder/ Technology owner/ Developer	Production start	Type of gasifier	Thermal fuel power MW_{th} or CHP capacity	Fuel type	Purpose	Development stage	Reference
Harboøre Varmværk / Harboøe	Babcock & Wilcox Vølund and Harboøere Varmeværk	1993	Updraft gasifier with combined heat and power	3.7	Wood chips	District heating	Commercial DH plant	[15]
BioSynergi CHP plant / Hillerød	BioSynergi Proces ApS/ Hillerød Bioforgasning P/S	2013/2014	Staged open core gasifier	1.3 / 0.3 MW_{el}, 0.75 MW_{th}	Forrest wood chips	Power and heat production	Demo / under construction	[33-35]
Pyroneer / Kalundborg	DONG Energy	2011	Low temperature circulation fluidised bed	6	Straw	Co-firing coal boiler	Demonstration	[20]
Skive Fjernevarme/Skive	Aæn A/S	2011	Carbona fluidize bed CHP	28	Wood pellets	District heating	Commercial	[22]
Viking/ Roskilde (Risø)	DTU	2002	2 stage gasification plant	0.07	Wood chips	Heat and power production	Demonstration	[25]
Two stage /Hillerød	Weiss A/S	2011	2 stage gasification	0.5 MW_{el}, 0.9 MW_{th}	Wood chips	Heat and power	Demo/Commercial	[26]
Not in operation or with unknown status due to the company closure								
Close coupled Gasification / Næstved	*EP Engineering ApS*	*2010*	*Vibrating grate fluidized bed*	-	*Wood chips*	*Heat and power*	*Pilot*	*[36]*
Barrit / Barrit	*Stirling DK*	*2010*	*Updraft gasifier with one Stirling engine*	*0.2 / 0.035 MW_{el}, 0.14 MW_{th}*	*Wood chips*	*Heat and power*	*Commercial*	*[32]*
DTU/ Lyngby	*Stirling DK*	*2009*	*Updraft gasifier with one Stirling engine*	*0.2 / 0.035 MW_{el}, 0.14 MW_{th}*	*Wood chips*	*Heat and power*	*Commercial*	*[31]*
BioSynergi CHP plant / Græsted	*BioSynergi Proces ApS*	*2003*	*Continuous open core gasifier*	*0.325*	*Forrest wood chips*	*Power and heat production*	*Pilot*	*[17]*

4.2. Overview of Swedish gasification plants and pilot projects

As a part of the **GoBiGas** project, a new gasification plant for biomethane gas production for the existing natural gas network is being built by Metso Power. Biomethane is produced from solid biofuels and forestry wastes. This is the first plant of its kind where the produced gas is going to be high calorific gas that can be transported in the existing grid [37]. The plant is being built in two phases; a demonstration phase in 2013 which will produce 20 MW of gas, and the second phase of 80-100 MW of output gas that should be finished in 2016. The plant is located in Rya Harbour attached to the Rya heating plant. The location is good since it is possible to access the gas, district heating and electricity networks [38]. In phase one, the plant is expected to consume 32 MW of wood pellets, 3 MW of electricity and 0.5 MW of bio-oil, while producing 20 MW of biomethane, 5 MW of district heating and 6 MW of heat for heat pumps [39].

The **Värö plant** was commissioned in 1987 by Götaverken, now owned by Metso. The gasifier is an atmospheric circulating fluidised bed gasifier with 30 MW of fuel capacity. It is the only commercial unit that is in operation for that long period of time. The gasifier is used for lime kiln applications and both gasifier and lime kiln are operating at constant load [40]. The lime kiln has been operated with produced gas from the gasification. A 2 MW pilot test plant was built beforehand that was based on collaboration between KTH and Götaverken, combining their experiences in combustion and gasification.

Chemrec black liquor to DME pilot production plant under the European BioDME project was inaugurated in 2010 [9]. The project was running from 2008 to 2010 as a collaboration of Chemrec, Volvo, Total, Haldor Topsøe, Delphi, ETC and Preem. The gasification technology was developed by Haldor Topsøe, Volvo was responsible for DME-fuelled trucks and Preem for covering the filling stations. This project was unique because it demonstrated the full chain, from the production of fuel to using the fuel on the roads. The objective was to log 450,000 km with good reliability and environmental benefits [41]. The first bio-DME and bio-methanol were produced in July 2011 and the four filling stations were installed in four cities. From the end of 2012 the ownership of the plant was transferred to Luleå University of Technology [42]. Another bioDME plant based on black liquor gasification was planned for Domsjö, but it was withdrawn in 2012 [43].

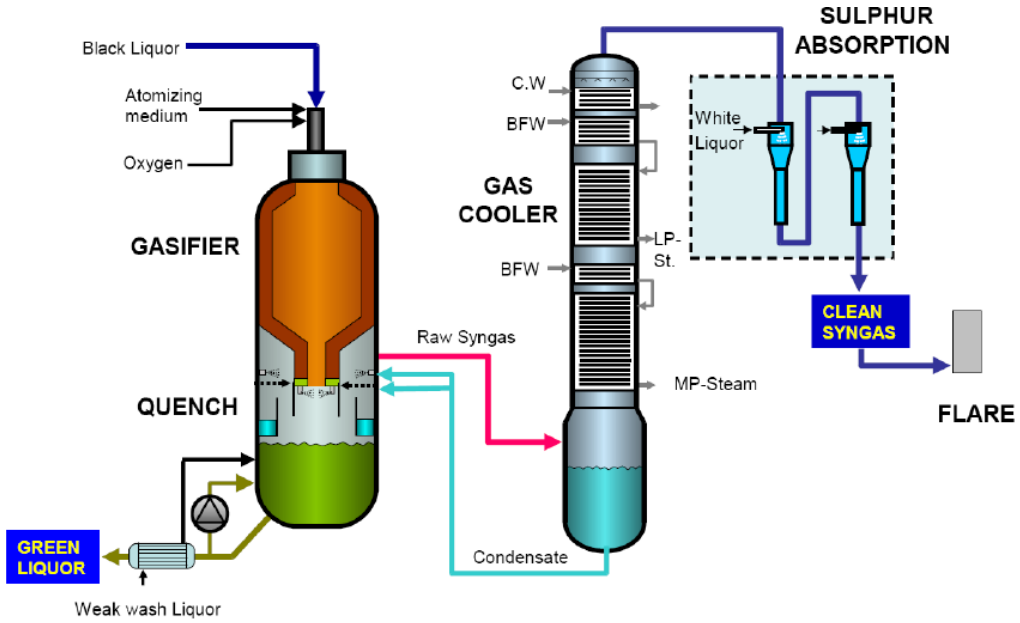

Figure 6. Black liquor gasifier by Chemrec [39]

Värnamo plant has been constructed at the beginning of the 1990's as an integrated gasification combined cycle (IGCC) demonstration plant. The demonstration/development was finished in 2000 from and the plant was mothballed [44]. The plant has an 18 MW fuel input, mainly from woodchips, that produces 6 MW_e and 9 MW_{th}. The project had four partners and was financed by Elforsk AB, The Swedish National Energy Administration and the European Commission. There were some attempts to start the operation of the plant, however that was not successfully addressed [39] . The plant was initially owned by Sydkraft, and was taken over by Värnamo Energi after changing the owners in January 2012.

MEVA VIPP test unit gasifier was installed at ECT in Piteå and it was based on developments from Luleå Technical University. This experimental unit was extended to a full pilot plant that had a thermal input of 500 kW. It is a cyclone gasifier powered by pulverized fuel and it is used as a small cogeneration unit. Another scaled-up demonstration plant was commissioned in 2012 in Hortlax. It is fuelled by wood chips or pellets producing 1.2 MW_e and 2.2 MW_{th} [45]. The plant uses exactly the same technology as a pilot plant but scaled up by factor of 7 [26]. The cyclone gasifier technology can rapidly adjust its production, which is a key feature for future integrated renewable energy systems. Also the output gas is cleaner because cleaning starts in the process.

Chalmers gasifier was developed as a demonstration plant for the GoBiGas project. The demonstration plant is an indirect gasifier with 2-4 MW of fuel capacity and the investment was 13 million SEK [46]. The gasifier is fuelled with dry pellets and wet biomass. It is a retrofit of a circulating fluidized bed (CFB) boiler with a thermal flywheel, and the gasifier was integrated into the boiler loop [47]

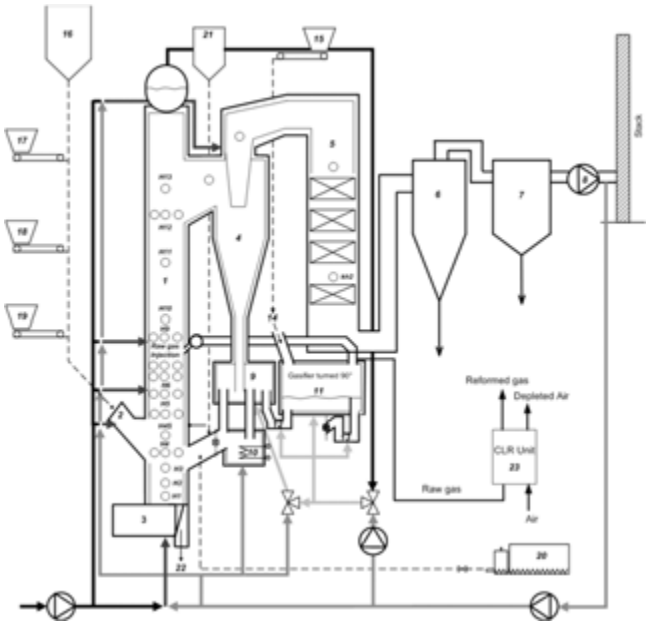

Figure 7. Chalmers gasifier [46]

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Table 7. Gasification plants in Sweden, future projects and existing ones

Gasifier name / Location	Stakeholder/ Technology owner/ Developer	Production starts	Type of gasifier	Thermal fuel power MW_{th}	Fuel type	Purpose	Development stage	Reference
Värö by Götaverken/ Värö	Metso Power	1987	Atmospheric fluid bed gasification	28	Dried bark and wood wastes	Limekiln application	Commercial plant	[40]
Värnamo/ Värnamo	Värnamo Energi	2000	Pressurized Circulating Fluidized Bed gasifier	9	Wood chops, pellets, RDF	Primarily build for power and heat, now conversion to fuel production	Demonstration plant	[44,49,50]
Chalmers/Gothenburg	Chalmers Institute of Technology	2008	Bubbling fluid bed gasifier	2-4	Dry pellets or wood chips	Power and heat	Pilot	[11]
BioDME / Piteå	Energy Technology Center Piteå (ETC)/Luleå University of technology (LTU)	2011	Pressurized, oxygen blown gasifier	3	Black liquor	Bio-methanol and bio-DME production	Pilot	[9]
VIPP-VORTEX/ ETC Piteå	MEVA	2011	Cyclone gasifier	0.5	Wood powder, reed canary grass, torrified biomass	Heat and power (R&D)	Pilot	[52]
VIPP/Hortlax	Pite Energi	2012	Cyclone gasifier	3.5	Crushed wood pellets	Heat and power	Demonstration (Commercial unit)	[45]
GoBiGas/Gothenburg	Göteborg Energi	2013	Indirect gasification at atmospheric pressure	32	Solid biofuels, forestry wastes	Bio-SNG for regional gas network	Demonstration	[48]
Cortus WoodRoll/ Köping	Cortus Energi	2013	Indirectly heated downdraft entrained flow gasifier	5 (planned expansion to 25)	Wood, bark	Power and heat generation	Demonstration plant	[11]
VärmlandsMetanol/Hagfors	VärmlandsMetanol AB	2014/2015	HTW-gasifier	111	Forrest biomass residues	Methanol production	Demonstration plant	[51]

4.3. Laboratory scale projects, gasifiers for R&D purposes and R&D projects

4.3.1. Denmark

The department of Chemical and Biochemical Engineering, Centre for Harmful Emission Control (CHEC) and the Biomass gasification group at the Danish Technical University has been involved in many projects related to biomass gasification. Below you can find a short overview of some of these projects.

The objective of the *Fuels from syngas* project is the improvement of thermal gasification and the catalytic synthesis of the output gas for the production of higher alcohols. The project was finished in 2010. The aim of the project was to develop a mathematical model to describe the gasification process and to develop better catalysts for the conversion of syngas to alcohols. The company Haldor Topsøe A/S participated as a partner in the project [53].

Another project *BioSOFC Third-generation Biomass CHP* investigated how decentralized small-scale CHP plants with biomass gasification could utilise solid oxide fuel cells (SOFC). The project delivered new information about the design, construction, and long term testing of gasifiers, as well as some new knowledge about SOFCs and the overall performance of the system [54]. The project was finished in the first quarter of 2013.

The project *Development and Application of Circulating Fluidized Bed Gasification of Biomass (DANCNGAS)* is aiming to develop a new biomass gasifier – a circulating fluidized bed type that enables the production of syngas with a high content of hydrogen at a high temperature or liquid products at relatively low temperature [55]. The results of the project are expected to enable the design and construction of a demo-scale gasification system. The project partner is the Chinese Institute of Process Engineering, with funding from The Danish Council for Technology and Innovation and the Chinese Ministry of Science and Technology. The project is on-going over the period of 2013-2016.

B4C – Biomass for Conversion is an on-going project with a completion date in the first quarter of 2014. The project gathered a big group of partners led by DONG Energy A/S. The aim of the project is to demonstrate the Pyroneer gasifier and to enable the design, operation and sale of the commercial units [21].

A selection of completed biomass gasification R&D projects can be found in [5].

4.3.2. Sweden

A gasification laboratory at the Energy Technology Centre (ETC) in Piteå, Sweden has installed an IVAB gasifier for the direct gasification of biomass to syngas. The gasifier is based on the pressurized entrained flow biomass gasifier and it will be used to validate the concept for commercialisation [56]. The objective is to produce high purity syngas from untreated forest residues, which was done by combining the ETC, Luleå Technical University and IVAB as a commercial partner [57]. The high quality produced syngas is perfect base for the fuel production due to the very low levels of hydrocarbons.

A laboratory scale indirect gasifier at Chalmers is being used for research that will enable the development of a real large scale facility of 2-4 MW. The research is focusing on the development of the reactor, the optimization of the conversion process, and gas cleaning research [58]. The unit was funded by STEM and Göteborg Energy Research Foundation and it is a support project for the GoBiGas project [39].

The Mid Sweden University at Härnösand, has built a biomass to liquid laboratory (BTL) that will help research on the production of synthetic biofuels from the gasification of biomass (see Figure 8). The laboratory is equipped with a 150 kW_{th} indirect gasifier: it is a dual fluidized bed (DFB) gasifier which is a

combination of a bubbling fluidized bed (BFB) steam gasifier and an exothermal circulating fluidized bed (CFB) combustion riser [59]. This gasifier was chosen to provide high energy content syngas that can be converted to liquid fuels. The gasification group is participating in the project FORE – Forest Industrial Gasification Technology where the aim is the development of small and medium-scale bioenergy production from biomass gasification in collaboration with the Swedish Gasification Centre [60].

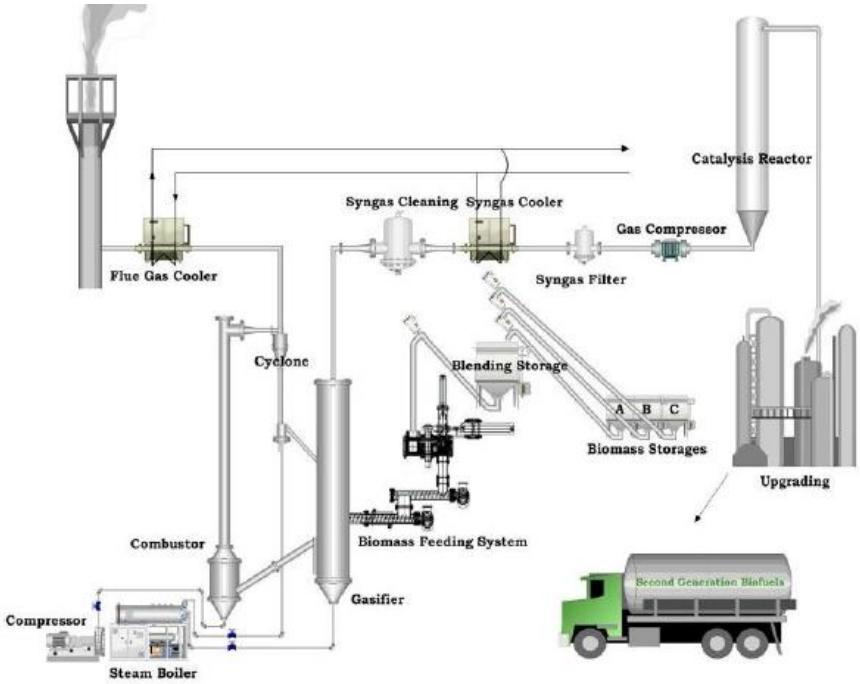

Figure 8. The biomass to liquid system at the laboratory [59]

5. Future projects in Denmark, Sweden and the Öresund region

5.1. Future projects in Denmark

The KINEC (Kalundborg Integrated Energy Concept) project should supply the Municipality of Kalundborg in Denmark with green energy for steam and heat production. The project is a collaboration between DONG Energy, Novo Nordisk, Novozymes, Kalundborg Varmeforsyning A/S and the Municipality of Kalundborg. The main idea is to convert Asnæs Power Station Unit 2 to a gas-firing unit. This project will integrate two DONG Energy technologies, REnscience and Pyroneer. Plants are to be constructed so that the green gas can be partially used for district heating from 2016 with full green gas operation in 2020 [67]. The design of the Kalundborg plant has already started: it is planned to have a capacity of 50 MW and possibly be in operation in 2015 [20].

FlowGas – Entrained Flow Gasification of Biomass is a two year project that started in July 2012. It is managed by TK Energi and the objective of the project is to develop a gasification technology that utilises low quality biomass in an efficient way. The result of the project is to upscale and demonstrate a slagging entrained flow gasification concept for 500 hours at 10 MW_{th} [66].

Most of the Danish projects are already in an on-going phase and new projects are not directly connected with the demonstration of new plants. In Denmark, the aim is to improve existing technologies by optimising specific issues such as the operation of gasifiers, char reforming, gas cleaning and upgrading technologies, the pre-treatment of biomass, and fuel flexibility.

5.2. Future projects in Sweden/ Öresund region

The world's first commercial biomass to methanol plant, VärmlandsMetanol AB, is going to be built in Hagfors, Sweden where production is expected to start in 2014/2015. Methanol will be produced from gasified forest biomass residues, and the excess heat produced will be used for district heating for the town of Hagfors [51].

E.ON Gasification Development AB (EGD) was involved in the Värnamo plant after Sydkraft was taken over by E.ON. Nowadays E.ON is very active in gasification projects, which all started in 2007 when the research on gasification for bio-methane production formed the EGD. They are involved in the GoBiGas project and Bio2G [61]. The Bio2G project is focused on the production of second generation bio-gas from forest biomass and it is based on high temperature gasification. The planned plant output is 200 MW of bio-methane, producing 1.6 TWh of energy each year [62]. Six locations were chosen as potential sites for the plant, of which four are in the Öresund region. The decision was narrowed to two locations, Malmö and Landskrona, and the NER 300[1] application is still under negotiation [63]. The location for the plant will be Landskrona.

SAKAB AB together with VärmlandsMetanol AB, E.ON Gasification Development AB, PEAB, Structor AB and the Municipality of Kumla are going to complete a conceptual study for building a bio-refinery for the production of bio-methane and biomethanol. By gasifying forest residues the plant will produce 250 MW of bio-methane and biomethanol and approximately 50 MW of heat for district heating [64]. It was planned to build the plant on the grounds of SAKAB facility, but VärmlandsMetanol AB is investigating another location for the plant close to a large sawmill.

The second stage of the GoBiGas project will involve the construction of an 80-100 MWgas commercial plant that should start its production in 2016. The second stage will be built near the first stage plant in Rya Harbour [48].

Cortus AB located in Stockholm patented a WoodRoll process [65] that produces a clean syngas by separating drying, pyrolysis and gasification by using indirect heated gasification. Their 5 MW demonstration plant in Köping will be expanded to 25 MW in 2 years [11]. This will cover almost all of the energy needs for Köping.

Rottneros Biorafinery AB has planned two commercial gasification plants for biomethanol production adjacent to the Rottneros Mill in Rottneros and Vallvik, both in Sweden. The plant in Rottneros is based on wood gasification, while the Vallvik one is a black liquor gasification plant. Both plants have the same capacity of 800-1300 GWh/year (150-250 million litres per year of biomethanol) [10]. Both projects have applied for NER300[1] funding.

[1] "NER300" is a financing instrument managed jointly by the European Commission, European Investment Bank and Member States, contains the provision to set aside 300 million allowances (rights to emit one tonne of carbon dioxide)

6. Possible experience exchange and conclusions

Both Denmark and Sweden have a lot of experience with gasification technologies, starting in the 1970's in Sweden and in 1988 in Denmark. There has been a key focus on research and development in both of these countries followed by many projects – at pilot, demonstration and commercial stages. Denmark's two concepts, the two-stage gasifier and Pyroneer technology, have established Denmark as an internationally recognized biomass gasification expert. Sweden has a 40 year tradition in bioenergy and biomass gasification with large-scale gasification plants and plenty of new projects, both for CHP purposes and fuel production. Both countries have patents on some gasification processes.

While the Swedish gasification development is connected mostly with universities and big companies, developments in Denmark are coming more from a single person or from small companies driven by personal enthusiasm. Sweden has established many large capacity power plants, whereas Denmark is concentrated more on small and medium scale that are eventually scaled up by certain factors. Therefore the Swedish gasification plants are up to the 100 MW scale, while the biggest Danish one is 6 MW.

The main difference between Denmark and Sweden in terms of research and development is that it seems that the gasification research community in Sweden is more organised and controlled due to the forming of the Swedish Gasification Centre. This could be used as an example in Denmark, to form a centre that will gather both industry and universities involved with biomass gasification. This would open a range of possibilities for knowledge transfer, different PhD positions in collaboration with industrial partners, easier funding opportunities and a good platform for knowledge dissemination.

From the perspective of fuels being gasified, Denmark is using wood chips and straw as the main fuel in all gasification plants. Sweden has a broader choice of gasified biomass from forestry wastes, black liquor, wood, bark, wood pellets and chips. Sweden is also planning to combine pulp mills with the production of fuels while in Denmark the primary goal is to replace coal district heating plants with combined heat and power based on gasified biomass. The fuel choice and available resources in both countries define the development of the existing technologies. While Denmark puts a high focus on providing heat for district heating from renewable sources, including biomass gasification, and has a fuel production as a hot R&D topic, Sweden has stepped away from the heating sector and is trying to provide a solution for the transport sector by being the first country to produce methanol from gasified biomass. Hence, there is a mutual benefit in both countries collaborating closely with one another, since biomass gasification will probably have a key a role to play in both the heating and transport sectors of both countries in the future. The broader scope of gasification technologies and resources used in Sweden could be a result of the longer presence of the technologies in the energy system.

The main difference between biomass gasification technologies for the heat and power sector and gasification for fuel production is the quality of synthetic gas produced. The composition of the gas is not a key issue when reusing the gas for power production, but there are important requirements for the synthetic gas quality when it is used to produce fuels for transport. For example, technologies for fuel production should not produce synthetic gas that contains nitrogen. The updraft fixed bed gasifier, used in Denmark, is one of the technologies that is not so suitable for up scaling, however the process efficiency is high as the gas exit temperature is low. Fluidized bed gasifiers used both in Denmark and Sweden are suitable for up scaling and relatively insensitive to the ash content or fuel specification, which enables different types of biomass to be utilised. The multistage gasification developed in Denmark is beneficial from the efficiency point of view; however the gas produced contains nitrogen if the process is air-blown so it is not suitable for fuel production. If it is not air-blown, then the gas can be cleaned and synthesised. The R&D in Sweden focuses on three major technologies: indirect, direct and suspension gasification which are all suitable for the fuel production and energy production because of the gas quality. Hence, depending on

the final application (i.e. power plants or fuels) and the development of these technologies (i.e. how efficiency and cost effective they become), both Denmark and Sweden could learn from one another when implementing gasification technologies in the future.

Exchanging experiences between Denmark and Sweden can only be beneficial. Denmark can benefit from the Swedish experience by up scaling technologies and developing gasification technologies for fuel production. Sweden on the other hand can benefit from the Danish perspective of using gasification for decentralization heat and power production, by using CHP units to provide heat to district heating networks while producing electricity at the same time. The Öresund region provides the ground for this knowledge and experience exchange due to the knowledge in the region and the connections between these two countries. Moreover, as Denmark and Sweden are developing different gasification technologies based on different resources, joining together can enhance research possibilities and development trends in both countries and settle their position as leaders in biomass gasification technology.

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