REPORT 2013:5

BIOMASS GASIFICATION - A SYNTHESIS OF TECHNICAL BARRIERS AND CURRENT RESEARCH ISSUES FOR DEPLOYMENT AT LARGE SCALE

Report from an f3 project

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Title page picture references:

Upper left corner:	Güssing gasifier (Source: Roman Hackl, private photograph).
Upper right corner:	Tars (Source: Wikimedia commons, Andrva, http://commons.wikimedia.org/wiki/File%3AMinimile9.jpg)
Lower left corner:	SEM picture (Source: Energy Technology Centre, Piteå)
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Centre:	MeOH from catalytic synthesis of syngas (Source: Energy Technology Centre, Piteå)

PREFACE

In search for solutions to the urgent climate changes, the increase in global energy demands and the fossil dependence, development efforts for biomass-based energy conversion technologies have gradually been intensified throughout the last decade. In this struggle, gasification technologies have an important role, especially considering production of advanced transportation fuels and chemicals from biomass. Still today, there are no biomass-based gasification alternatives mature enough to provide complete solutions to the apparent problems. Furthermore, an increased use of forest-based biomass in state-of-the-art gasification concepts would just partly (or regionally) provide solutions to the global problem issues. However, through the gained experiences and knowledge obtained within on-going R&D projects in Sweden and Europe, partial solutions based on biomass gasification may be provided at full industrial scale by 2020!

This report has been focused on the key critical technology challenges for the biomass-based gasification concepts mainly being considered in Sweden today: direct Fluidised Bed Gasification (FBG); Entrained Flow Gasification (EFG); indirect Dual Fluidised Bed Gasification (DFBG). The inputs to each of these three technology concepts and the compiling of information were mainly provided by Stefan Heyne (Doctoral candidate at Chalmers), Magnus Marklund (Managing Director at ETC, Piteå), and Truls Liliedahl (Docent at KTH). The synthesis work was performed by the institutes leading the three different nodes within the Swedish Gasification Centre and financially supported by the Swedish Knowledge Centre for Renewable Transportation Fuels (f3 – fossil free fuels).

The authors are grateful for all the responses provided by the contacted experts and especially for the total amount of answers finally collected. It should be noted that the choice of individuals is by no means considered to be complete in terms of global coverage of the most competent and experienced experts in the field. However, the chosen persons are believed to well represent a solid expertise and experience with biomass gasification, both from industry and academia. Finally, even though this report should neither be considered as strictly scientific nor fully covering in detail, the authors still see the report as a compact up-to-date compilation of the major barriers, from a technical perspective, for large-scale industrial deployment. We hope that the reading will be of great value for many parts of the biomass-based gasification community.

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EXECUTIVE SUMMARY

Thermal gasification at large scale for cogeneration of power and heat and/or production of fuels and materials is a main pathway for a sustainable deployment of biomass resources. However, so far no such full scale production exists and biomass gasification projects remain at the pilot or demonstration scale.

This report focuses on the key critical technology challenges for the large-scale deployment of the following biomass-based gasification concepts: direct Fluidised Bed Gasification (FBG), Entrained Flow Gasification (EFG) and indirect Dual Fluidised Bed Gasification (DFBG).

The main content in this report is based on responses from a number of experts in biomass gasification obtained from a questionnaire. The survey was composed of a number of more or less specific questions on technical barriers as to the three gasification concepts considered. For formalising the questionnaire, the concept of Technology Readiness Level (TRL 1-9) was used for grading the level of technical maturity of the different sub-processes within the three generic biomass gasification technologies.

For direct fluidised bed gasification (FBG) it is mentioned that the technology is already available at commercial scale as air-blown technology and thus that air-blown FBG gasification may be reckoned a mature technology. The remaining technical challenge is the conversion to operation on oxygen with the final goal of producing chemicals or transport fuels. Tar reduction, in particular, and gas cleaning and upgrading in general are by far the most frequently named technical issues considered problematic. Other important aspects are problems that may occur when operating on low-grade fuels – i.e. low-cost fuels. These problems include bed agglomeration/ash sintering as well as alkali fouling. Even the preparation and feeding of these low-grade fuels tend to be problematic and require further development to be used on a commercial scale. Furthermore, efficient char conversion is mentioned by some as a main technical barrier for direct fluidised bed gasification. Finally, operation under pressurised conditions and associated feeding problems are also regarded as potential difficulties by more than one expert.

The by far most stressed technical barriers to large-scale entrained flow gasification (EFG) of biomass are fuel pre-treatment and fuel feeding which are not considered mature and have not yet been demonstrated commercially. The costs for this treatment and associated energy losses are also considered to be barriers. The cost aspect is also highlighted for the overall system as such and as EFG calls for large-scale operation to reduce costs, the problems associated with transport logistics are also considered problematic. In addition, complete fuel conversion and efficient use of excess heat are mentioned as major barriers. Material problems, fuel and ash behaviour, as well as uncertainties/lack of experience when operating on low-grade fuels are additional issues raised. Finally, particle and gas separation, gas upgrading, oxygen supply and the fact that ash from EFG is not usable as fertiliser are also considered possible major technical barriers.

As for direct fluidised bed gasification, the major technical barrier in relation to indirect dual fluidised bed (DFBG) technology is gas cleaning and upgrading, including the associated tar problems. The gas cleaning is seen as key to commercial applications and high-temperature gas

cleaning is a necessary technology not yet available at commercial scale. An additional issue is the fact that indirect gasification technology is limited in the level of pressurisation and in consequence is limited in feasible size. The complexity of DFBG with two interconnected fluidised beds may be considered problematic for up-scaling. Less frequently mentioned barriers include gas cooling, heat recovery, fouling, limited availability of the system and limited experience with low-grade fuels, fuel flexibility and fuel conversion.

The estimations on maximum possible size of the three gasification concepts vary considerably, but the general trend on a relative scale between the technologies are similar; the entrained flow gasifier can be scaled up the most with some experts estimating possible sizes even above 1000 MW_{th} input. For direct fluidised bed gasification the maximum sizes mentioned are in the 600-700 MW_{th} range and most experts consider indirect fluidised bed gasification maximum sizes to be somewhat lower than those for FBG since that no pressurised DFBG concept is currently available and unlikely will be in the medium term. Using the mean of the values/ranges indicated by the experts gives a very rough approximation, but still represents the general trend: EFG has a maximum size of about 680 MW_{th}, followed by FBG at about 240 MW_{th}, and finally DFBG at about 130 MW_{th}.

An additional aspect raised with respect to the feasible maximum size of a biomass gasification system is the fact that the system might be restricted by biomass logistics rather than the technical limitations for up-scaling. A range of 300 MW_{th} is mentioned as a maximum conceivable size considering logistics basically making all three gasification technologies applicable.

In summary, for EFG the aspects of preparation, feeding flexibility of the fuel are considered not mature and thus in principle not solved. However, the tar-related problems are less for the EFG design than for the other two concepts. For the DFBG design the aspects of pressurisation, up-scaling and maximum size are considered not mature and thus problematic. For both FBG and DFBG gasification concepts the issue of tar generation is a main if not the main problem area.

The expert community, however, is convinced that the technical barriers will be overcome and actually do not constitute the critical barrier for biomass gasification deployment. The foremost barrier for biomass gasification is associated with the economic risk. Technical solutions exist for most of the problems, but are not demonstrated at large scale due to the associated economic risks. As is evidenced by the answers to the survey, experts are convinced that biomass gasification will be applied at large scale as soon as policy measures ensuring economic viability of the projects have been adopted.

CONTENT

1 INTRODUCTION

The total world energy demand is estimated to increase by 40 % within the next couple of decades and one of the fastest growing sectors is the transportation sector (World Energy Council 2012). With biomass standing for about 10 % of the global primary energy supply in 2010, coupled with projected increases in the absolute use of biomass (IEA 2011), an efficient use of this resource is indispensable. Biomass gasification for the production of power and heat, and in particular, biomass-based fuels and compounds, is one of the main pathways for large-scale production in the near to medium term future (see e.g. Cherubini *et al*. 2009, Kumar *et al*. 2009). In comparison with coal gasification, the main differences for biomass can be summarised in higher fuel reactivity; higher organic sulphur, chlorine and alkaline content; higher content of produced tars; and more CO_2 and CH_4 in the syngas. However, so far no large-scale production has been demonstrated and biomass gasification projects remain at the pilot or demonstration scale. In this report the major barriers, from a technical perspective, to large-scale deployment are presented with a critical discussion of the future prospects for solving them. The considered general technology concepts are: direct Fluidised Bed Gasification (FBG); Entrained Flow Gasification (EFG); indirect Dual Fluidised Bed Gasification (DFBG).

Reports for estimating and comparing costs for producing biomass-to-liquid fuels (BtL) following the different gasification routes include the EUCAR-CONCAWE-JRC 2007 report, as well as those by Anex *et al.* (2010), Swanson *et al.* (2010) and Trippe *et al.* (2011).

General reviews on thermochemical conversion of biomass are numerous in literature, and the authors of this report have therefore decided to focus on the key critical aspects for the respective gasification technology. For a more general review of issues in biomass gasification the reader is referred to reviews available in literature (e.g. Held 2011, Kumar *et al*. 2009, and Wang 2008). Instead, the main content in the current report is based on responses from some of the world-leading experts in biomass gasification obtained from an electronic questionnaire performed in January 2013 (see form used in Appendix A).

The survey was composed of a number of general questions on technical barriers to large scale biomass gasification in order to highlight the up-to-date key aspects that – from the experts' viewpoints – still need to be resolved to enable a larger dissemination of biomass gasification at large scale. The experts asked to participate in the survey have long experience with biomass gasification; the survey was aimed at contacting people both from industry and academia. Most of the people inquired are from Europe but the survey also includes a number of experts from the United States. To our knowledge this survey on technical barriers in biomass gasification is the first of its kind. In total, 37 chosen experts were invited to respond anonymously.

2 BACKGROUND

There is a wide range of processes available for converting solid biomass and waste into more valuable fuels or energy carriers. One of them is partial oxidation or gasification in which a gas is produced from a solid fuel at elevated temperatures using oxidizing agents such as air, oxygen, steam, carbon dioxide or a combination of these. In the case of gasification, the temperatures are typically between 600 and 1000 °C.

The different steps when gasifying biomass or other solid feedstock are graphically represented in Figure 1. The first step in this thermochemical conversion of the fuel is drying, followed by pyrolysis to produce a solid residue (char) and volatiles, made up of permanent and condensable gases.

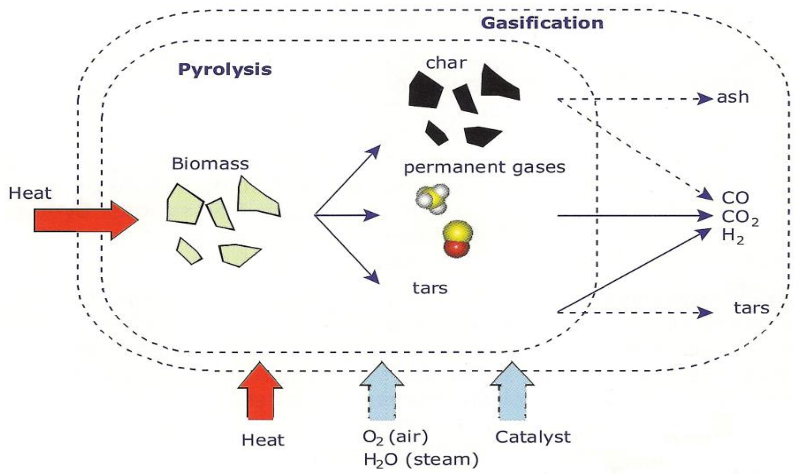

Figure 1. Graphic representation exemplifying the processes during the thermochemical conversion of biomass in a gasifier (modified from Knoef 2012).

The processes represented graphically may be described by the main chemical reactions R1 to R6.

Feedstock $\rightarrow$ char + tars + CO_2 + H_2O + CH_4 + CO + H_2 + ($C_2 - C_5$) + impurities			R1
C + ½O_2 $\rightarrow$ CO	ΔH_r^0 = -109 kJ/mol	(partial oxidation)	R2
C + $CO_2 \leftrightarrow$ 2CO	ΔH_r^0 = +172 kJ/mol	(reverse Boudouard)	R3
C + $H_2O \leftrightarrow$ CO + H_2	ΔH_r^0 = +131 kJ/mol	(water gas reaction)	R4
CH_4 + $H_2O \leftrightarrow$ CO + 3H_2	ΔH_r^0 = +159 kJ/mol	(steam reforming)	R5
CO + $H_2O \leftrightarrow CO_2$ + H_2	ΔH_r^0 = -42 kJ/mol	(water gas shift)	R6

R1 describes the initial endothermic pyrolysis. For biomass this step is especially important due to the large fraction of volatiles in biomass (70-80 % dry basis). The subsequent reactions R2 to R6 represent the gasification process. Heat for the endothermic reactions can be supplied either by direct partial oxidation, via R2, or from an indirect external heat source. Additional reactions that may influence the product gas yield and composition include the thermal or catalytic cracking of the tars, reactions R7 to R9:

$pC_nH_x \leftrightarrow qC_mH_x + rH_2$	(thermal conversion)	R7
$C_nH_x + nH_2O \leftrightarrow (n+x/2)H_2 + nCO$	(catalytic steam reforming)	R8
$C_nH_x + nCO_2 \leftrightarrow (x/2)H_2 + 2nCO$	(catalytic dry reforming)	R9

In the reactions R7 to R9 C_nH_x represents tar, and C_mH_y a hydrocarbon with the carbon number $m < n$. The thermal conversion reaction (R7) is a simplification as this decomposition is much more complicated, as indicated by Devi *et al.* (2002).

Over the years a number of generic reactor designs have evolved as being suitable for gasification of biomass. These principal design concepts include fixed beds (updraft, downdraft and crossdraft), fluidised beds and entrained flow reactors. Although each of these reactor concepts is capable of carrying out the gasification process, each of them is a compromise between technical aspects such as the product gas quality, conversion efficiency, suitability for handling varying feedstocks coupled to the complexity of the design and operation, and economic ones such as investment and running costs. Additionally, although pressurised operation puts significant additional requirements on the design and operation of a gasifier, it is often desirable.

It is generally believed that the fluidised bed reactor design concept complies the best, with the requirements for the production of bio-syngas for the synthesis of liquid transportation fuels via the thermochemical gasification route (Siedlecki 2011). Additionally, the amount of experience with the fluidised bed technology and its characteristics makes it a mature and reliable technology. However, considering system pressurisation and resulting fuel conversion, the EFG concept is advantageous. Since pressures up to 80 bar are technically and economically feasible today and the conversion most often approaches 100 %, EFG in theory exhibits the highest capacity of all gasifiers used for biomass (Knoef 2012).

Tar in the product gas is a commonly encountered problem when gasifying biomass, especially in fluidised bed concepts. It may affect and clog the downstream equipment, resulting in the need for extensive downstream gas treatment and upgrading. On the other hand, the most favourable result with EFG (at optimal operating conditions) is that the produced syngas has very low tar content. Still, tar is historically the most cumbersome problem issue for biomass gasification. Regarding the characteristics of the biomass, the most problematic feedstocks in fluidised bed gasification tend to be those with high ash and alkali contents. Loss of fluidisation due to bed sintering is an often encountered problem as well as slagging/material problems in EFG.

3 FLUIDISED BED GASIFICATION (FBG)

The basis for the fluidised bed reactor configuration is the principle of fluidisation. Forcing a gas stream (fluidisation medium) through a particle bed in a vessel the bed will, if the flow velocity is high enough, lift and behave like a fluid. Air, steam, or steam/oxygen mixtures are examples of commonly used fluidisation media. Silica sand is the most extensively used bed material, but other bulk solids, preferably such that may also exhibit catalytic activity, are also employed.

Depending on the velocity of the fluidisation medium the fluidised bed gasifiers may be divided into two categories, bubbling fluidised bed gasifiers (BFBG) and circulating fluidised bed gasifiers (CFBG). These basic reactor configurations are shown in Figure 2.

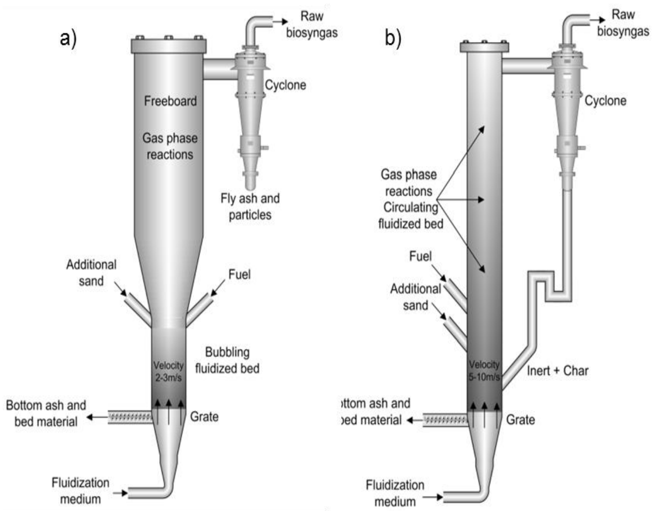

Figure 2. Configurations of fluidised bed reactors. Left: Bubbling fluidised bed (BFB), right: circulating fluidised bed (CFB) (Olofsson *et al.* 2005).

These fluidised bed biomass gasification design concepts are targeted at mid-scale capacities of ~10 MW_{th} towards large-scale exceeding 100 MW_{th}.

In the CFBG, as in the BFBG, the fluidising gases are introduced into the bottom of the reactor with such a high velocity that the solids are entrained with the gas stream (~ 0.5-2 m/s). However, in contrast to the BFBG, the cross-sectional area is in principle constant throughout the CFBG resulting in the solids being entrained out of the reactor with the outgoing gas. The entrained solids in the CFBG are subsequently separated from the gas in a cyclone and recycled back into the gasifier. The high gas velocities (3 - 10 m/s) in the CBFG coupled with the recycling results in the raw product gas having relatively high dust content. For larger CFB gasifiers, it is often preferable to employ a few smaller cyclones in parallel as compared to a single large cyclone.

In the BFBG, the gasification agent is, as mentioned, blown through the bed at a gas velocity above the minimal fluidization velocity of the bed particles in the narrow bottom section of the gasifier. In the upper part of the gasifier, i.e. the freeboard, the gas velocity will be 4-5 times lower due to the larger cross sectional area. Thus, in contrast to the CFBG, in the BFBG the char and bed particles will fall back into bottom part of the reactor as the gas velocity in the freeboard will be below the minimum fluidisation velocity. In the BFBG the major part of the gasification reactions will therefore take place in the dense fluidised bed part in the bottom. In some reactions, especially homogeneous thermal tar cracking and reforming reactions, the homogeneous water-gas shift reaction, and the heterogeneous gasification of entrained small char particles will, however, continue in the freeboard.

For fly ash/dust removal in both configurations a cyclone and particle filter are employed.

The inert bed material will enhance the heat and mass exchange between the particles, and therefore the fluidised beds will operate under almost isothermal conditions. For both configurations, the maximum operating temperature is limited by the ash-induced melting point of the bed material, which typically will lie between 800 and 900 °C. At these relatively low temperatures, coupled with the prevailing relatively short gas residence times, the (slow), especially heterogeneous, gasification reactions will normally not reach chemical equilibrium. This is especially true for the faster CFBG. Thus methane concentrations, for example, tend to be (much) higher than suggested by the chemical equilibrium.

3.1 GENERAL PERFORMANCE

Both the BFBG and the CFBG designs are relatively easy to operate. The intense mixing and the gas-solid contact allow good temperature control, and the reactor, performing well over a broad fuel particle size distribution, starts already with relatively fine particles. However, particulates in the product gas are for both design concepts higher than in fixed beds, and the tar concentrations tend to be between those of the downdraft and the updraft fixed bed gasifiers.

Due to the simple geometry and the excellent mixing properties fluidised beds may be scaled up with confidence. However, fuel distribution may become problematic in large beds, although multiple feeding may partly solve the problem.

The carbon conversion in the BFBG is normally well above 90 %, due to the long residence time of the biomass particles and the residual conversion when they are entrained to the freeboard, this only, though, if the carryover of fines is limited. Because of the relatively low gas velocities in the BFBG freeboard elutriation is minimal and the addition of new bed material limited. In contrast to the BFBG in-bed more sophisticated catalytic processing is not possible for the CFBG.

The energy throughput per unit of reactor cross-sectional area is higher for the CFBG than for the BFBG. Both configurations may be operated under pressurised conditions, which will further increase the energy throughput. Furthermore, in contrast to most other reactor configurations, fluidised bed gasification allows the possibility of using additives, e.g., for in-situ removal of pollutants or primary measures to increase tar conversion via employment of catalytically active bed materials.

Both concepts are available at commercial scale as air-blown technology and in principle both represent mature technologies. However, there is a difference in maturity between the atmospheric and pressurised design concepts.

Advantages of both fluidised bed concepts include the compact construction due to the high heat exchange and fast reaction rates caused by the intense mixing in the bed. Both gasification designs also exhibit flexibility to changes in fuel properties, sizes and shapes implying acceptance of fuel moisture contents up to 60 % and fuel ash contents of almost 50 %. This includes the possibility of dealing with fluffy and fine-grained materials that have high ash content, low bulk density or both. However, in general the CFBG is more flexible in operation than the BFBG, since the circulation rate of the bed material may be used for additional control.

The drawbacks with both of these fluidised bed configurations may include high tar and dust contents in product gas and incomplete carbon burnout. Additionally, the operation may be complex because of the need to control the supply of air, bed material and fuel simultaneously. The product gas from especially the CFBG may be (very) high in particulates (from the suspended bed material, ash and soot), and their rapid transport and circulation may result in equipment erosion.

3.2 CONCEPT REQUIREMENTS

For synthetic fuel applications (i.e. production of fuels and chemicals from the syngas) the requirements on product gas purification are very high to prevent poisoning of the catalysts. Additional challenges for these applications include operation with oxygen at pressurised conditions, and associated fuel-feeding problems.

Pressurisation results in lower volumetric gas flow rates, which means smaller size of the reactor and downstream gas cleaning and upgrading equipment. Secondly, many downstream processes require pressurised conditions (e.g., Fischer-Tropsch process, gas turbines), and the fact is that it is sometimes easier to pressurise the reactants separately (lock-hopper system for the solids, compressors for the gases) than to compress the hot, combustible, moist hydrogen and tar-rich product gas compensates for the technical and operational complications (Beenackers and van Swaaij 1984). Compression of the product gas will require gas cooling and removal of tar and moisture below their dew points to avoid condensation during compression. However, process improvements are still needed, for instance in the high-pressure fuel feeding, although commercially available more or less reliable feeders exist (TK Energi 2013). Pressurisation may also influence the gasification process. The equilibrium reactions that are not equimolar will be driven towards the condition with the lowest volume. This may in turn influence the methane yield which maybe higher at pressurised than at atmospheric conditions, this at least at higher temperatures and long residence times.

Both the BFB and CFB gasification design concepts are well established for heat and power applications. For biomass though only the CFBG is well established at larger scale. For the biomass to liquid (BTL) applications, scaling up to larger systems is ongoing with pilot-plants under construction. The number of developers of the BTL route is limited, most of them being small players.

3.3 INDUSTRIAL R&D ACTIVITIES

Technology developers and providers for BFBG concept include Foster Wheeler and Andritz/Carbona, both with gasification activities in Finland. An example of this design configuration is the air blown gasifier in Skive, Denmark. It produces CHP through three gas engines (Jenbacher) and is equipped with a tar cracker. Andritz/Carbona has provided the technology and the plant is designed for a capacity of 20 MW_{th} and 6 MW_{el} (η_{el} = 32 %).

An example of the circulating fluidised bed concept is the ~12 MW_{th} CFBG supplied by Foster Wheeler in Varkaus, Finland for lime kiln application. The CFB gasifier at Värö Bruk, Sweden with a capacity of 28 MW_{th} was delivered by Götaverken (now Metso Power). The gasifier has been in operation since 1987. Bark is used as feedstock and the produced gas is used to replace oil in the lime kiln.

3.4 GENERAL BARRIERS FOR BFBG AND CFBG

Two of the most important operational barriers for both the BFBG and CFBG configurations are the risk for defluidisation and the presence of tar in the product gas.

The loss of fluidisation due to particle agglomeration is an often encountered problem during fluidised bed gasification of biomass (Nordin 1994). This is especially true for agricultural crops and waste, whilst woody biomass tends to be less problematic. Alkali, such as sodium and potassium, from biomass ash may form low-melting eutectics with the silica in the sand, which is the most often used bed material. This may result in sintering and particle agglomeration which subsequently may lead to loss of fluidisation i.e. bed defluidisation. The presence of chlorine will amplify this problematic effect, as alkali and chlorine tend to go together. The defluidisation during fluidised bed operation may be seen as being triggered by the formation of a thin sticky quartz-alkali coating around the bed particles. Once this unfavourable coating is formed defluidisation may follow almost instantaneously. The choice of the bed material is important and the choice will normally be a compromise between mechanical stability, agglomeration resistance, catalytic activity and price. Whenever a silica-rich bed material is to be used with alkali-rich fuels the agglomeration problem may, at least partly, be counteracted by using in-bed additives with alkali-abstracting properties. Known such additives that are supposed to reduce the agglomeration phenomenon include kaolin, calcium oxide, calcium carbonate and bauxite. Introduction of alumina-rich compounds, such as kaolin, may result in the formation of alkali-aluminium silicates, which have higher melting temperatures than the alkali silicate formed otherwise (Bartels *et al.* 2008). With biomass of high ash/alkali content it may otherwise be advisable to use alternative bed materials such as alumina or magnesite. The main drawback with these more sophisticated non-natural bed materials is that of cost.

An additional often encountered problem is the presence of tars in the product gas. When gasifying, it is in principle impossible to avoid at least some production of tar. The tars can be tolerated, though, if the gas is to be used as fuel and is closely coupled to the application, such as a boiler or a kiln. However, in more demanding applications, tars in the product gases, even at low concentrations, can create major handling problems. As soon as the temperature of the producer gas drops below the dew point, tars will either form aerosols or directly condense on the inner surfaces of the equipment, resulting in plugging and fouling of pipes, tubes, and other components downstream the gasifier. The most important consideration is often to maintain the gas above the tar dew point (~ 400 °C), thus avoiding condensation. Internal combustion (IC) engines and synthesis applications downstream require the gas to be cooled before final use though.

Two basic approaches may be identified for removing tars from product gas streams, physical or thermal and catalytic processes.

The physical methods are utilised for removing condensed tar aerosols, using technologies similar to those used for particulate removal in wet scrubbers, electrostatic precipitators, etc.

The thermal and catalytic tar reduction methods have been studied extensively with the aim of converting the tars to permanent gases. Thermal decomposition at high temperatures may lead to troublesome soot formation; however this and the difficulties of achieving complete thermal cracking, in parallel with operating and economic considerations, often make thermal cracking less attractive.

There are many technical and economic reasons, such as thermal efficiency, environmental emissions compliance, and tar effluent-treatment costs, which may justify catalytic cracking and reforming of the tars. The catalytic methods for tar decomposition may be sub-divided into two different types, depending on where in the process the catalysts perform; primary and secondary catalysts. Primary catalysts are added and mixed with the biomass prior to gasification, whilst the secondary catalysts are placed in a secondary reactor downstream the gasifier. The catalytic materials most comprehensively studied are dolomites, both as primary and secondary catalysts, nickel-based, mainly as secondary catalyst and alkali metals, mainly as primary catalyst.

4 ENTRAINED FLOW GASIFICATION (EFG)

The entrained flow gasification (EFG) concept is well-known from direct coal gasification and thoroughly presented in the literature, e.g. by Higman and van der Burgt (2008). The main advantages of using this concept in coal-based applications are the flexibility in firing a wide variety of coal feedstocks, and the production of a clean, tar-free product gas. However, the main penalties (from an energy point of view) are relatively high oxygen consumption and the need for finely ground feedstock. The entrained flow gasification reactors (see schematic example in Figure 3) usually operate at pressures between 20-70 bar and temperatures in the range of 1200 -1800 °C, depending on the type of fuel and application (Figure 3). The fuel (in form of solid, liquid, slurry or gas) is fed co-currently with the oxidant (either air or oxygen with possible addition of steam and/or carbon dioxide) into the gasification reactor in a given direction depending on the type of entrained flow process (e.g. top-fired, side-fired, or tangential-fired). Subsequently, the main part of the fuel in the form of particles or liquid droplets is entrained with the main flowing stream of gas in the reactor.

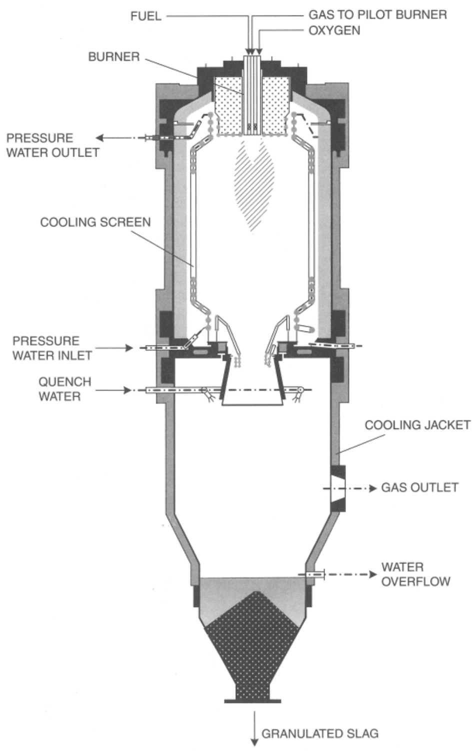

Figure 3. Schematic of Siemens EFG gasifier (Higman and van der Burgt, 2008).

The EFG concept applied to biomass is nicely reviewed in the handbook by the BTG Biomass Technology Group (Knoef 2012). Even though the temperatures in the EFG gasifiers generally are high (compared to fluidised bed processes) and, hence, generate low concentrations of tars and condensable gases when applied to biomass, there are always some amounts of higher hydrocarbon species present in the product gas (mostly as methane). Disregarding these amounts, the composition of the main species in the product gas at these high temperatures will be close to those indicated by the chemical equilibrium, even though the bulk residence times are short, i.e. in the order of seconds. Under proper conditions the resulting fuel carbon conversion with the entrained flow concepts approaches 100 % and exhibits the highest capacity of all gasifiers used for biomass, at least in theory (Knoef 2012). However, the high-temperature operation creates problems, e.g. regarding materials selection and handling of slag (i.e. molten ash).

After pre-treatment of solid biomass feedstock (which is required and costly in general), the prepared material enters the entrained flow gasifier as a relatively fine powder (~10^2 μm in characteristic diameter) via either a pneumatic or mechanically based feeding system. In order to obtain optimal gasification of the injected fuel particles, it is important to apply suitable burner design, reactor shape and powder characteristics. A required achievement is a stable flame generated by the partial oxidation of initial conversion gases from pyrolysis of the fuel particles and re-circulated product gas formed in the reactor. Furthermore, maintained intense heat transfer to the particles on entrance to the reactor as well as sufficient residence times of the fuel particles is needed. A disadvantage of the under stoichiometric fuel conversion taking place at high temperatures, is soot formation in the reactor. In order to minimise the formation of soot, addition of steam (in a proportion of ~0.1 kg steam per kg supplied oxygen) can be utilised (Qin et al. 2012).

Entrained flow gasifiers may conceptually be found as slagging or non-slagging. In the case of slagging gasifiers, molten slag products (originating from the ash constituents of the fuel) are condensed and accumulate on the reactor wall, forming a viscous slag layer that will partly solidify and protect the inside wall from the hot and corrosive atmosphere of gas and slag in the reactor. The outermost layer of flowing viscous slag will eventually reach the outlet of the reactor, where it is important to maintain conditions for the slag to leave the reactor without creating any slag solidification that eventually may cause plugging. In order to obtain this so-called fluxing material must usually be added to obtain a liquid slag with the right viscosity at the given temperature. In coal-based power plants, limestone or other Ca-rich materials are often added with the fuel. For the non-slagging entrained flow gasifiers, slag formation is unwanted and limited by operation at temperatures well below the ash melting temperatures determined by the composition of minerals in the ashes. In this case, some soot generated by the gasification process may be advantageous to obtain condensation surfaces in the gas bulk via nucleation, preventing unwanted slag fouling on the gasifier wall.

4.1 GENERAL PERFORMANCE

In general, the entrained flow gasification concept can be customised for a variety of applications based on finely fractionated biomass powders or finely atomized bio-oil at large capacity, high pressures, high temperatures and short residence times. The main advantages with EFG are the combined fuel-load-product flexibility and the possibility of high system pressurisation (up to 80 bar is technically and economically feasible today). The favourable result, which is strived for at these conditions, is a syngas with very low tar content. However, depending on the end use of the produced syngas, the purification requirements and limitations on methane content (and other lower HCs) may differ significantly. The drawbacks with operating at high temperatures, and especially in slagging mode, are the altered durability of the containment materials and, from a system efficiency point of view, increased need for efficient recovery of sensible and latent heat in the hot, and often, steam-saturated syngas. Note that the latter aspect does not affect the cold gas efficiency (CGE) from gasification, which is essential when considering further synthesis of the syngas (CGE from bio-EFG is generally aimed to fall in the range 60-80%). In this case, the relatively complex technology of producing synthetic fuels requires large-scale production in order to enable economical operation.

Considering general criteria for biomass-based EFG, the following overall aspects should be optimized:

- Maximise process availability
- Maximise CGE with respect to considered application
- Minimize the fuel pre-treatment requirements
- Minimize soot and tar formation in reactor
- Maximize particulate separation from product gas
- Minimize needs for handling process water in the plant

4.2 CONCEPT REQUIREMENTS

Depending on the specific end application (i.e. value chain) considered for biomass-based EFG, different requirements have to be met in order to realise cost-effective operation. The main alternatives are: fuel gas production, power and heat generation, and synthetic fuel applications. In general, the level of syngas cleaning requirement for these alternatives increases in the given order of appearance (i.e. the highest syngas quality is required for the synthetic fuel application). For all applications, the important biomass pre-treatment step needs proper and thorough considerations, except for EFG of black liquor and other available liquid residues that would only need pre-heating before gasification (Carlsson *et al.* 2010). Depending on the specific EFG implementation and its system economics (including possible logistics, feedstock variations, feeding technology, and general integration possibilities), the pre-treatment requirements on the solid biomass differ. For direct use of the virgin biomass (i.e. not in combination with other biorefinery processes) the following pre-treatment routes are discussed today (Knoef 2012):

- Drying + fine grinding
- Torrefaction + fine grinding
- Coarsening + liquefaction (i.e. pyrolysis oil and char production) + separation
- Coarsening + liquefaction + mixing (i.e. bio-oil slurries)

In applications aimed to produce energy-rich fuel gas the most important challenges are to limit the extent of particulate matter in the gas and to efficiently reform the tars into fuel gases. In this case, the fluidised bed alternatives are more often used than the EFG concept. However, considering efficient power and heat generation (preferably via so-called Integrated Gasification Combined Cycle, IGCC) the EFG is most suitable since e.g. the level of operating system pressures is an important efficiency aspect and favourable for EFG. Regarding purification in this case, the particulate matter in the syngas needs to be very low in order not to negatively affect the operation of the gas turbine.

For synthetic fuel applications (i.e. production of fuels and chemicals from syngas) the requirements on syngas purification are very high. If not, the catalysts used in the synthesis of the fuel product will be deactivated prematurely, which in turn will be costly. Basically, all components other than H_2 and CO need to be removed below ppm levels. The exception is CO_2, which for some reactions is even used at a small concentration. In some catalytic systems, inerts such as N_2 and CH_4 will accumulate and will therefore have to be removed/limited. Condensable hydrocarbons in the syngas also need to be removed. Although important results can be obtained in small bench-scale tests (Häggström *et al.* 2012), pilot-scale testing is necessary before commercial scale since long-term testing and verification of process function is crucial. Since nitrogen (as an inert) needs to be excluded in the synthesis process, an oxygen plant is also required and constitutes an important aspect of the system analysis in order to obtain proper economy of scale of the plant.

Considering operating conditions for synthesis applications, increasing the operating pressure in the gasifier decreases the production costs the most. This is due to the high pressures used in conventional synthesis processes downstream the gasification plant and the energy penalty resulting from the need to raise the syngas pressure. Therefore, the operating pressures for EFG in synthesis applications are generally in the range 30-80 bar. Furthermore, the introduction of additional steam as gasification agent generally has negative effects on production costs in the considered gasification facility (Trippe *et al.* 2011). However, for cases including synthesis gas upgrading and whenever the input fuel has properties enhancing soot formation and resulting in unfavourably low H_2 content (e.g. very low moisture content), addition of steam may still be beneficial overall.

4.3 INDUSTRIAL R&D ACTIVITIES

There are a number of on-going R&D initiatives around EFG of biomass, both nationally and around the world. Most of the research is done in lab scale, but there are also pilot-scale research activities, e.g. the PEBG plant at ETC in Sweden (Weiland *et al.* 2013). Below follows recently updated lists of biomass-based EFG demonstration/industrial plants gathered from Landälv (2013), which are all based on the synthetic fuel application. Considering industrialised demonstration scale plants (~1-15 MW_{th}), the following plants/projects are currently active (start-up year in parenthesis):

- BLG-BioDME plant (2005/2011) at LTU Syngas Centre in Piteå, Sweden
- KIT-BioLiq DME/gasoline plant (2008/2013) in Karlsruhe, Germany
- BioTfueL FT-products plant (2014) in Venette, France

Regarding planned fully industrial plants based on the EFG concept and synthetic fuel production, the following projects should be mentioned:

- Forest BtL Project with Vapo in Ajos, Finland, producing FT-products from forest residues
- Woodspirit Project with BioMCN, Siemens, Linde, and Visser & Smit Hanab for torrefied biomass in the province of Groningen, the Netherlands

4.4 GENERAL BARRIERS FOR EFG

Considering the pre-treatment requirements and subsequent feeding possibilities for virgin biomass resources (excluding available bio-liquids, e.g. black liquor), Svoboda (2009) shows that there is no ideal method and combination to be used in pressurised EFG applications. As mentioned above, a number of differently combined solutions for pre-treatment and feeding exist but these need to be adjusted from a complete system point of view (complete values chain) rather than just from the EFG technology concept point of view.

The choice of refractory lining in the gasifier is critical and Clayton *et al.* (2002) have identified improved refractory materials as the number one out of top 20 research areas needed in order to make gasification more economically viable. Severe attacks due to corrosive ashes have been indicated (Scudeller 1990) and measurements in operating gasifiers and theoretical considerations indicate the same (Coda *et al*. 2007, Turn *et al*. 2007). Hence, controlling the ash slagging properties is important in order to provide fuel-flexible EFG-based technology concepts. This would in turn require process control instrumentation for in-situ slag build up identification and feedback-controlled adjustment of suitable fuel additives.

The purification of synthetic gas has generally been mastered for decades for fossil based feedstock. However, the technology needs to be adapted and validated when produced from biomass-based feedstock. For example the effects from impurities specific to the nature of the biomass, need to be considered in more detail in order for complete and successful concept demonstration. Especially for synthetic fuel applications where the requirements on syngas purification are very high (see section 4.2 above).

The syngas produced in EFG is often cooled and separated from other gasification products in a quench (following the hot gasification reactor) prior to further upgrading in a series of downstream processes. In the case of water spray quenching, a resulting issue is proper handling of the quench water. In commercial operation the quench water needs to be circulated and reused without causing operational problems due to accumulation of contaminants. In order to choose the correct combination of water treatments (e.g. coagulation/flocculation, filtration and sedimentation), thorough characterization of the process water is needed in order to tailor proper cleanup techniques. Besides turbidity and acidity, the quench water is defined by the dissolved organic substances (e.g. aliphatics, benzene and polyaromatic hydrocarbons). Considering suspended contaminants in the quench water, two general categories exist: Particulates that readily sediment out of the water, and non-polar organic substances in the form of colloids.

Regarding economy of scale, the costs for the oxygen plant and the key performance parameter in the form of product capacity per generated tonne of oxygen are of great importance. However, the cost for the raw material in order to make biomass gasification economically viable is in the end the most important parameter. To summarise, the prioritised R&D areas for the EFG concept are considered to be (Landälv 2013):

- Pre-treatment scale-up and related cost optimisation
- The level and physical boundary of system pressurisation
- Syngas purification technology and cost
- Optimised overall integration

5 DUAL FLUIDISED BED GASIFICATION (DFBG)

A dual fluidised bed gasifier (DFBG) or indirect gasifier basically consists of two vessels, one for gasification and another for combustion providing the heat for gasification. The general setup of two DFBG concepts that have been built at pilot scale is illustrated in Figure 4.

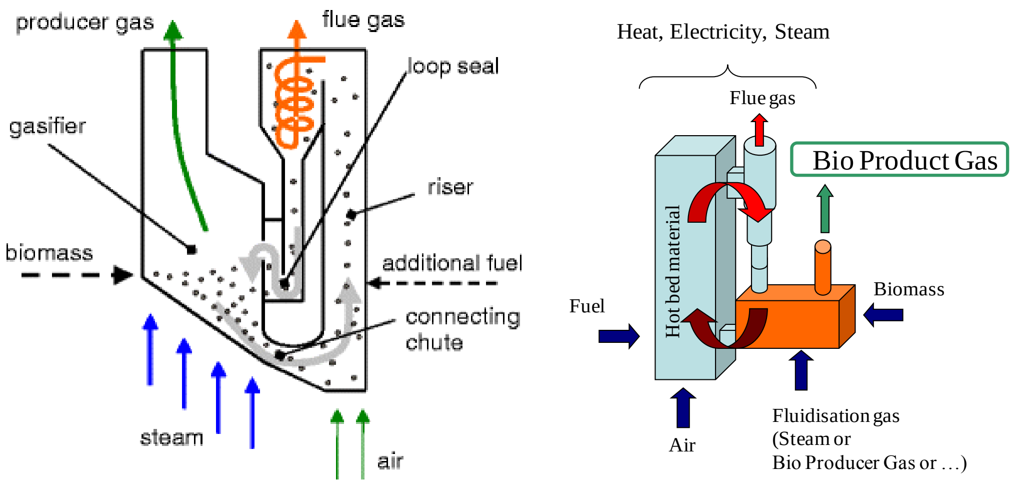

Figure 4. Dual bed fluidised steam gasifier concepts. Left: Fast internally circulating fluidised bed (FICFB) gasifier (8 MW_{th}) (Pfeifer *et al.* 2011), right: Chalmers gasifier (2-4 MW_{th}) (Thunman and Seemann 2009).

A circulating fluidised bed combustion chamber (riser) supplied with air and fuel (no fuel supply is needed in case there is enough unconverted biomass char from the gasifier transported back to the combustion unit) is heating up bed material that transfers heat to the (bubbling) fluidised bed gasification chamber. The two chambers are separated by loop seals preventing combustion air from entering the gasification unit, resulting in a virtually nitrogen-free product gas with a lower heating value in the range of 10-14 MJ/Nm^3 dry gas.

The operating conditions are similar to those for direct gasification in fluidised bed reactors with the constraint that combustion temperature has to be higher than the gasification temperature (50-100 ºC) in order to enable sufficient heat transfer with the bed material. And the combustion temperature in turn is limited by ash melting and bed agglomeration limits. This implies that the upper temperature limit of an indirect biomass gasifier is lower than the one for a direct gasifier for a specific combination of biomass fuel and bed material.

The major advantage of an indirect gasifier is that a nitrogen-free product gas may be produced without the need of using oxygen as gasification/combustion agent. As the two chambers are separated by loop seals that are fluidised with e.g. steam, little or no combustion gases enter the gasification part of the system with the circulating bed material that provides the heat for gasification.

4.5 GENERAL PERFORMANCE

As the indirect DFBG concept operates in the lower temperature range (usually 600-900 ºC), it generates – in a manner similar to the FBG technology – tars in the product gas. On the other hand, the product gas in consequence also contains high concentrations of methane and lower hydrocarbons, making the DFBG of interest for production of biomass-based synthetic natural gas (bio-SNG), also referred to as biomethane or biogas. But the range of application is in no way limited to methane, any synthetic transportation fuel or biomass-based chemical may be produced from DFBG.

Char conversion during gasification in DFBG is not that much of an issue compared to FBG where the unconverted char ends up in the fly ash. In DFBG concepts the unconverted char serves as fuel in the combustion chamber. As the air supply to the combustion chamber should be at the lower limit to avoid leakage of combustion gases (in particular CO_2 and N_2) to the gasification chamber, some DFBG concepts use a post-combustion chamber to allow for sufficient residence time of the particles for complete burn-off (Pröll *et al.* 2007).

4.6 CONCEPT REQUIREMENTS

The fact that there is no need for production of oxygen when aiming at producing nitrogen-free product gas makes DFBG an interesting technology for the medium-scale range of about 10 to 200 MW_{th}. In general the size of indirect gasification plants may be in the same range as biomass combustion units using fluidised bed technology. Given the similarities between the technologies indirect biomass gasification units with a thermal capacity of around 500 MW_{LHV} should not pose any problems from a technical viewpoint, with CFB boilers being available in this size range (Nevelainen 2012). Of course it might be favourable to pressurise the units at very large scale in order to limit the size of equipment. Pressurisation is not a realistically envisaged choice for DFBG even though it may be done in theory. This would involve pressurising both the gasification and combustion chambers in order to keep the pressure differential between the two reactors at the desired levels. The recovery of the pressure energy from the flue gases would be necessary in order to make the concept viable.

The fact that the DFBG concept basically is an externally heated gasification unit coupled to a combustion unit opens up for retrofitting existing combustion infrastructure extending it with a gasification process. This has been demonstrated at the pilot-scale plant at Chalmers (Thunman and Seemann 2009) also indicating a rather large flexibility for switching the retrofitted unit between operation in pure combustion mode and in gasification mode.

4.7 INDUSTRIAL R&D ACTIVITIES

The demonstrated scale for indirect gasification of biomass is at around 10 MW_{th} thermal input. The most prominent indirect gasifier is the fast internally circulating fluidised bed (FICFB) gasifier in Güssing, Austria with a thermal input of 8 MW_{th} (Hofbauer *et al.* 2002) that is producing power and heat using the product gas in cogeneration engines, but also has been used for demonstrating process chains to both synthetic natural gas (SNG) and Fischer-Tropsch (FT) diesel (Bio-SNG 2009, Ripfel-Nitsche *et al.* 2007).

Based on this gasification concept a number of cogeneration plants in the same size range have been built. The largest project is being under construction in Gothenburg/Sweden where Göteborg Energi AB is going to produce 20 MW_{LHV} of SNG based on indirect gasification (GoBiGas 2010). Göteborg Energi AB is investigating possibilities to extend the production to 100 $MW_{LHV,SNG}$ in the future based on the experience from their first plant. Also based on the FICFB technology, an indirect gasification concept with in-situ absorption of CO_2 using limestone as bed material was tested for generation of H_2-rich product gas (Koppatz *et al.* 2009). Plans existed for a 10 MW_{th} demonstration plant for polygeneration of SNG, power, and heat, but due to high biomass prices the project was aborted (Marquard-Möllenstedt *et al*. 2009).[1]

At the Energy Research Centre of the Netherlands (ECN) an indirect gasification technology called MILENA has been developed that integrates the gasification and combustion units in a single vessel. Plans are on-going to build a 10 MW_{th} gasification unit based on the technology for cogeneration of heat and power from waste wood. In the case of successful operation a further increase in scale to 50 MW_{th} input with the aim of producing Bio-SNG is envisaged (van der Meijden *et al*. 2009, van der Meijden *et al.* 2010).

The Rentech-Silvagas (former FERCO Silvagas) indirect gasification process developed in the United States is a DFBG gasification concept with two circulating fluidised beds that are connected; the process has been successfully demonstrated in a CHP plant in Burlington at a design-scale of about 40 MW_{th} that was even operated with a thermal input of about 60 MW_{th} on a lower heating value basis (Paisley *et al*. 2004).[2]

4.8 GENERAL BARRIERS FOR DFBG

The major barrier for DFBG is the gas cleaning with tar conversion or removal in particular. A number of scientific reviews address this topic (Richardson *et al*. 2012, Anis and Zainal 2011). There are commercially available tar removal technologies based on scrubbing technologies; examples are the OLGA two-stage scrubbing technology (Zwart *et al*. 2009) and RME scrubbing applied in the Güssing plant (Rehling *et al*. 2011) that will also be used in the GoBiGas plant. In general the high operating costs (for RME scrubbing a considerable amount of biodiesel used for scrubbing is purged and burnt in the combustion chamber together with the scrubbed tars) are a drawback for these technologies. In addition they put constraints on the opportunities for heat recovery as the tar-loaded gas cannot be cooled down below the tar dew point (at around 300-400 ºC) without the risk for equipment fouling. A solution to this problem could be high-temperature tar reforming technologies that are on the verge of becoming commercial. Research activities focus on identifying suitable catalytic materials for tar reforming depending on the desired product gas application (e.g. Lind *et al*. 2011). As an alternative to these secondary measures for reforming of the tars generated, primary measures applied inside the gasifier are available. Richardson *et al*. (2012) give an overview of gas

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[1] According to a German newspaper article from 17th November 2011 the price of biomass increased from 50 €/dry tonne to more than 100 €/dry tonne during the planning phase, rendering the project uneconomic ("Leuchtturm" ist gekippt, Manfred Bomm, 2011-11-17, Südwest Presse, http://www.swp.de/1216974, accessed 2013-02-12)

[2] The Silvagas gasifier at Burlington was designed for 200 wet tons (182 dry tons) per day but was even operated at feed rates of 300 wet tons (274 dry tons) per day; assumed LHV of wet biomass (9 % moisture) is 16.5 MJ/kg wet.

purification technologies and their intensification; catalytically active bed materials for gasification or filters in the freeboard of the gasifier are mentioned among process alternatives.

The tar-loaded product gas thus generates several problems for the downstream operations that may be considered technical barriers to large-scale operation. Among others, efficient heat recovery is not possible at a safe level. For large scale processes the integration of a steam cycle for co-generation of power and heat might help to improve the economic prospects of a given concept.

Due to the limitation to operation at atmospheric conditions, the scale-up to very large sizes is not obvious and no manufacturer offers indirect gasification at a scale of >100 MW_{th}. Processes involving a synthesis step are usually very cost intensive and need to be operated at large scale in order to lower the specific costs per energy unit of produced fuel. A large uncertainty concerning the feasibility of DFBG technology at large scale results in a lack of interest from investors and therefore represents a considerable barrier for the deployment of this technology.

In conclusion, the R&D focus areas for DFBG are considered to be:

- Efficient and cost effective tar removal and gas cleaning
- In connection to gas cleaning: efficient heat recovery and process integration as important steps to design economically viable process concepts based on DFBG
- The scale-up limits for DFBG have to be defined in order to consider optimum process chains at the given scale.

5 RESULTS OF THE ONLINE SURVEY

In the following paragraphs the general results of the online survey conducted as a key element of this report will be presented. In total 37 experts on biomass gasification were invited to contribute with their answers on basically five questions on technical barriers within biomass gasification, each classified for the three technologies considered within this work, namely direct Fluidised Bed Gasification (FBG), Entrained Flow Gasification (EFG), and indirect Dual Fluidised Bed Gasification (DFBG). The experts that were asked to participate in the survey have long experience with biomass gasification and the survey was aimed at contacting people both from industry and academia. Most of the people inquired are from Europe but the survey also includes a number of experts from the United States. With the ambition of formalizing the questionnaire to the maximum possible extent, the concept of Technology Readiness Level (TRL 1-9) as applied in DOE (2009) was used for grading the level of technical maturity of the different subprocesses within the three biomass gasification technologies considered. Note, for technical reasons (limitations in the web form), the TRL grading used in the questionnaire was limited to 5 levels (1; 3; 5; 7; 9). The used TRL can basically be described by the following:

1 = “basic principles observed / immature / extensive development needed”

3 = “technology concept formed / low degree of maturity / initial development performed”

5 = “subsystem validated in relevant environment / relatively mature / some development needed”

7 = “subsystem demonstrated in commercial environment / mature / only optimisation development needed”

9 = “successfully proven commercially in full scale / fully mature / no further development needed”

The five tasks in the survey were basically the following:

1) To judge the Technology Readiness Level of different sub-processes within biomass gasification
2) To identify the single most important technical barrier for each gasification technology
3) To assess the maximum thermal scale each technology currently can deliver
4) To identify of possible non-technical barriers for the three gasification technologies
5) Additional comments the experts considered relevant and/or missed in the survey

The complete questionnaire that was sent out to the considered experts is presented in Appendix A (not presented as in the final web format) and in total 32 responses were collected. The experts were free to choose to answer only the questions related to the specific gasification technology in which they consider themselves to be most competent, but the majority chose to answer all questions. One expert actively declined to answer the questions with the argument that the formulation of the questionnaire was too general and might lead to misinterpretation of the answers. The survey was conducted anonymously and no individual answers will be presented, neither any expert’s name nor his/her affiliation. In order to illustrate the broad coverage of both countries and affiliations the reparation of the 32 experts who answered the survey is represented in Figure 5. Considering the affiliation of the interviewees the majority has an academic background being associated to either a university or a research institute but still a considerable number of experts (about 22%) are involved in industry, this category covering equipment manufacturers, technology developers and utility companies.

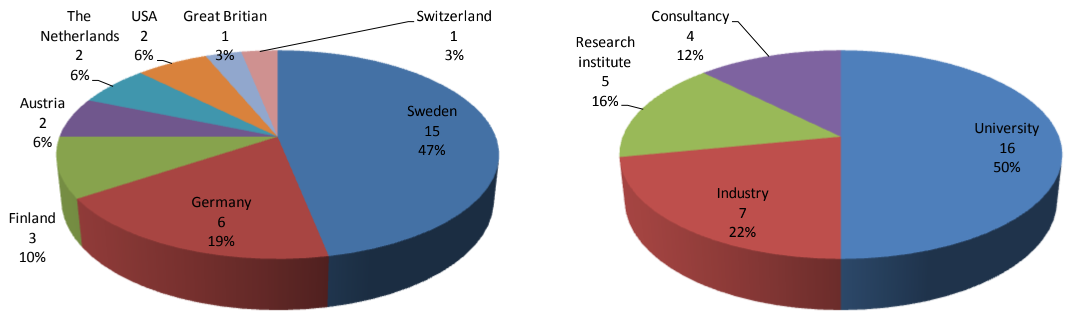

Figure 5. Geographical distribution (left) and repartition of the affiliation (right) of the 32 experts who answered the questionnaire.

In the following subsections, a summary of the responses to the online survey will be presented. For the first question covering specific issues, quantifiable results in form of the mean TRL obtained from the experts' answers as well as measures of the spread and variation of the answers are presented. For the remaining more informal questions and specific comments, compiled overall notions for each of the specific issue are summarised. Detailed responses from the individual experts are found in Appendix B where all answers are collected and represented as received (except for obvious typographic errors).

5.1 TECHNOLOGY READINESS LEVEL OF THE DIFFERENT TECHNOLOGIES

In Figure 6 the average scores for the Technology Readiness Level for different technical issues related to biomass gasification are presented.

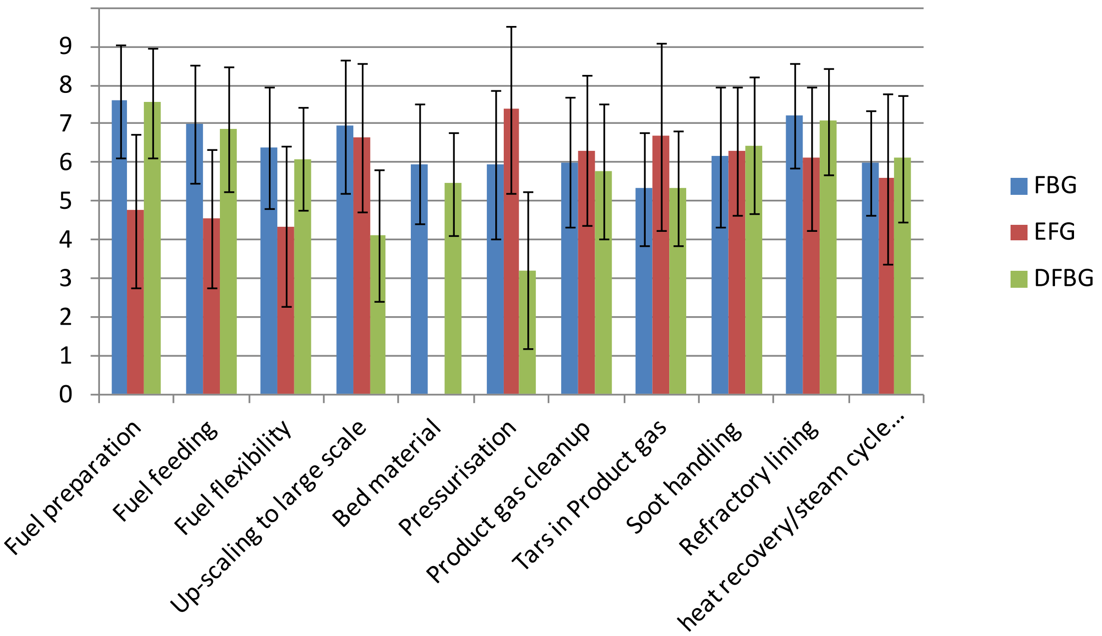

Figure 6. Average values for Technology Readiness Level (TRL) for the different technical issues for the three gasification technologies. Error bars indicate standard deviation as measure of the spread of the answers.

It has to be pointed out that the results in 6 are not considered a guideline for ranking the three gasification technologies, but rather as an indicator for the areas of research & development that should be focused on when trying to promote a given technology. In the following a more detailed review of the questionnaire answers and comments given by the experts will be presented for each of the 11 considered technical issues.

5.1.1 Fuel preparation

Table 1. Technology readiness level considering fuel preparation for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**7.6**	**4.8**	**7.5**
Total answers	32	28	31
Standard deviation	1.46	1.99	1.41

The fuel preparation for both fluidised bed technologies (FBG and DFBG) is considered mature as these technologies can handle a number of different feedstocks. Necessary development issues within fluidised bed gasification fuel preparation might be the handling of waste and low grade biomass fuels. For entrained flow gasification there is a large spread in the judgement of TRL among the experts. It is stated that pyrolysis and torrefaction as possible pre-treatment technologies still need to be further developed for EFG. The level of TRL also heavily depends on the nature of the fuel, black liquor gasification being rather mature whilst other biomass technologies with e.g. pyrolysis as pre-treatment still need substantial development for deployment at large scale.

5.1.2 Fuel feeding

Table 2. Technology readiness level considering fuel feeding for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**7.0**	**4.6**	**6.9**
Total answers	32	27	31
Standard deviation	1.52	1.78	1.63

Similar to the fuel preparation issues, the feeding of the fuel is considered rather mature for the two fluidised bed gasification technologies. A number of successful demonstration plants, such as the Güssing plant in Austria and the Värnamo plant in Sweden, are mentioned. Pressurisation of fluidised bed reactors is highlighted as possible problem for the fuel feeding. For EFG the average TRL value is lower and the answers are more widespread. Co-feeding with coal or coke is mentioned as a mature technology for entrained flow gasification that has been demonstrated as well as the feeding of liquid fuels (e.g. black liquor).

5.1.3 Fuel flexibility

Table 3. Technology readiness level considering fuel flexibility for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**6.4**	**4.3**	**6.1**
Total answers	32	27	31
Standard deviation	1.56	2.08	1.35

Even though fuel flexibility strictly speaking cannot be judged directly by Technology Readiness Level, as pointed out by one interviewee, the grading gives an impression of the current capability of the three gasification technologies to handle different kinds of fuels and in particular low-grade fuels on a large scale. Compared to fuel preparation and feeding, the fuel flexibility is considered less mature for all three technologies. Fluidised bed gasification technologies have been demonstrated for a number of different fuels, but more work is necessary to prove operability on e.g. waste fuels. The fuel flexibility also is considered different for atmospheric and pressurised conditions. The clear definition of the fuel properties is an important aspect to ensure safe operation of the plants. For entrained flow gasification, ground biomass needs to be provided, making the grindability of the material a crucial aspect for large scale application.

5.1.4 Up-scaling to large scale

Table 4. Technology readiness level considering up-scaling aspects for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**6.9**	**6.7**	**4.1**
Total answers	32	29	31
Standard deviation	1.72	1.93	1.70

Considering the scale-up to large scale in the several 100 MW range, both FBG and EFG are considered scalable to the maximum projectable scale for biomass production units. EFG is mentioned as already being sold as 500 MW units as coal technology and existing large scale air-blown gasifiers operating on biomass in Finland are given as examples. DFBG on the contrary gets a lower score TRL and up-scaling to large scale is considered a significant challenge for this technology. A necessary differentiation between pressurised and atmospheric technologies is highlighted with pressurised technologies being scalable to larger sizes.

5.1.5 Bed material

Table 5. Technology readiness level considering bed material for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**6.0**		**5.5**
Total answers	31		31
Standard deviation	1.54		1.34

The bed material question only applies to the two fluidised bed technologies as EFG does not use any bed material. The TRL given by the experts for both fluidised bed gasification technologies is in the average range, having been demonstrated at several plants, but still with a considerable need for further development. Issues mentioned are e.g. the task of finding environmentally acceptable bed materials that may be used at large scale or the ability of catalytically active bed materials to handle low-grade fuels and to reduce the tar level in the product gas. One expert sees slight advantages for FBG over DFBG as problems with recalcination of the bed material are less probable to occur.

5.1.6 Pressurisation

Table 6. Technology readiness level considering pressurisation for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**6.0**	**7.5**	**3.2**
Total answers	31	26	29
Standard deviation	1.92	2.00	2.02

EFG clearly has the highest ranking for pressurisation TRL with plants being operated at high pressure level by default. The positive effect of pressurisation also is pointed out as being most pronounced for EFG as the size reduction effect with increasing pressure is largest due to the design of the technology. FBG is considered being more or less mature at moderate pressures of up to 10 bar but higher pressures comparable to EFG are considered to be a challenge. Fuel preparation for and feeding to pressurised units is also mentioned as a critical issue in this context by the experts. DFBG technology is the one considered least ready for pressurisation. While the concept is considered feasible – even though challenging – by some experts there also are interviewees that consider DFBG unavailable for pressurisation at large scale (at least not higher pressures in the > 20 bar range).

5.1.7 Product gas cleanup

Table 7. Technology readiness level considering product gas cleanup for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**6.0**	**6.3**	**5.8**
Total answers	32	29	31
Standard deviation	1.68	1.95	1.76

The product gas cleanup TRL for all three technologies lies at around 6, with EFG obtaining the highest score. Gas cleanup is stated by the experts to be proven on a commercial scale but still having a need for further development to improve process efficiency and lower costs. Low-temperature cleaning is the most mature alternative but even high-temperature cleaning with e.g. ceramic filters is on the edge of being fully commercial with hot gas filters being installed in commercial gasification plants. Again the rich experience from coal-based gasification in EFG is a main reason for the higher score in the TRL ranking.

5.1.8 Tar removal

Table 8. Technology readiness level considering tar removal for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**5.3**	**6.7**	**5.3**
Total answers	31	25	30
Standard deviation	1.47	2.43	1.49

The tars are considered by a number of experts as not being an issue for EFG. Both fluidised bed technologies get average TRL ranking in the range of 5, with scrubbing technologies being available for tar removal mentioned in the comments. These scrubbing technologies, however, put penalties on the energy efficiency and operating costs. Alternative processes such as thermal or catalytic cracking are to be preferred but have not yet reached commercial scale. It is also pointed out that the tar problems are heavily dependent on the way the gasifier is operated and that general ranking is therefore difficult.

5.1.9 Soot handling

Table 9. Technology readiness level considering soot handling for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**6.2**	**6.3**	**6.4**
Total answers	26	23	25
Standard deviation	1.80	1.66	1.78

The TRL value for all three gasification technologies considering soot handling is in the range of 6. Some experts state that soot is not an issue at all. Soot (or char in fly ash) is assumed to be removed with the fly ash, resulting in energy losses, and the problem in consequence is reduced to an optimisation task improving char conversion in the gasifier, according to one expert.

5.1.10 Refractory lining

Table 10. Technology readiness level considering refractory lining for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**7.2**	**6.1**	**7.1**
Total answers	29	27	28
Standard deviation	1.35	1.87	1.39

Refractory lining issues are more relevant for EFG with a TRL mean value of 6.1, while the two fluidised bed technologies are just above a TRL of 7. Coal experience for EFG is a positive aspect, but differences in the mineral matter between biomass and coal ash make it difficult to directly transfer that knowledge. According to one expert, refractory lining issues "will never become mature"; low cost and long lifetime are two parameters that always will lead to a strive for improvement in this matter. Another expert points out that EFG might not even use refractory lining, but rely on a cooled molten ash layer for equipment protection instead (i.e. using a so-called cooling screen).

5.1.11 Heat recovery/steam cycle integration

Table 11. Technology readiness level considering heat recovery and steam cycle integration aspects for the three gasification technologies.

	FBG	EFG	DFBG
Mean TRL value	**6.0**	**5.6**	**6.1**
Total answers	30	27	29
Standard deviation	1.36	2.21	1.65

The TRL values for all three technologies are moderate, indicating a further need for development of heat recovery and steam cycle integration issues. But the nature of the question was also considered too general to be judged properly by one expert, the integration being highly dependent on the specific application and boundary conditions. Hot gas cleaning at commercial scale is an important milestone for the two fluidised bed gasification technologies in order to enable safe high temperature heat recovery. EFG with a steam quench and subsequent heat recovery steam generator on the other hand is commercial technology.

5.2 SINGLE FOREMOST TECHNICAL BARRIER OF EACH TECHNOLOGY FOR LARGE SCALE DEPLOYMENT

5.2.1 Direct Fluidised Bed Gasification (FBG)

For direct fluidised bed gasification (FBG) a number of experts actually mention that the technology already is available at commercial scale as air-blown technology and that air-blown FBG gasifiers are mature technology. It is considered important to distinguish between atmospheric and pressurised technologies as there are considerable differences in the level of maturity. The remaining challenge from their viewpoint is the conversion to operation on oxygen with the final goal of producing chemicals or transport fuels. This is also where the most often mentioned major technological barriers come into play – tar reduction in particular and gas cleaning and upgrading on a general level are by far the most frequently named ones. The respondents identify development needs both in primary (in the gasifier, e.g. by using catalytic bed materials) and secondary measures (e.g. tar reforming or removal) for tar reduction, as well as hot gas filters for efficient particle removal as important hurdles to overcome. Other aspects mentioned by several experts are potential problems that may occur in fluidised bed gasification when operating on low-grade fuels (e.g. agricultural wastes). These problems include bed agglomeration/ash sintering as well as alkali fouling. Even the preparation and feeding of these low-grade fuels are problematic and require further development to be used on a commercial scale. Furthermore, efficient char conversion to avoid problems with char in the fly ash is mentioned by some experts as the main technical barrier for direct fluidised bed gasification. The need for efficient heat recovery and risks for fouling of heat recovery equipment are also taken up by some of the respondents. Finally, operation under pressurised conditions and associated feeding problems are other issues mentioned by more than one expert. The least frequent issues that were only mentioned specifically by one of the experts (not all are of a purely technical nature, actually) include the total costs of the system, risks for low plant availability, transport logistics, oxygen demand in syngas applications, and the unknown fuel/ash behaviour in oxygen-blown gasification.

5.2.2 Entrained Flow Gasification (EFG)

The comments given on question 2 for EFG represent well the trend in the TRL grading asked for in question 1. The by far most frequent answer on the foremost technical barrier for large-scale entrained flow gasification of biomass given by the experts is on fuel pre-treatment and on feeding into the reactor. The pre-treatment and feeding are not yet considered mature and have not yet been demonstrated commercially. But even the costs for the pre-treatment and associated energy losses are often mentioned as barriers. Even the cost for the overall system of EFG is mentioned by a number of experts, and in relation to that the size of EFG is simply considered too large (as it needs to be large to be economic) for biomass operation – problems associated with transport logistics are taken up by a number of respondents. In addition, one expert mentions little experience with operation on biomass only as an issue for EFG. Associated to efficiency issues, complete fuel conversion and efficient use of excess heat, are also named as major barriers. Material problems, fuel/ash behaviour and uncertainties or lack of experience when operating on low-grade fuels in general, are other issues taken up by several experts. Finally, particle and gas separation, gas upgrading, oxygen supply and the fact that ash from EFG is not usable as fertiliser are each considered the major technical barrier by one expert.

5.2.3 Indirect Dual Fluidised Bed Gasification (DFBG)

As for direct fluidised bed gasification, the technical barrier in relation to indirect dual fluidised bed (DFBG) technology mentioned most frequently by the experts is gas cleaning and upgrading, with a number of experts referring more specifically to tar problems. The gas cleaning is seen as key to commercial applications and high-temperature gas cleaning a necessary technology not yet available at commercial scale. Less expensive gas cleaning technologies to make the process viable from an economic perspective are also identified being necessary. The second most frequent issue taken up by the respondents is the fact that indirect gasification technology is limited in the level of pressurisation and in consequence is limited in feasible size. Another expert sees limits in scale due to excess heat only being used for district heating, while the complexity of DFBG with two interconnected fluidised beds is considered an issue for up-scaling by another one. The less frequent barriers mentioned as being foremost include gas cooling and heat recovery equipment fouling issues, limited availability of the system, methane reforming issues for syngas applications, little experience with low-grade fuel resulting in low levels of maturity considering fuel flexibility, and fuel conversion issues related to the integration between the two reactors in DFBG. Finally, barriers only mentioned by one expert each include, feeding issues, alkali fouling (could be related to heat recovery equipment fouling), transport logistics, and problems of designing an economically viable process, in particular for CHP applications where less expensive alternatives exist even though they might be less efficient from a thermodynamic viewpoint.

5.3 MAXIMUM THERMAL INPUT SCALE THE GASIFICATION TECHNOLOGIES CAN BE BUILT AT AS OF TODAY

The estimations on maximum possible scale of the three gasification units vary considerably between the different experts in absolute numbers, but the general trends on a relative scale between the technologies are similar; the entrained flow gasifier can be scaled up most with some experts estimating possible scales even above 1000 MW_{th} input. For direct fluidised bed gasification the maximum sizes mentioned are in the 600-700 MW_{th} range and most experts consider indirect fluidised bed gasification maximum scales to be somewhat lower than for FBG due to the fact that no pressurised concept is currently available and unlikely will be in the medium term. Using the mean value by counting all numbers given by the experts (average scale used when a range is indicated) gives a very rough approximation but still represents the general trend of EFG being the technology possible at large scale (average maximum scale at about 680 MW_{th}), followed by FBG (about 240 MW_{th}), and finally DFBG (about 130 MW_{th}). As pointed out by one expert, the question of maximum scale may be considered not that relevant as it always is possible, and to some extent even desirable (plant availability), to install parallel units. This would theoretically allow scaling up all three technologies to any desired capacity, even though economic benefits of scale are lost when using a modular approach. Another important aspect raised by some respondents is the fact that the maximum scale of a biomass gasification system might be restricted by biomass logistics rather than the technical limitations for up-scaling. A range of 300 MW_{th} is mentioned as a maximum conceivable size considering logistics basically making all three gasification technologies available (maybe in a modular approach for DFBG and FBG).

5.4 NON-TECHNICAL BARRIERS FOR LARE-SCALE DEPLOYMENT OF BIOMASS GASIFICATION

For all three gasification technologies the major non-technical barrier mentioned by the experts is of economic nature. On the one hand there are high investment costs to be expected for the first generation of biomass gasification plants, and on the other hand market prices are subject to large fluctuations with biomass prices being high in relation to fossil alternatives. This leaves little to no margin for profit and therefore decreases the interest of private investors. Long-term policy measures (e.g. CO_2 tax relief) for biofuels and investment support are considered necessary by the experts to enable large scale deployment of biomass gasification. As the size of plants needs to be large in order to gain on economies of scale, the biomass supply also is a large barrier. It might be difficult to fix a long-term supply contract for biomass at these scales. Competition with other biomass applications that have lower specific costs (as e.g. biomass CHP), is also mentioned as a serious barrier. One expert mentions the lack of suppliers of technology that can build turn-key plants with guarantees as a large barrier for all three technologies. More specific barriers for each of the three technologies mentioned by the experts are presented in the following.

5.4.1 Direct Fluidised Bed Gasification

For direct fluidised bed gasification the lack of long-term experience with plants and several negative examples of mothballed plants may have lead to a negative public perception of the technology, now representing a considerable non-technical barrier for this technology. The need for efficient system integration and usage of the excess heat available from the process also figure among barriers mentioned. Finally, risks for fire hazard from the carbon-containing ash and problems meeting emission regulations when using the product gas in engines are other barriers mentioned by one expert each.

5.4.2 Entrained Flow Gasification

Uncertainties with EFG technology and possibly negative public perception are among the non-technical barriers for entrained flow gasification that are taken up. Grinding of the fuel (actually being a technical barrier) and meeting emission regulations are two more barriers that are mentioned by single respondents. Finally, the efficiency penalty of the high temperature process for EFG is referred to as non-technical barrier by another expert.

5.4.3 Indirect Dual Fluidised Bed Gasification

For indirect dual fluidised bed gasification negative public perception (possibly caused by mixing up FBG and DFBG) is mentioned by one expert as a barrier of non-technical nature. In a similar way lack of public knowledge may hinder the large-scale deployment of DFBG according to another interviewee. Lack of incentives for cogeneration from biomass, and difficulties meeting engine emission regulations when using product gas from DFBG, are two more barriers mentioned. A lack of long-term experience with different fuels and the competition with other biomass technologies with lower capital costs are two more barriers, according to the expert survey.

5.5 FURTHER COMMENTS AND REFLECTIONS

The general comment given by the experts on aspects lacking in the survey is basically a summary of the answers condensed in the preceding paragraphs. Lack of long-term experience with large scale units, uncertain economic boundary conditions in combination with high investment costs, negative experiences, and public perception of biomass gasification, are all mentioned among the comments. A need for reducing the complexity of the systems, in order to decrease costs, is identified and mainly feeding and tar cleaning/product gas cleaning are pointed out as the bottlenecks in biomass gasification that still need further development. Again, competition with other biomass-based applications that already are commercial and perform well is pointed out as a barrier for the large-scale deployment of biomass gasification. As gasification technologies already have been demonstrated for coal, a difficult task for biomass gasification is the choice between trying to adapt the fuel to coal properties (e.g. by torrefaction or pyrolysis), or modifying the technology itself to fit biomass feedstock with all its differing fuel properties compared to coal. The general consensus is that there are numerous technical solutions available but due to high costs they have not yet been demonstrated in the long term at large scale. Given economic profitability, experts consider all technical barriers rather easy to overcome and are also optimistic concerning large scale deployment as there are by now three large companies offering biomass gasification technology concepts. With today’s focus on thermal efficiency biomass, gasification is still outperformed by conventional technologies such as combined heat and power technology. However, advanced concepts for energy-carrier generation, e.g. CH_4 production by addition of H_2 from electrolysis for complete methanation of biomass-based syngas (100 % carbon conversion from biomass to product possible), clearly offer advantages for biomass gasification in comparison to conventional biomass applications considering the value chain.

6 DISCUSSION AND CONCLUSIONS

A general question that partly arose from the comments given by the experts, concerns the conceptual thinking when planning biomass-based production of fuels and chemicals. The common approach is to start from the processes that initially were developed for fossil-based feedstock and to try to adapt biomass gasification to fit considering the requirements on the product gas. A problematic issue with this approach is that – in order to design an economically viable process – processes usually need to be at a very large scale. For example, a petroleum oil refinery thermal throughput exceeds by far what can be expected of biomass gasification-based systems.[3] In consequence, it is difficult to develop processes that are economically feasible. Another approach is to try to develop processes specifically adapted for biomass-derived product gas. This could imply developing catalysts with a better resistance against trace components, reducing the needs for product gas cleaning. An example of a process specifically adapted for biomass is the methanation technology developed in connection with the methanation tests in Güssing (Seemann 2006). In general, technologies that allow economic operation even at small scale, compared to fossil-based refining processes, need to be aimed for.

Economic aspects are also taken up by most of the experts to represent the major non-technical barrier. A consensus among the experts is that technology for large-scale gasification basically exists but that high price levels of biomass fuels in comparison to the competing fossil fuels do not result in incentives for companies to actually invest in large-scale processes. Clear and long-term policy measures are necessary to ensure production of biomass-based transportation fuels from gasification in the medium term.

Independently of type of gasification concept, Tom Reed (Milne *et al*. 1998) summarises the main hurdle for success as: “While a great deal of time and money has been spent on biomass gasification in the last two decades, there are very few truly commercial gasifiers, operating without government support or subsidies, day in, day out, generating useful gas from biomass. The typical project starts with new ideas, announcements at meetings, construction of the new gasifier. Then it is found that the gas contains 0.1-10 % ‘tars’. The rest of the time and money is spent trying to solve this problem. Most of the gasifier projects then quietly disappear. In some cases the cost of cleaning up the experimental site exceeds the cost of the project! Thus ‘tars’ can be considered the Achilles heel of biomass gasification. In the gasification of coal, a more mature technology, the ‘tars’ (benzene, toluene, xylene, coal tar) are useful fuels and chemicals. The oxygenated ‘tars’ from biomass have only minor use. With current environmental and health concerns, we can no longer afford to relegate ‘tars’ to the nearest dump or stream.”

In the following, conclusions specific to the three gasification technologies that can be drawn from this report are summarised.

[3] The Preem refinery in Gothenburg, Sweden (one of the smaller refineries in Europe) is refining about 6 million tonnes of crude oil (assumed lower heating value of 42.7 GJ/t) per year, corresponding to a thermal input of 8100 MW

6.1 FLUIDISED BED GASIFICATION

The presence of tar in the product gas poses a great problem and challenge for the FBG process concept. There is still not a robust, economic method for handling the tars generated; a combination of primary and secondary measures is needed.

Bed agglomeration and defluidisation especially when operated on oxygen is problematic, this, though, in principle only with non-woody biomasses.

Gas cleaning, especially hot gas particle removal, is an important aspect and not fully solved today. If for syngas application and upgrading a combination of particle removal, tar removal, CO shift, cooling and methane reforming is needed. If for fuel gas application (power generation) though a focus on particle removal and tar removal suffices.

For pressurised synthesis gas production a separate oxygen supply is needed, which calls for (very) large-scale applications. Problems with pressurisation include fuel feeding and oxygen-blown operation. Pressurised applications for synthesis gas upgrading have been demonstrated at pilot scale, but not on a larger scale. It is important to find a less costly solution to feeding biomass into pressurised gasifiers than pelletisation.

Additional aspects of importance include the expensive pelletisation of biomass in general, the transport logistics of a fuel with low energy density such as biomass and an efficient char conversion/burn out.

6.2 ENTRAINED FLOW GASIFICATON

Besides all the economic aspects related to the price of the biomass, it is clear that, in order to make further short-term progress for biomass based EFG applications, successful commercial demonstrations are needed. This is especially motivated by the relatively low TRL scoring presented for upstream processing of the biomass (i.e. pre-treatment, feeding and flexibility) for EFG and the need for positive public perception of the technology concept. However, in order to achieve this, long-term policy measures for biofuels and investment support are needed (e.g. NER 300 initiatives and tax policies). For more economically viable implementations in long-term, simple technology solutions should be sought for in order to make the scale of plant a secondary issue and thereby widen the range of scales for possible installations. The main apparent challenges in this case are to obtain: Efficient use of excess heat; cost-effective syngas upgrading; and low-cost oxygen generation.

In order to achieve long-term development of the EFG concept, successful demonstration of feeding of different biomass feedstock is of most importance since this is often a cause operational failure. Furthermore, research should be focussed on further technology improvement for complete fuel conversion (including soot and higher HCs) and materials science related to fuel/ash/refractory behaviour, especially for a wide range of low-grade biomass feedstock. It is believed that low cost and long lifetime are two parameters that always will strive for improvement of the refractory material in EFG.

6.3 DUAL FLUIDISED BED GASIFICATION

For indirect DFBG technology the major technological barrier is related to the amount of tars generated and treatment needed as well as to the gas cleaning in general. Aiming at production of transportation fuels or chemicals a synthesis step is necessary and these synthesis steps require a very clean product gas. Techniques for performing the tasks of tar removal and gas cleaning exist, but at the current state of development they penalise the process in several ways: First of all they limit opportunities for heat recovery and efficient cogeneration of heat, and – at larger scale – power (via a Rankine cycle). Secondly, currently available tar scrubbing technologies lead to increased operating costs, reducing the economic competitiveness of the process.

For large-scale production of biofuels and chemicals DFBG is the technology that currently has the smallest available scale on a commercial basis. But even though pressurisation for scaling up to the maximum ranges of >500 MW_{th} is an unlikely development due to the complexity of the system, scaling up DFBG to about 200-300 MW_{th} should not pose any technical problems. Therefore the size of DFBG is not considered a serious barrier in the future; modular approaches will allow for large plants, while it actually is questionable whether the size of biomass-based plants will pass the range of 300 MW_{th} due to limits in biomass logistics.

Fuel flexibility, including the capability to use low-grade fuels, is another issue that still needs attention. Fuel size and mechanical properties are not a problem, but trace elements in for instance the ash of the fuel, may lead to serious problems in operating fluidised beds as bed material sintering and as a consequence complete gasifier turn-down is a potential hazard. Also gas cleaning will have to be adapted to make sure the downstream processes can operate safely without for catalysts being poisoned.

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APPENDIX A - QUESTIONNAIRE

Questionnaire

Biomass gasification – a synthesis of technical barriers and current research issues for deployment at large scale

This simple questionnaire focuses on the key critical technology challenges for the biomass-based gasification concepts mainly being considered in Sweden today: direct Fluidised Bed Gasification (**FBG**); Entrained Flow Gasification (**EFG**); indirect Dual Fluidised Bed Gasification (**DFBG**). The purpose is to provide the most up-to-date input from some of the experts in the field (approx. 35 international experts) as a common (anonymous) compiled part of a synthesis report work being carried out by researchers within the Swedish Gasification Centre and financially supported by the Swedish Knowledge Centre for Renewable Transportation Fuels (f^3).

Name: ____

Affiliation:____

1) From your best and most objective point of view, please rate the appropriate Technology Readiness Level for each of the listed technical issues and technologies below on a scale from 1 to 9 (where 1 = "basic principles observed/low degree of maturity/extensive development needed"; 6 = "subsystem demonstrated in relevant pilot environment/mature/some development needed" and 9 = "successfully proven commercially in full scale/fully mature/no further development needed"). Note, put a dash (-) in places where you find it difficult or not applicable to provide a number and add a comment if needed:

Technical issue	FBG	EFG	DFBG	Short comment
Fuel preparation				
Fuel feeding				
Fuel flexibility				
Up-scaling to large scale (>100 MW range)				
Bed material				
Pressurisation				
Product gas cleanup (general)				
Tars in product gas				
Soot handling				
Refractory lining				
Heat recovery/steam cycle integration				

2) From your viewpoint, what is the **single foremost technical barrier for large scale deployment** of the following biomass gasification technologies (put a dash (-) for the ones you find it difficult to give an answer to):

a. direct Fluidised Bed Gasification (**FBG**)

____

b. Entrained Flow Gasification (**EFG**)

____

c. indirect Dual Fluidised Bed Gasification (**DFBG**)

____

3) As of today, what do you consider to be the **maximum thermal input scale** that the following gasification technologies can be built for?

a. direct Fluidised Bed Gasification (**FBG**)

____

b. Entrained Flow Gasification (**EFG**)

____

c. indirect Dual Fluidised Bed Gasification (**DFBG**)

____

4) Are there any **non-technical barriers** for large-scale technology deployment that need special attention for each technology?

a. direct Fluidised Bed Gasification (**FBG**)

____

b. Entrained Flow Gasification (**EFG**)

____

c. indirect Dual Fluidised Bed Gasification (**DFBG**)

____

5) Based on your expertise and reflection on the questions above, would like to add any further comments on technical barriers, specific or in general?

____

____

____

____

APPENDIX B – DETAILED QUESTIONNAIRE RESULTS

In the following the results of the online survey conducted are presented in their original form. Expert comments on the different questions are listed and the data for the grading of the technology readiness level (TRL) for the different technology aspects of the three gasification technologies given by the experts are presented. For the TRL data, several indicators are given in tables that are defined in the following:

Total answers: The total number of experts N that answered the question

Mean value: The average TRL value TRL_{mean} calculated from all answers

Range: Range of TRL between minimum and maximum value (e.g. answers in the range of TRL = 3 to TRL = 9 => Range = 6)

Absolute deviation: Absolute deviation according to

$$dev_{abs} = \frac{1}{N}\sum_{i=1}^{N}\left|\left(TRL_i - TRL_{mean}\right)\right|$$

Variance: Variance according to

$$\text{var} = \frac{1}{N-1}\sum_{i=1}^{N}\left(TRL_i - TRL_{mean}\right)^2$$

Standard deviation: Standard deviation according to $\sigma = \sqrt[2]{\text{var}}$

B 1-1. TRL – FUEL PREPATATION

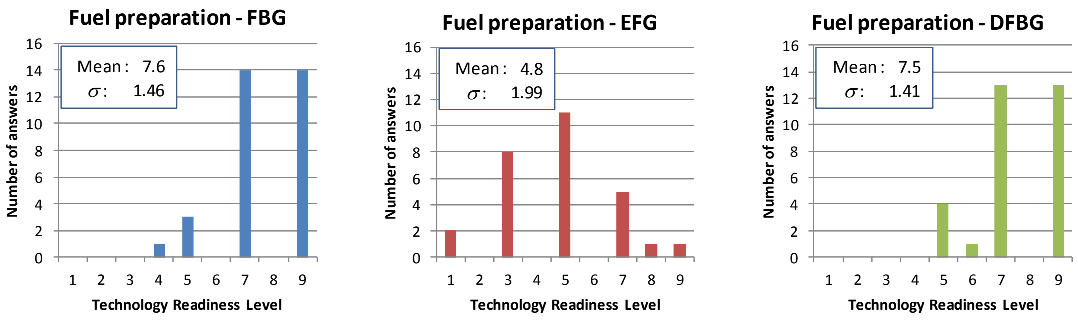

Figure B-1. Technology readiness level judgement on fuel preparation aspects for FBG (blue), EFG (red), and DFBG (green).[4]

Table B-1. Data for the TRL answers collected considering fuel preparation.

	FBG	EFG	DFBG
Total answers	32	28	31
Mean value	7.6	4.8	7.5
Range	5	8	4
Absolute deviation	1.23	1.54	1.22
Variance	2.12	3.97	1.99
Standard deviation σ	1.46	1.99	1.41

Comments:

- EFG: torrefaction or pyrolysis assumed as processes.
- Responses different for non-woody biomasses, which are less mature.
- EFG pyrolysis/milling/torrefaction development and demonstration needed.
- Further development needed to handle low rank fuels and waste.
- EFG may have a 5 - Bioliq[5] process or a 9 Chemrec[6].
- Depends on type of pre-treatment assumed.
- Including also pyrolysis oil as feed to EFG.

[4] The scale of the Technology Readiness Level was refined for this question (whole scale from 1-9) as one expert asked for that in a comment.

[5] Biomass to Liquid - the bioliq Process, http://www.bioliq.de/english/55.php, 2013-02-05

[6] Chemrec - a gasification technology inherently more efficient, http://www.chemrec.se/, 2013-02-05

B 1-2. TRL – FUEL FEEDING

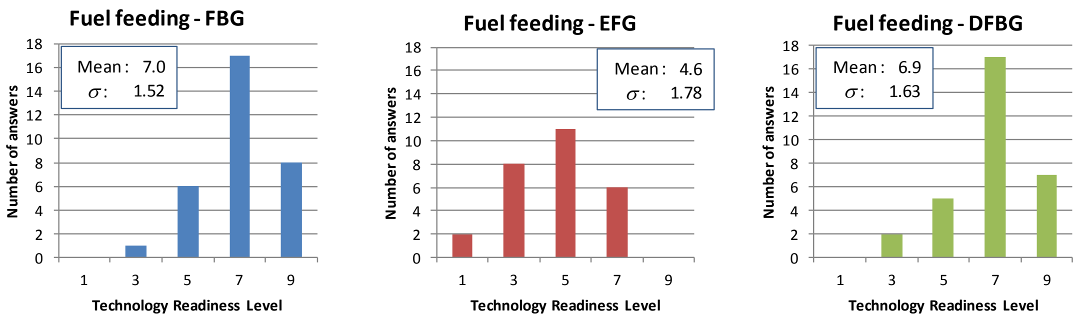

Figure B-2. Technology readiness level judgement on fuel feeding aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-2. Data for the TRL answers collected considering fuel feeding.

	FBG	**EFG**	**DFBG**
Total answers	32	27	31
Mean value	7.0	4.6	6.9
Range	6	6	6
Absolute deviation	1.00	1.45	1.10
Variance	2.32	3.18	2.65
Standard deviation σ	1.52	1.78	1.63

Comments:

- Co-feeding with coal/coke in EFG demonstrated commercially.
- Promising for EFG, but still after existing FB systems.
- FBG: atmospheric operation.
  EFG: liquids easier than solid powders.
- Depends on reactor pressure.
- FBG, DFBG successful demos in e g Värnamo/Sweden[7], Skive/Denmark[8], Güssing/Austria[9] etc.
- EFG: For liquid fuels (black liquor, pyrolysis oil and similar fuels fuel feeding is mature (TRL: 9)[10] .
- FBG for pressurised.
- For liquid biomass fuels it works nicely. For solid fuels OK for atmospheric, but more difficult for pressurized systems.
- Note that FBG and EFG are considered HP while DFBG LP.
- Different numbers for atmospheric and pressurized technologies would be required[11].

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[7] Växjö Värnamo Biomass Gasification Centre http://www.vvbgc.se/ (In Swedish), 2013-02-05

[8] First-of-its-kind at Skive http://spectrum.andritz.com/index/iss_20/art_20_16.htm, 2013-02-05

[9] FICFB-Reactor - Thermal Gasification, http://www.guessingrenewable.com/htcms/en/wer-was-wie-wo-wann/wie/thermische-vergasungficfb-reaktor.html, 2012-02-05

[10] The expert has rated EFG Fuel feeding TRL to 3 in the questionnaire

[11] The expert only rated FBG (TRL: 5)

B 1-3. TRL – FUEL FLEXIBILITY

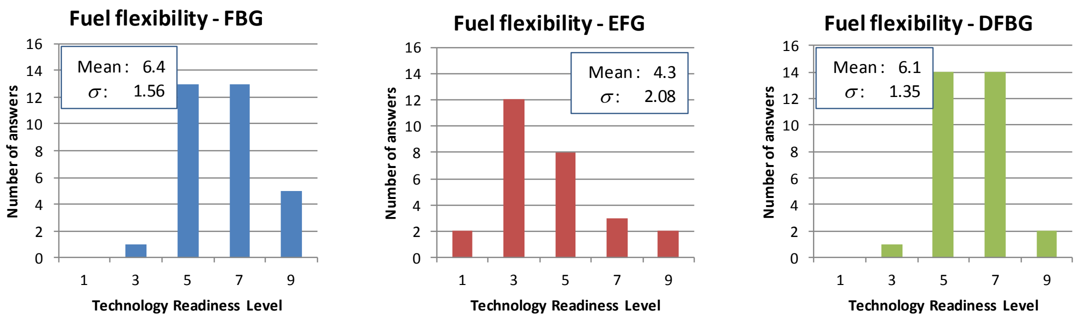

Figure B-3. Technology readiness level judgement on fuel flexibility aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-3. Data for the TRL answers collected considering fuel flexibility.

	FBG	**EFG**	**DFBG**
Total answers	32	27	31
Mean value	6.4	4.3	6.1
Range	6	8	6
Absolute deviation	1.33	1.68	1.19
Variance	2.44	4.31	1.82
Standard deviation σ	1.56	2.08	1.35

Comments:

- Depending largely on grindability for EFG.
- All types of processes sensitive to ash behaviour, but in different ways, still need extensive work.
- Fuel properties an important variable where more development is needed.
- Different types of biomass need a clear definition.
- To my knowledge there is no DFBG plant operating on waste as fuel, the EFG needs finely ground biomass.
- Pressurized oxygen blown gasification.
- FBG - extensive tests performed in Värnamo & GTI. Outcome generally positive but still need for further mapping of fuel envelope and practical measures.
  DFBG/Repotec - still very limited fuel envelope demonstrated.
- This topic may not be judged by TRL?
- Different numbers for atmospheric and pressurized technologies would be required.[12]

[12] The expert only rated FBG (TRL: 7)

B 1-4. TRL – UP-SCALING TO LARGE SCALE

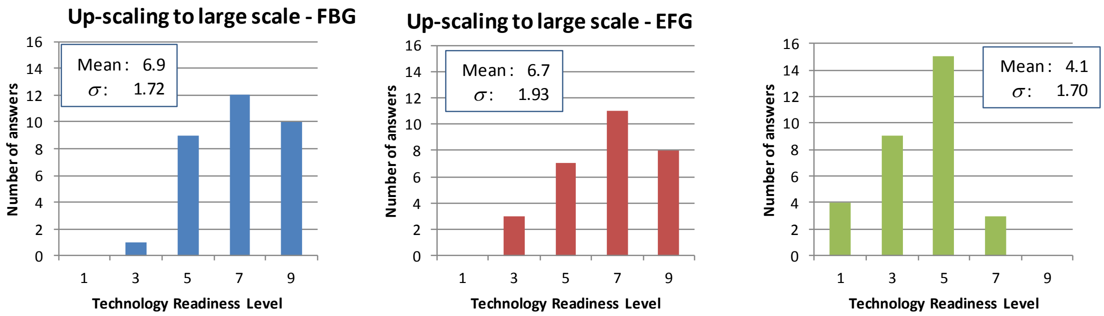

Figure B-4. Technology readiness level judgement on up-scaling aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-4. Data for the TRL answers collected considering up-scaling to large scale.

	FBG	**EFG**	**DFBG**
Total answers	32	29	31
Mean value	6.9	6.7	4.1
Range	6	6	6
Absolute deviation	1.34	1.56	1.44
Variance	2.96	3.73	2.89
Standard deviation σ	1.72	1.93	1.70

Comments:

- FBG, for oxygen steam blown, for air blown it is a 9[13].
- EFG system typically already sold as 500MW gasifiers (for coal).
- DFBG-up-scaling significant challenge. Viable concept still missing.
- The EFG principle is scalable to very large scales but fuel feeding of dry solids/powders needs further development.
- Atmospheric CFBs already exist in Finland.
- FBG and EFG have the capability but not LP DFBG.
- Different numbers for atmospheric and pressurized technologies would be required.[14]

[13] The expert rated the TRL for FBG up-scaling to 5

[14] The expert only rated FBG (TRL: 5)

B 1-5. TRL – BED MATERIAL

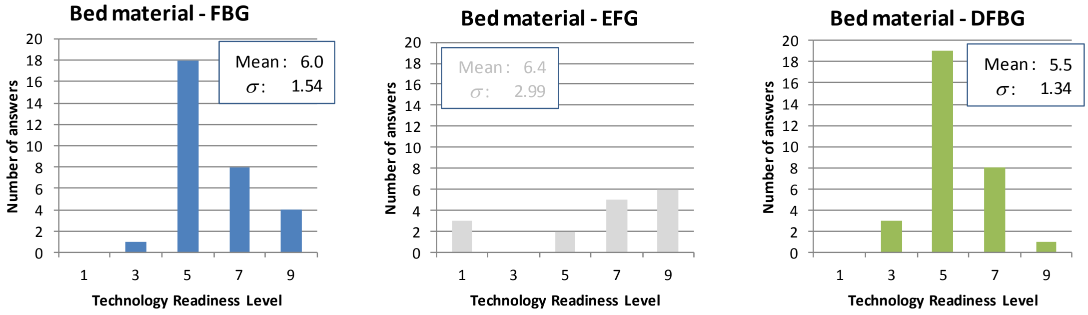

Figure B-5. Technology readiness level judgement on bed material aspects for FBG (blue), EFG (grey) – not relevant, and DFBG (green).[15]

Table B-5. Data for the TRL answers collected considering bed material.

	FBG	EFG	DFBG
Total answers	31	16	31
Mean value	6.0	6.4	5.5
Range	6	8	6
Absolute deviation	1.32	2.36	1.03
Variance	2.37	8.92	1.79
Standard deviation σ	1.54	2.99	1.34

Comments:

- Environmentally acceptable bed material is also an issue.
- No bed material in EFG.
- EFG also needs control of ash behaviour.
- Does not apply to EFG.
- Question not relevant for EFG.
- EFG does not need bed material.
- Not relevant for EFG.
- Not an issue for EFG, room for improvement for FBG and DFBG.
- EFG has no bed material; FBG and DFBG are operated on commercial basis. However, development needed for improved operation (e.g. catalytically active bed material to reduce tar levels).
- EFG irrelevant here.
- In EFG bed material is not needed.
- EFG n a. FBG several demos and also less prone to problems with recalcination than DFBG.
- Not relevant in EFG.
- EFG: Question is not relevant.
- EFG has another issue running in slagging mode. Experiences limited (except for Black Liq).

[15]As pointed out by the expert, entrained flow gasification units operate without bed material and the question therefore is not relevant for EFG.

B 1-6. TRL – PRESSURISATION

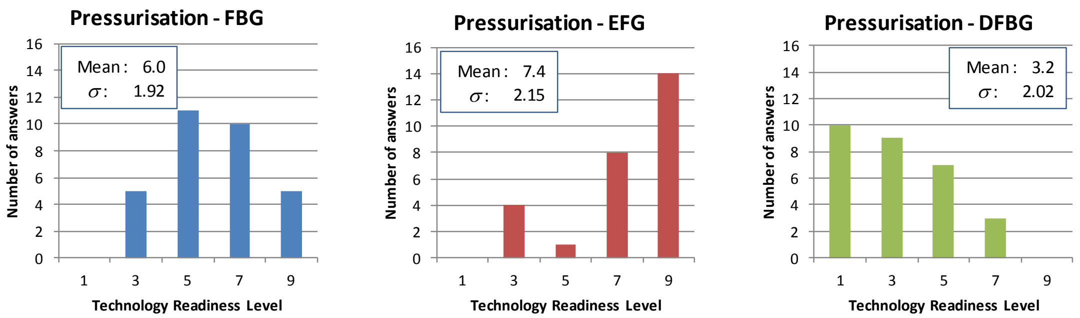

Figure B-6. Technology readiness level judgement on pressurisation aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-6. Data for the TRL answers collected considering pressurisation.

	FBG	EFG	DFBG
Total answers	31	27	29
Mean value	6.0	7.4	3.2
Range	6	6	6
Absolute deviation	1.64	1.69	1.65
Variance	3.70	4.63	4.10
Standard deviation σ	1.92	2.15	2.02

Comments:

- DFGB needs to include a compressor for the combustion air and a turbine on the flue gas stream, which makes it more suitable to operate the gasifier at atmospheric pressure and compress the low amount of dry product gas. The technical solution for pressurising is, however, available e.g. in Värtan[16].
- Most likely not an issue for DFBG.
- FBG up to ~6-10 bar semi-mature, higher pressure is a challenge. EFG conditioned fuel preparation successful should not pose significant problems. DFBG - see above.
- EFG except fuel feeding
- DFBG: Questionable if it will ever be possible to operate at >20 bar. EFG vs FBG: Size reduction with increasing pressure more rapid with EFG. Fuel residence time in flight is the design parameter for EFG while for FBG it is dictated by the fuel residence time in the bed and this is not affected by pressure. Only the freeboard residence time is affected by pressure.
- EFG: If PO (pyrolysis oil) then pressure >20 bar OK (TRL: 4). Dry feed needs further development (TRL: 2); DFBG not suited for HP.

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[16] Two pressurised fluidised bed combustors (PFBC) with a total thermal effect of about 450 MW_{th} installed at Värtaverket in Stockholm/Sweden operating on coal with co-feeding of crushed olive pits Värtaverket CHP-plant, http://www.fortum.com/en/energy-production/combined-heat-and-power/sweden/Documents/Download%20V%C3%A4rta%20CHP%20power%20plant%20brochure.pdf, 2013-02-08.

Miljörapport 2011 – Värtaverket (Environmental report in Swedish), http://www.fortum.com/countries/se/SiteCollectionDocuments/vartaverket-miljorapport-2011.pdf, 2013-02-08.

B 1-7. TRL – PRODUCT GAS CLEANUP

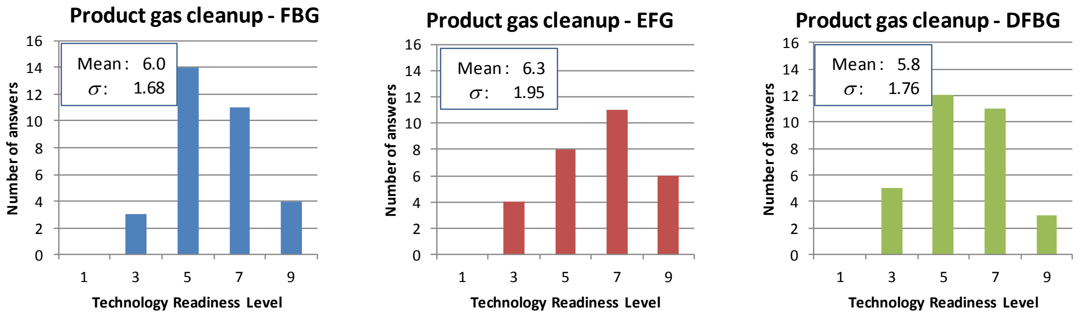

Figure B-7. Technology readiness level judgement on product gas cleanup aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-7. Data for the TRL answers collected considering product gas cleanup.

	FBG	EFG	DFBG
Total answers	32	29	31
Mean value	6.0	6.3	5.8
Range	6	6	6
Absolute deviation	1.44	1.64	1.49
Variance	2.84	3.79	3.11
Standard deviation σ	1.68	1.95	1.76

Comments:

- Depends on process layout - is the particle removal made below 450 C it is a 9.[17]
- Reduce costs, plenty of experience from coal-EFG.
- Maybe I am ignorant but I am not aware of any EFG operating on biomass (except the Black Liquor gasification pilot in Piteå) I put a lower value on that one. The FBG and DFBG are operated on commercial basis so the clean up works but it can of course always be improved, e.g. development of high temperature filtration in combination with catalytic tar conversion.[18]
- Rating based on working gasifiers - see above.[19]
- You need to define purity of gas.
- Assuming clean up for synthesis (tars and sulphur compounds in the ppb level).[20]
- Low temperature filters with pre-coat are working nicely but less experience for higher temperature with ceramic filters, although now full scale implemented in Lahti for CFB.[21]
- For generation of syngas.

[17] The comment refers to both FBG and DFBG that the expert rated to 7 on the TRL scale.

[18] The experts rating on TRL for gas cleanup is: FBG: 9, EFG: 7, DFBG: 9.

[19] The experts rating on TRL for gas cleanup is: FBG: 5, EFG: 7, DFBG: 3.

[20] The experts rating on TRL for gas cleanup is: FBG: 5, EFG: 9, DFBG: 5.

[21] Lahti CHP gasification plant, http://www.lahtigasification.com/, 2013-02-10.

B 1-8. TRL – TAR REMOVAL

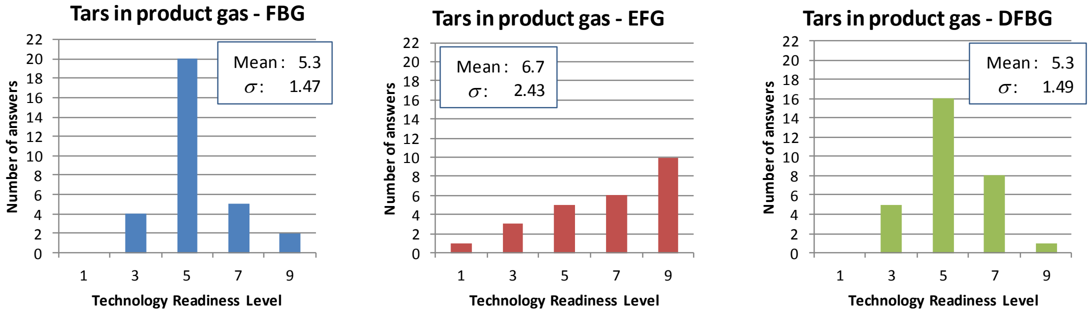

Figure B-8. Technology readiness level judgement on tar removal aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-8. Data for the TRL answers collected considering tar removal.

	FBG	EFG	DFBG
Total answers	31	25	30
Mean value	5.3	6.7	5.3
Range	6	8	6
Absolute deviation	1.02	2.01	1.13
Variance	2.16	5.89	2.23
Standard deviation σ	1.47	2.43	1.49

Comments:

- Scrubbing technologies are commercially available, however catalytic cracking is preferred from the viewpoint of energy efficiency and this is still not proven commercially.
- Different types of tar removal in commercial practice for each type of gasifier.
- This question (like 1.7) is not dependent on the gasifier design.
- Not relevant to EFG.
- Not an issue for EFG, room for improvement for FBG and DFBG depending on the application of the syngas.
- It's not easy to answer since it depends on at which temperature the gasifier is operated. EFG is normally operated at high temperatures and shouldn't suffer from tars, FBG is normally operated at higher temperatures than DFBG. There are tar removal techniques for DFBG but they are costly so further development is needed to increase efficiency and lower the gas cleaning cost.
- It is not always needed to remove the tars.
- DFBG rely on tar scrubbing by RME - a very primitive technique (adaptable to FBG as well). FBG more developed concepts demonstrated to some extent. EFG full conversion part of concept
- EFG: less relevant.
- For EFG perhaps not relevant.
- Exist for coal, but haven´t heard that there is commercially for biomass??

B 1-9. TRL – SOOT HANDLING

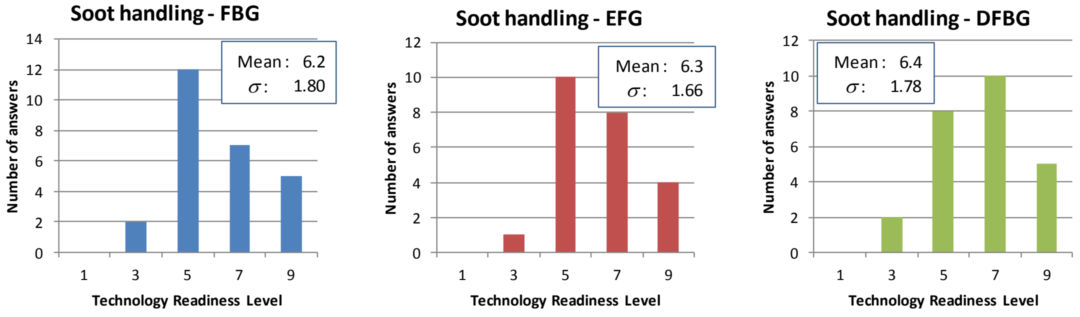

Figure B-9. Technology readiness level judgement on soot handling aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-9. Data for the TRL answers collected considering soot handling.

	FBG	EFG	DFBG
Total answers	26	23	25
Mean value	6.2	6.3	6.4
Range	6	6	6
Absolute deviation	1.55	1.42	1.47
Variance	3.26	2.77	3.17
Standard deviation σ	1.80	1.66	1.78

Comments:

- Not an issue.
- No clue.
- Soot normally not converted but removed.
- Question a bit odd - assume char in fly ash is the relevant one. Techniques exists - mainly an optimization task.
- For EFG perhaps not relevant.
- FBG and DFBG not relevant.
- Imagine FBG and DFBG have quite a lot experience through operations. Not the case with EFG.

B 1-10. TRL – REFRACTORY LINING

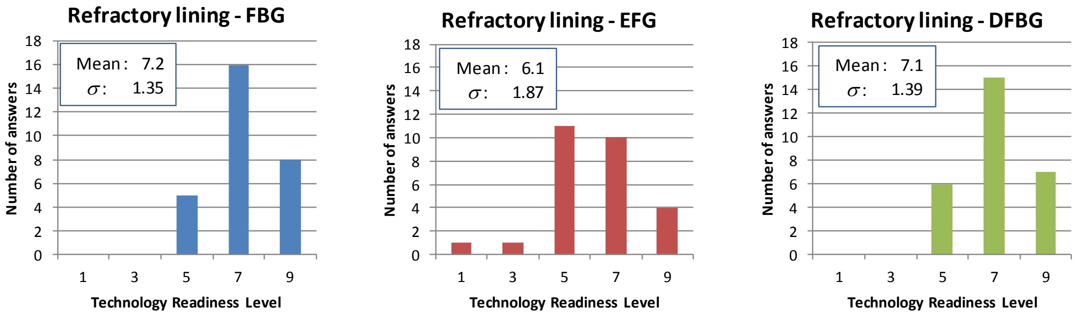

Figure B-10. Technology readiness level judgement on fuel flexibility aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-10. Data for the TRL answers collected considering refractory lining.

	FBG	EFG	DFBG
Total answers	29	27	28
Mean value	7.2	6.1	7.1
Range	4	8	4
Absolute deviation	0.99	1.51	0.96
Variance	1.81	3.49	1.92
Standard deviation σ	1.35	1.87	1.39

Comments:

- Refractory on EFG with low biomass mineral matter is not known.
- Utilising coal experience is beneficial for EFG, but on the other hand more harsh environment.
- EFG normally not refractory lined but with cooled molten ash layer.
- Sufficiently demonstrated for FBG/DFBG. Situation more unclear for EFG considering chemical activity of ash at elevated temperatures.
- This is an issue that will never become mature. Price is an important parameter, lifetime another and the ultimate goal is zero price and infinite life time which will never occur.
- FBG for pressurised CFB.

B 1-11. TRL – HEAT RECOVERY/STEAM CYCLE INTEGRATION

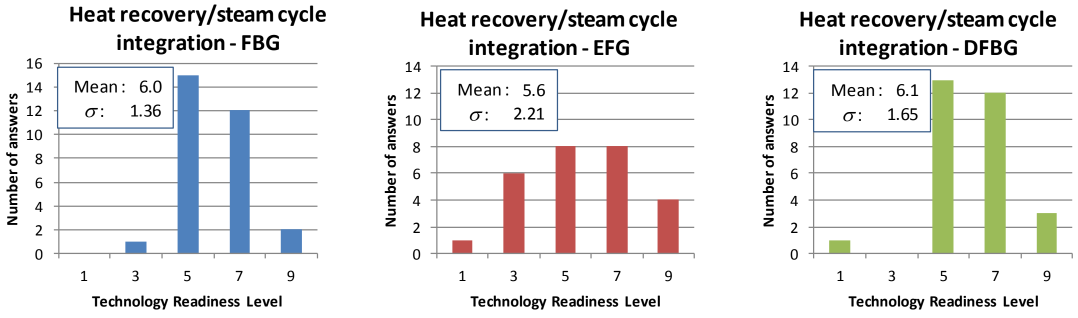

Figure B-11. Technology readiness level judgement on heat recovery/steam cycle integration aspects for FBG (blue), EFG (red), and DFBG (green).

Table B-11. Data for the TRL answers collected considering fuel preparation.

	FBG	EFG	DFBG
Total answers	30	27	29
Mean value	6.0	5.6	6.1
Range	6	8	8
Absolute deviation	1.20	1.84	1.34
Variance	1.86	4.87	2.74
Standard deviation σ	1.36	2.21	1.65

Comments:

- A very general question - hard to set a fair rating - many conditions to include.
- High temperature filters are very important for fluidised bed gasification. This is challenging due to the high amount of tars and particles in the raw gas. For EFG the design often incorporates a quench and a heat recovery steam generator which is mature technology.

B-2. FROM YOUR VIEWPOINT, WHAT IS THE SINGLE FOREMOST TECHNICAL BARRIER FOR LARGE SCALE DEPLOYMENT OF THE FOLLOWING BIOMASS GASIFICATION TECHNOLOGIES?

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
1	Oxygen blown gasification, efficient char conversion and an efficient combination of primary and secondary measures to reduce tars.	Cost and energy efficient fuel pre-treatment.	Efficient primary and secondary measures to convert tars.
2	Conversion / carbon in ash; low heating value in combination with engine or oxygen demand; agglomeration, especially when operated on oxygen.	Feeding the fuel.	FICFB: fuel flexibility (but related to gas cleaning) MILENA: tar / gas cooling.
3	Gas cleaning and upgrading.	-	Gas cleaning and upgrading
4	Feed chemistry from agricultural residues - preparation, feeding, and bed agglomeration.	Economical feed preparation.	Limited pressure, air-blown operation.
5	For co-firing in coal boilers almost commercial, for CHP applications not economic and for synthesis gas production oxygen is needed, so only very large scale applications.	Commercial for coal gasification, so the development goes to torrefaction, to make from biomass something similar to coal. But conversion of biomass so that it can be fed into EFG is not demonstrated yet in larger scale. Main technical barrier is that no demonstration plant is in operation, so no investment in any commercial plant is done.	Successful operation in Güssing, Oberwart, no technical barrier, but the economic barrier for CHP are the high investment costs, so optimisation is needed; for synthesis gas only demonstration in small scale is available and actually no money to scale up, except GoBiGas.
6	Total costs.	Total costs due to the technical status, and the lack of risk-taking investors (semi-technical); Not demonstrated with sufficient hours; Actually there is not a single foremost barrier - it is the total uncertainties and costs	Immature.
7	There is still not a robust, economic method for handling of tars produced.	Fuel pre-processing/feeding/injecting into a pressurized environment.	Integration between the two reactors and associated fuel conversion.
8	Tar removal; Methane reforming; Alkali fouling and heat recovery.	The cost and energy losses associated with fuel pre-treatment; Pressurised feeding complexity for biomass-derived powders. Efficiency issues (high oxygen consumption, low cold gas efficiency rel. other technologies, limited heat recovery after quenching).	Tar removal; Methane reforming; Alkali fouling and heat recovery
9	Reliable feeding and fouling of heat recovery equipment.	Scale of operation, which might be too large for biomass conversion	Reliable feeding and fouling of heat recovery equipment

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
10	Limited size due to the use of excess heat of syngas for e.g. district heat.	Availability of biomass due to the necessity for big plants >100 MW Use of excess heat of syngas for e.g. district heat if no steam cycle for electricity generation is added (e.g. IGCC-PP)	Limited size due to the use of excess heat of syngas for e.g. district heat.
11	Gas cleaning.	Fuel pre-treatment and feeding	Up-scaling and pressurisation
12	Full conversion of biomass in gasification process.	fuel feeding, full conversion in gasification process	cost efficient scale up
13	-	-	The technical barriers are interlinked with the economy. There is a need for more efficient and cheaper gas cleaning to make the technology economically more feasible.
14	Air-blown atmospheric pressure: available technology for woody biomasses, for other biomasses ash/bed behaviour technical barrier. Oxygen blown pressurized gasification. Fuel/ash behaviour unknown and unproven.	Oxygen blown pressurized: as above	Overall process technology, availability etc.
15	It's ready.	-	Scaling to large scale.
16	-Fuel feeding into a high pressure vessel. -Oxygen production at site. - Transport logistics with high volume fuel.	- Fuel handling. - Transport logistics with high volume fuel. - High costs for pre-treatment of fuel.	- Big size of the gasifier because of low pressure - transport logistics.
17	-Hot gas filtering at temperatures in range 700 - 900 C - is close to commercialization so maybe not a barrier but real challenge and also some potential problems must be addressed. -Pressurization and oxygen blowing - promising demos exists but more is needed.	-Fuel preparation is the major one. -Impact of biomass composition still a factor that might cause problems (ash behaviour, corrosion etc.).	-Pressurization is major one -Gas cleaning still very "primitive" - better concepts needed in order to exploit potential advantages -No major developer has yet undertaken the task of up-scaling
18	Sintering and slagging. Gas clean up.	Feed preparation.	Carbon conversion. Gas clean up.
19	- Fuel flexibility - Pressurized system	- Economy of scale. - Feed logistics.	- Fuel flexibility. -Pressurised system.
20	Sensitivity of pressurised oxygen-blown gasification to ash sintering with all high-alkali fuels like agro biomasses	Suitable only to liquid feedstock and fine pulverized solid - fuel pre-treatment and feeding into pressure with solid fuels.	Scaling-up to the size required in syngas applications.

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
21	Tar reforming and gas cleaning.	Fuel feeding and materials in contact with slag and hot gas.	Pressurisation, tar reforming, gas cleaning and scale-up.
22	Particle and gas separation. Tar cleaning.	Particle and gas separation.	Particle and gas separation. Tar cleaning.
23	Availability.	-	Availability.
24	High temperature gas cleaning.	Fuel feeding and materials problem.	High temperature gas cleaning.
25	The gas upgrading is the key to commercial applications. Operations with oxygen enrichment and/or steam would be interesting as well.	The gas upgrading is the key to commercial applications, but also experience with less good fuels than pellets.	The gas upgrading is the key to commercial applications, but also experience with less good fuels than pellets.
26	Hot gas clean up, especially dust removal.	Milling and feeding of biomass.	-
27	Demonstration at larger scale.	Milling of fuel.	- Up-scaling for large scale. - Conversion of methane for synthesis gas.
28	Depends on product! If for syngas: - Combination of (1) particle removal, (2) tar removal, (3) CO shift, (4) cooling and (5) methane reformation. - If for fuel gas (power generation): Focus on (1) and (2) makes it considerably simpler. Less stringent demands If to SNG: Similar to syngas but without the CH4 reformer which makes it simpler.	At the current stage it is not obvious where the most problematic area actually is. Compared to CFB for syngas - Combination of cooling, particle removal and tar handling/removal downstream an EFG gasifier.	Do not see this technology for any other use than the concepts already in operation in Austria and Germany and soon in GoBiGas. Only realistic for smaller plants e.g. with gas engines or maybe, as in Gothenburg, for SNG (but this plant I see as just too small for such a complicated scheme). For larger SNG plants (as planned for GoBiGas, Phase 2 and by E.ON.) I think the concept then will go for CFB.
29	Biomass pelletisation is quite expensive and energy intensive. It is important to find a solution to feed biomass into pressurised gasifiers with cheaper solutions than pelletisation. Everything from entrance to the gasifier to the final product is proven and commercialised from coal gasification for decades.	Commercial feasibility is the foremost barrier; technology is highly developed. Feeding of torrefied biomass is smaller challenge, but still to be fully commercialised for biomass gasification applications.	No large-scale experience available. We don't know what we don't know yet.

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
30	From my point of view in general this questionnaire should have been split into two parts. a) Atmospheric applications aiming at power and heat production and b) pressurized applications for IGCC and future synthesis applications. Atmospheric applications can be supplied in large scale today. Raw gas applications with commercial guarantees and clean gas applications with limited guarantees due to the first of a kind, demonstration type of plants. Pressurized applications for IGCC plants were demonstrated in 1990's and some challenges (mainly mechanical) remained for further development. Pressurized applications for future synthesis have been demonstrated in pilot scale, but the size of the first commercial scale plant is very big in all discussions. So, the big size of the first commercial scale plant causes question marks since the technology is demonstrated only in pilot scale. The size of the first commercial scale demonstration plant vs. risks should be evaluated very carefully and considered if some kind of mid-size plant would be the next step in demonstrating this technology.	Fuel handling and fuel preparation. Furthermore, experience on 100% biomass gasification in EFG is very limited.	Complexity of the process when considering the scalability issues.
31	Tars, pressurization.	Pneumatic biomass feeding requires pre-treatment such as torrefaction or HTC.	Tars, pressurization.
32	Oxygen demand for syngas generation.	Biomass ash not usable as fertilizer / oxygen demand.	Ash/attrition of bed material not usable as fertilizer (olivine use).

B-3. AS OF TODAY, WHAT DO YOU CONSIDER TO BE THE MAXIMUM THERMAL INPUT SCALE THAT THE FOLLOWING GASIFICATION TECHNOLOGIES CAN BE BUILT FOR?

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
1	600-800 MW	2000 MW	600-800 MW
2	100-200 MW for single train	1000 MW for single train gasifier, pre-treatment scale may have much smaller scale!	100-200 MW single train
3	-	-	-
4	250 MW today with raw feed, but 100 MW with pretreated feed	1000 MW	25 MW
5	~ 100-200 MW, as the largest FBG is about 80 MW in Lahti.	any scale of commercial coal EFG, if biomass is terrified	Actual about 100 MW, with new concepts also >300 MW possible, but for new concepts R&D time is necessary.
6	Limited.	Done already for 1000 MW	Even more limited
7	30 MW	100 MW	100 MW
8	Atmospheric: 150 MWth, approx 30 ton/hr Pressurised: 300- 400 MWth. Different for BFB and CFB+ constraints of need for multiple feed points and maximum capacity of feed systems.	>400 MWth. Multi-burner systems can overcome feed system limitations.	Atmospheric: < 100 MWth. Geometrical constraints for interconnections between gasifier and combustor due to large diameters of cyclones and reactors. Multiple feed points will be required. Pressurised operation: Not feasible due to need for exact pressure control of moving bed sealing between gasifier and combustor, the differential pressure cannot be increased while absolute pressure increases significantly.
9	For me, this is not a very relevant question. To be more flexible, I would recommend multiple units instead of one large capacity gasifier, so you can shut down one unit in case there is for instance no heat demand or malfunctioning of equipment.		
10	200 MW	500 MW	100 MW
11	300 MW	500 MW	100MW
12	-	250 - 500 MWth	50 MW
13	Several hundreds of MW	>1000 MWth. With pretreated biomass (e.g. torrefaction) it should be possible to build plants in the same size as for coal gasification.	100 MWth for atmospheric gasification. If moderately pressurized a few hundreds of MWth. However, pressurization is not that obvious since both reactors (combustor and gasifier) have to be pressurized.
14	Air-blown: up to 100+ MWth. Oxygen-blown, pressurized: not commercially available.	-	-

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
15	500 MW fuel input	-	300 MW
16	2-300 MW	3-400 MW	1-200 MW
17	In the region of 300 MWth (~150 MWth is in principle offered by Foster Wheeler and Carbona at present). For all three alternatives the fuel logistics is probably the real limiting factor. Plants larger than 300 MWth are not very likely considering this	Lower threshold in the region ~200 MWth Upper in the region 600 - 1000 MWth and mainly related to fuel supply.	In the region 50 MWth as long as a concept for pressurization is missing. A modular approach is of course applicable but probably not economically viable.
18	10 t/h biomass dry basis	200 t/h biomass	10 t/h biomass dry basis.
19	50 MW	50 MW	50 MW
20	200-400 MW with single gasifier train depending whether BFB or CFB	?	70 MW
21	>100 MW	App. 500 MW	<100 MW
22	200 MW	200MW	40MW
23	for single line: appr. 100 MW	-	For single line: appr. 100 MW
24	> 500 - 600 MW	> 1000 MW	< 100 MW
25	some 3-400 MW	Some 3-400 MW	some 3-400 MW
26	150 MWth	-	40 MWth
27	200MW	-	50 MW
28	Somewhere around 150 MW.	Somewhere around 150 MW	20-30 MW
29	500-600 MWth per gasifier (proven from coal gasification side).	1200 MWth per gasifier (proven from coal gasification side).	Don't know.
30	Atmospheric raw gas applications ~150 MW.	-	-
31	Atmospheric clean gas applications ~100 MW.	1000 MW	200 MW
32	Pressurized air blown applications ~ 200...300 MW (First of a kind, limited guarantees). Pressurized oxygen-steam blown applications ~300...400 MW (First of a kind, limited guarantees).	500 MW	50 MW

B-4. ARE THERE ANY NON-TECHNICAL BARRIERS FOR LARGE-SCALE TECHNOLOGY DEPLOYMENT THAT NEEDS SPECIAL ATTENTION FOR THE RESPECTIVE TECHNOLOGY?

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
1	Manufacture that offer the technology with guarantees.		
2	Fire hazard of carbon containing ash engine emissions.	-	Engine emissions.
3	-	-	-
4	-	Efficiency penalty for high temperature, slagging operation.	-
5	Availability of biomass at reasonable price risk money for large scale demonstration is necessary, go from R&D to commercial scale.	Risk money for large scale demonstration is necessary, go from R&D to commercial scale.	Availability of biomass at reasonable price risk money for large scale demonstration is necessary, go from R&D to commercial scale.
6	Cost reduction, investment support.	Total cost reduction, investment support	Total cost reduction, investment support.
7	At this point, perhaps FBG's reputation as a viable technology is hurting. FBG processes have been under development for several decades, but there are still no systems operating long-term, day in, day out. I'm not sure if special attention can solve this, but if there are indeed successful large-scale systems in the world, advertising that success would help the reputation.	Lack of operating experience and too many unknowns with the technology. B-EFG is in the middle of its development history, and things seem to be progressing well, so perhaps these issues will get addressed as development progresses to demo and commercial scale.	In my opinion, DFBG is superior to FBG. It may be that DFBG is confused with FBG by some, and the many unsuccessful experiences with FBG is harming the reputation of DFBG.
8	General problem of demonstrating new technology with initial high costs and high technical and commercial risks. Product competitiveness relative to fossil-based products or alternative biomass technologies for CHP.	Deployment limited to synthesis gas. General problem of demonstrating new technology with initial high costs and high technical and commercial risks. Product competitiveness relative to fossil-based products.	General problem of demonstrating new technology with initial high costs and high technical and commercial risks. Product competitiveness relative to fossil-based products or alternative biomass technologies for CHP.
9	1. Availability of biomass in terms of price level, contracting, sustainability and quantity 2. Public perception 3. Meeting emission regulation 4. Gasification is often by permitting authorities considered being combustion or incineration.		
10	Fuel price, fuel availability, and excess heat usage.		

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
11	Stable market conditions and incentives to replace oil and increase share of renewables in the electricity sector.	Long term incentives for replacing fossil fuel in the chemical industry.	Indirect gasification is mainly applicable in smaller scale making in suitable for cogeneration. Better incentives for small scale biomass based cogeneration would thus provide more incentives for DFBG.
12	Investment & operation costs (without fuel cost).		
13	For Swedish conditions fuels for the transportation sector is of major interest. This implies large plants (>> 100 MWth) and hence a huge investment cost (and risk). The problem is that the revenue for the coming 20-30 years that the plant will be operated depend on political decisions, the development of the price for the fossil fuels that will be replaced (petrol, diesel, natural gas) and competing renewable alternatives (e.g. ethanol through fermentation, rape seed oil, biogas through anaerobic digestion etcetera).	For Swedish conditions fuels for the transportation sector is of major interest. This implies large plants (>> 100 MWth) and hence a huge investment cost (and risk). The problem is that the revenue for the coming 20-30 years that the plant will be operated depend on political decisions, the development of the price for the fossil fuels that will be replaced (petrol, diesel and competing renewable alternatives (e.g. ethanol through fermentation, rape seed oil, etcetera). I don't see EFG as a good candidate for bioSNG production since there normally is no or very low levels of methane present in the gas.	For Swedish conditions bioSNG-production using DFBG seems promising. The plant can be built in small and medium scale (<100 MWth) with a lower economical risk, better possibility to secure the feedstock needed to operate the plant and to integrate excess process heat with the local heat demand. However, the knowledge of indirect gasification and its opportunities are not very well known. There is a huge need of information about the technology. This is even more pronounced due to the fact that most of the development has taken place the last decade and at an increasing speed.
14	Gas cleaning requirements differ from application to application: - gas for burning in kilns/other furnaces - simple cleaning – available - gas for gas turbine combustion - ceramic/metal filters - not proven - gas for synthesis - not proven, not available Biomass gasification always competes with combustion in high steam pressure boilers - fuel quality and local conditions decide who wins.		
15	General for all gasification technologies: In order for the produced gas or liquid to be competitive with fossil ditto it is needed that the biomass based fuels are relieved from CO2 taxes and that fossil ones have CO2 taxes. The rules have to be long term, e.g. compare with the green certificates for electricity that last		
16	-	Acceptance of pretreated fuel from long distance.	-
17	General (all alternatives): -Financial risks are high and need to be reduced with e g support/incentives (investment/operations) for first plants. -Market outlook not clear and potential barrier for plant owners as well as developers/suppliers to dedicate necessary resources and take on risks. -Fuel price market also major uncertainty -Lack of clear policies from EU, Swedish Gov etc underline uncertainties in risk and market considerations.		
18	High investments		

Expert	Direct Fluidised Bed Gasification (FBG)	Entrained Flow Gasification (EFG)	Indirect Dual Fluidised Bed Gasification (DFBG)
19	- Feed supply contract - long term.	- large scale (> 100MW) required => feed logistics / supply contacts	- feed supply contract - long term
20	High capital cost of first large-scale demo units.	Limited feedstock basis and high cost for pre-treatment	High cost in fuel gas applications and limited capacity in syngas applications
21	-	-	-
22	Cost for first generation.	Cost for first generation.	-
23	Overall costs and negative examples.	-	Overall costs and immaturity.
24	Lack of public funding to reduce the risks of introduction of untested technology.		
25	Need good system integration as combined with combustors, upgrading of gas to CH4 and other fuels and flexibility for polygeneration systems (CHP+chemicals).	Grinding of fuel to make it suitable. Gas upgrading.	Long term operations of system for different fuels. Gas upgrading
26	-	-	-
27	-	-	-
28	In general risk mitigation for the first installations.	In general risk mitigation for the first installations	No comment.
29	project financeable, as long as similarity to coal gasification can be clearly outlined. in general: biomass gasification only works within very extraordinary project situations, usually only with significant subsidies or high political pressure.	project financeable, as long as similarity to coal gasification can be clearly outlined. in general: biomass gasification only works within very extraordinary project situations, usually only with significant subsidies or high political pressure.	Non-proven technologies are usually not financeable in non-recourse project financing.
30	With regard to the atmospheric applications there are not necessarily any specific non-technical barriers at the moment. Concerning the applications aiming at the future synthesis e.g. the subsidies are always a topic of discussion. Furthermore, the target value (timeline and share/amount) for various biomass based products (transportation sector fuels, etc) is not always very clear and can vary in discussions. Generally, what is the real biomass potential available for different applications is also one of the discussion topics. The size of the first demo plant vs. technical risks is an issue to be optimized.	-	-
31	Costs	No	Costs
32	Economic efficiency		

B-5. BASED ON YOUR EXPERTISE AND REFLECTION ON THE QUESTIONS ABOVE, WOULD LIKE TO ADD ANY FURTHER COMMENTS ON TECHNICAL BARRIERS, SPECIFIC OR IN GENERAL?

Expert	General comment
1	In general the problem is mainly to gain experience from building large units that is lacking. For all technologies the biggest problem is the overall cost for biomass to biofuel that makes it hard to motivate a company to build one of these units.
2	Questions do generally have a simple answer. Technical problems of FBG and DFBG depend on the application of the gas. If that is direct coupled boiler, nothing really is a problem. In CHP/engine application, tar is an issue, engine emission limits may be hard to meet. For EFG, the general perception is the use for biofuels production. That means that oxygen/steam is needed. FBG can also be used using oxygen, then it will become a big challenge to control temperatures and avoid agglomeration when using certain fuels. So, opinions are based on certain assumptions on fuel type, scale, application, gas cleaning, …that have not been mentioned explicitly.
3	-
4	The answers will vary some based on feed material and on the product to be produced from the syngas.
5	There were in the past some failures in gasification, like Choren, Range Fuels and others. This makes it difficult to get the necessary money for demonstration and first commercial plants.
6	The results from the questionnaire might well be appended with a somewhat similar questionnaire sent to the main commercial suppliers of the specific systems. What are their opinions, and what are the costs of some three different sized systems of the three different kind?
7	Generally speaking, the big issues to address are still fuel feeding, tars management, affordable syngas cleaning and demonstration of long-term, efficient operation.
8	-
9	-
10	Scale-up form existing size plants difficult due to lack of technical and economic data. Economic calculations difficult due to a lack of data regarding operating hours, down times, maintenance times. Fluctuation or difficultly assessable fuel price in the future.
11	The main barriers for biomass gasification are non-technical and more of a structural character. Commercial biomass gasification plants have been built since the 80's but fluctuating oil prices and lack of consequent long term incentives have stopped gasification from a break through.
12	- cost reduction of gasification/gas cleaning system - reduce complexity of the gasification/gas cleaning system
13	Some of technologies (EFG and FBG) are already commercial with coal as feedstock. Then there are two options; to adopt the biomass fuel to resemble coal or coal slurries (e.g. torrefaction and pyrolysis oil) or to adopt the commercial coal plants to biomass. However, since there is no real market (egg and hen situation) for large scale biomass gasifiers the development takes place on lab and pilot plant scale, which leaves us with the up-scaling problem. There is no real motivation to build EFG or FBG for production of transportation fuel (Swedish focus) in the medium scale since it's already on forehand a bad investment. So still we are awaiting the first large scale biomass based plant for production of transportation fuel. The DFBG is not developed for coal gasification and does not face the same up-scaling problem since it can be built in the medium size scale. On the other hand the development has to rely entirely on the biomass community and the need for strong industrial stakeholders and suppliers is evident.
14	-
15	-
16	It is very important that Gasification technology and gas cleaning technologies can be demonstrated in large scale to overcome the difficulties with the technology

Expert	General comment
17	Rating 1-9 is a relatively rough approach and should be considered more as a relative ranking of the alternatives and not necessarily a measure of an absolute position.
18	-
19	-
20	-
21	-
22	-
23	-
24	-
25	We have several options: 1) produce gas used in a combined cycle with GT + ST 2) combine a gasifier with production of CH4 which is separated to inject in NG system and combust rest in combustor 3) combine gasifier with catalyst which gives products like CH4, DME and bio-diesel Not clear which alternative will be the winner. Maybe all three in parallel for different applications
26	For Nordic applications where district heating is common the overall low efficiency of gasification systems (40 - 60 %) is a barrier for generation of vehicle fuels. For CHP plants combustion with condensation scrubbers for heat recovery gives 90-95 % efficiency. This technology is also proven in hundreds of plants for different fuels.
27	-
28	-
29	Technical barriers will all only be overcome, if the commercial barriers are lifted. This can only occur by specific subsidy programs or political requirements.
30	With regard to the fluidized bed technology applications in large scale, hopefully the situation in general gets better since nowadays there are three big companies offering that technology. Hopefully, the product gets known better and better and more interested customers as well as executed projects would come up. In general the number of commercial scale FB gasifiers is very small compared to the number of FB boilers. The gasifiers have been a hot topic in conferences for a long time, but commercial success stories have been missing.
31	EFG is competitive to FB even including pre-treatment.
32	main advantage of biomass gasification is a 100% conversion of carbon-in-biomass to carbon-in-fuel; the addition of (electrolytic) H2 allows a more than two times higher amount of secondary energy carriers (e.g. CH4); this principal advantage is not focus of biomass utilisation today