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"BIOSYNGAS"

Description of R&D trajectory necessary to reach large-scale implementation of renewable syngas from biomass

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PREFACE

This report describes the results of the ECN task of the project "*BIOSYNGAS: Multifunctional intermediary for the production of renewable power, gaseous energy carriers, transportation fuels, and chemicals from biomass*". The work was co-financed by the SenterNovem (formerly: the Netherlands Agency for Energy and the Environment) within the framework of the OTC ("Ondersteuning Transitie-Coalities") programme under project number 5005-03-20-01-001 and order number 4800002894. Applicable ECN project number was 7.5268. The overall project results are reported in ECN report C--04-116.

KEYWORDS

Biomass, biosyngas, gasification, entrained flow, large-scale, biomass import, R&D trajectory, implementation, pretreatment, feeding, biomass-to-biosyngas efficiency, ash and slag behaviour, gas cleaning.

ABSTRACT

Renewable syngas from biomass, or "biosyngas" will be an important intermediary in the future energy infrastructure for the production of renewable electricity, gaseous energy carriers, transportation fuels, and chemicals. A large total installed biosyngas production capacity with large individual plants is required to meet the ambitious renewable energy targets. The overall objective of the research and development trajectory is to develop the technology for dedicated biomass-fired entrained flow gasification systems for reliable, high-efficient, and cost-effective production of biosyngas from multiple biomass streams. The technology should be proven in a full-scale (>100 MW_{th}) demonstration plant. Starting point of the phased research and development trajectory is the existing coal-based gasification technology. To bridge the gap between existing and proven technology for coal and the implementation of biomass-fired entrained flow gasifiers, a research and development trajectory is necessary with focus on four interrelated themes: (i) Biomass pretreatment & feeding; (ii) Gasification & burner design; (iii) Ash and slag behaviour; and (iv) Hot gas treatment (cooling, cleaning, and conditioning).

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1. INTRODUCTION

1.1. Background

To date, syngas is an important intermediate product in chemical industry. Annually, a total of about 6000 PJ of syngas is produced worldwide, corresponding to almost 2% of the present total worldwide energy consumption. The world market for syngas (mainly from fossil energy sources like coal, natural gas and oil/residues) is dominated by the ammonia industry (53%). Other main applications are found for the production of hydrogen for use in refineries, *e.g.* hydrogenation steps (23%), and for the production of methanol (11%). Figure 1.1 shows the present syngas market distribution [1].

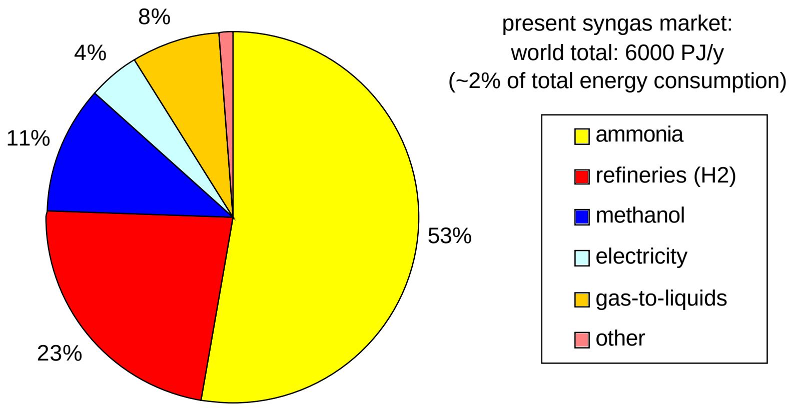

***Figure 1.1**. Present world syngas market.*

Today's, global use of syngas for the production of transportation fuels in the so-called "gas-to-liquids" processes (GTL) correspond to approx. 500 PJ per year, *i.e.* from the Fischer-Tropsch processes of Sasol in South Africa and of Shell in Bintulu, Malaysia. In the future, syngas will become increasingly important for the production of cleaner fuels to comply with the stringent emission standards, *e.g.* methanol/DME, ethanol, and/or Fischer-Tropsch diesel. The huge potential market for syngas is illustrated by the fact that approximately 30% of the world primary energy consumption is for the transportation fuels and chemicals [2].

Biomass is heading for a great future as renewable energy source. It not only is available in large quantities, it also is the only renewable energy source that is suitable for the sustainable production of (generally carbon containing) transportation fuels and chemicals. Therefore, the application of biomass as feedstock for the production of fuels and chemicals (and electricity) allows the reduction of fossil fuel consumption and the accompanying CO_2-emmissions [3,4,5].

In the Bio-fuel Directive of the European Commission a target of 5.75% is defined for substitution of fossil fuels by bio-fuels in 2010, while a targeted share of 15% bio-fuels is expected for 2020. In the Netherlands, the Ministry of Economic Affairs has developed a long-term biomass transition vision for 2040. Based on this Dutch concept vision, participating actors have projected a 20-45% substitution of fossil energy used in industry by biomass. Renewable syngas or "biosyngas", which is produced via gasification of biomass, is the key-intermediate in the production of renewable fuels and chemicals. The fuels for the future will be ultra-clean designer fuels from GTL processes; transportation fuels directly produced from biomass (*e.g*. biodiesel, pyrolysis oils) will have only very limited application [6].

When an average of 30% substitution of fossil fuels by biosyngas is assumed, translated to the world energy consumption, the total annual syngas market will be increased to approx. 50,000 PJ in 2040. The world (bio) syngas market will then look as shown in Figure 1.2 (assuming no changes for the other applications). The major share of the syngas will be used for production of fuels (biomass-to-liquids; BTL) and another major part for the production of renewable chemicals (biomass-to-chemicals) [1].

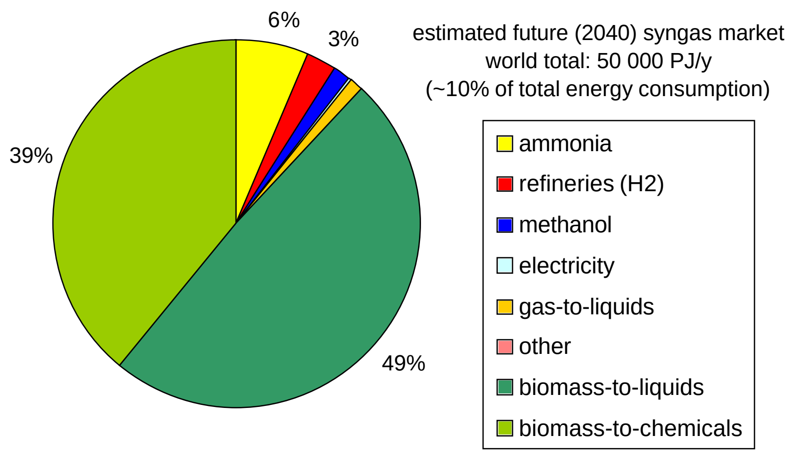

***Figure 1.2**. Predicted world syngas market in 2040 (speculative).*

The future biosyngas demand exceeds the present syngas consumption by a factor of eight. Therefore, it is clear that large biosyngas production capacities are needed to meet the European and national renewable energy and CO_2-emission reduction targets. Not only are large installed capacities necessary, also the individual plants have to be large considering the typical plant scales for the two main applications, *i.e.*:

- Transportation fuels in BTL plants: several 1000 MW;
- Chemical sector: 50-200 MW.

1.2. Objective

A large total installed biosyngas production capacity with large individual plants is required to meet the ambitious renewable energy targets. This requires a robust, fuel-flexible, and high-efficient technology for optimum biomass utilisation and to guarantee availability. In developing bio-fuelled power production, two possible routes can be followed, see Figure 1.3.

The first route comprises up-scaling of the small and medium scale gasification technologies that are currently mostly used for distributed heat and power (CHP) production. In this route it will take a long time before a significant biosyngas production capacity is installed. Either, a large number of plants have to be put in operation or the technology has to up-scaled, which will take an additional development period of a decade. Therefore, it is questionable if the ambitious renewable energy targets can be met by following this route.

The second and preferred route comprises adapting today's large-scale coal-based gasification technology. In this way the accumulated installed biosyngas capacity can be increased rapidly, as the basic technology is already proven on large scale.

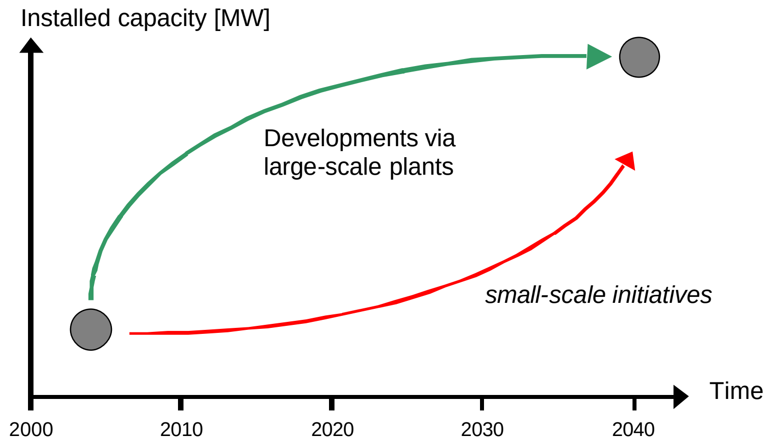

***Figure 1.3**. Roadmap to reach for large-scale implementation of biosyngas, with two possible routes indicated.*

1.3. Issue definition

To date, no mature technology exists for large-scale biosyngas production via biomass gasification and to develop the appropriate technology, a research and development trajectory is necessary.

1.4. Objectives

Objective of the project was to define the necessary research and development (R&D) trajectory to reach implementation of large-scale production of renewable syngas (*i.e.* biosyngas) from biomass.

1.5. Approach & Projected results

The approach followed was that first a "Biosyngas Vision" was determined, this is described in Chapter 2, including reference to the current state-of-the-art of biosyngas production. From the Vision follows what developments and R&D are necessary to come from the present situation to a sustainable society with an important role for biosyngas. The R&D trajectory is described in Chapter 3. Conclusions and an outlook are presented in Chapter 4.

2. BIOSYNGAS VISION

The “Biosyngas vision” is the basis of the R&D trajectory. In this Chapter will be described which choices are made and what is the underlying motivation.

2.1. Background

In the last years large research efforts have been made on the production of liquid (Fischer-Tropsch) transportation fuels from biomass. Initially the research was aimed at determining the necessary gas cleaning to make product gas from biomass gasification suitable for Fischer-Tropsch synthesis [7]. In the course of that research, important developments in biomass gasification and gas cleaning technologies were made and new insights were generated with respect to the preferred scale and layout of an optimum biomass Fischer-Tropsch plant [8].

The crucial conclusion was that, as biomass is relative expensive compared to the fossil fuels (on energy basis), the cost price of the biomass feedstock will significantly contribute to the production costs of the fuels or chemicals. Therefore, dedicated production processes (*i.e.* no tri-generation because of the higher specific costs) with maximum biomass-to-product efficiencies are needed to benefit from the economy of scale and for most cost-effective production [9].

2.2. Optimum biosyngas production

High biomass-to-syngas efficiencies are required for cost effective production of biosyngas. This implies that upon gasification of biomass the maximum share of energy contained in the biomass should be converted into the syngas components H_2 and CO, *i.e.* upon biomass gasification a *biosyngas* instead of a *product gas* must be produced (Figure 2.1) [7]. In *product gas* from low temperature gasification the syngas components H_2 and CO typically contain only ~50% of the energy in the gas, while the remainder is contained in CH_4 and higher (aromatic) hydrocarbons. Upon high temperature gasification (>1200°C) all the biomass is completely converted into *biosyngas*. Biosyngas is chemically similar to syngas derived from fossil sources and can replace its fossil equivalent in all applications.

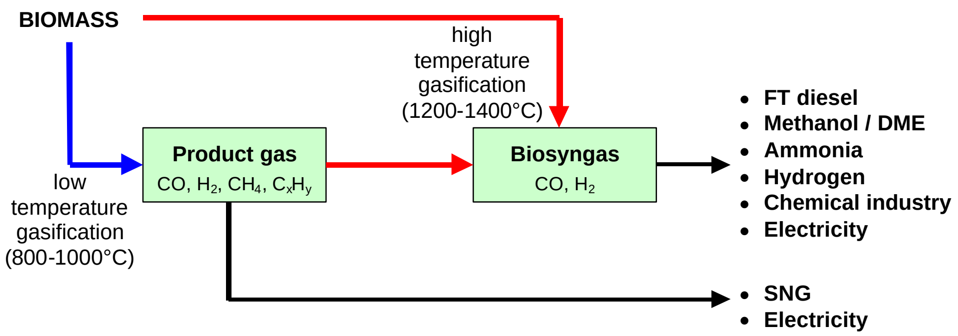

***Figure 2.1**. Two biomass-derived gases via gasification at different temperature levels: ‘biosyngas’ and ‘product gas’ and their typical applications.*

2.3. Scale and location of biosyngas production

Syngas demands for liquid fuel synthesis will typically be >1,000 MW (to benefit from economy of scale, which is necessary to reduce costs). For illustration, the Shell GTL plant in Malaysia of 12,500 bbpd (*i.e.* ~1,000 MW) is considered as a demonstration plant and the new plant in Qatar will have a six times higher capacity (75,000 bbpd or ~6,000 MW). The typical syngas demands for chemical processes correspond to 50-200 MW_{th}. Even though the scale of an individual biosyngas plant may be relatively small, in most cases the plant will be part of a larger centralised chemical infrastructure with several other processes and plants to optimise energy and product integration (*i.e.* the syngas consumer). There is only a limited market for small-scale biosyngas production for distributed chemical plants (although there will always be exceptions).

To ensure cost-effective biomass supply (*i.e.* avoid land transport; see below) biosyngas production plants will be constructed close to ports or larger waterways. For the selection of the location the same considerations apply as for current coal-fired power plants and their coal logistics. Also the main large concentrations of chemical industry are located on locations easy accessible from water, *e.g.* the Maasvlakte near Rotterdam and the German Ruhrgebiet.

2.4. Biomass considerations

Approximately 50% of the biomass globally available for energy purposes (*i.e.* the technical potential) is wood or wood residues. A further 20% is straw-like, which share will increase to 40% when straw-like crops are selected as energy crops [10]. Therefore, for utilisation of the large amounts of biomass for biosyngas production, it is important to develop technical routes to utilise both wood and straw materials. Biomass materials like manure and waste streams will play only a minor role in the biosyngas production, as the absolute amounts of these streams available for biosyngas production are very low compared to the required total amounts of biomass. Therefore, they are not of significance for large-scale biosyngas production.[1]

Due to the distributed and global generation of the biomass large transport distances are unavoidable. Transport by truck is the major cost driver in biomass transport, therefore, the transport over land should be minimised [9]. Wood is relatively high-energy dense it will preferable be transported by ship to the large centralised conversion facilities. Straw-like materials have a much lower bulk energy density, which would result in higher transport and transhipment costs. Therefore, energy densification of straw is desired to reduce transport costs and allow easier handling, *viz*. grasses and straw are converted into a bioslurry via flash pyrolysis [6].

The transition to green alternatives therefore requires biomass, which should be available in large quantities. Since wood and grass-like material make up 70-90% of the total technically available amount of biomass worldwide, it is reasonable to focus on these biomass fuels as main renewable energy sources for chemicals and fuels [11].

1. Furthermore, manures will preferable be used for biological conversion processes due to their high moisture contents. Alternatively, these streams can be converted in the HTU process to produce biocrude or by super critical gasification to produce hydrogen or SNG.

2.5. Optimum gasification technology (State-of-the-Art)

Several general types of gasification technologies are suitable for biomass gasification, *i.e.* fixed bed (either downdraft or updraft), fluidised bed, and entrained flow. The criteria for evaluation of the suitability of biomass gasification processes for biosyngas production are:

- **High biomass-to-biosyngas efficiencies**. To achieve high biomass-to-biosyngas (B-t-B) efficiencies, gasification should take place at a high temperature to ensure complete carbon conversion and to yield a biosyngas. Alternatively, a product gas from a low-temperature gasifier (containing hydrocarbons) must be subjected to a high-temperature or catalytic step to achieve complete conversion of the gas to biosyngas.
- **Fuel-flexible for biomass firing**. The term 'biomass' comprises a very broad range of heterogeneous materials from different origins. It is hardly possible (and often economically not preferred) to operate a plant on one specific feedstock due to the uncertainty of availability and variations in the quality of the biomass. To improve the operating security and reducing dependency on the availability of specific biomass materials, the gasifier must be able to process different types of (pre-treated) woody and straw-like biomass.
- **Fuel-flexible for coal firing**. It should also be possible to use coal to have a fallback alternative in case of a discontinuity in the biomass supply, i.e. the plant does not have to be shut down but can change to coal firing. Furthermore, it also allows a gradual change from coal to biomass firing in existing plants.
- **Suitable for large-scale**. The technology must be suitable for up-scaling and application in large-scale systems of several hundreds to several thousands MWs.

2.5.1. Fixed bed gasifiers

Downdraft fixed-bed gasifiers are limited in scale and require a well-defined fuel, making them not fuel-flexible. Updraft fixed-bed gasifiers can be scaled up, however, they produce a product gas with very high tar concentrations. This tar should be removed for the major part from the gas, creating a gas-cleaning problem. Examples of updraft gasifiers comprise the British Gas/Lurgi plant at Schwarze Pumpe (Germany), the Sasol plants (South Africa), and the Harboøre plant (Denmark). At Sasol they have chosen to work-up and fractionate the removed tar to produce chemicals (*i.e.* like a oil refinery). In the Harboøre CHP plant the water-tar mixture from the gas cleaning is processed in a parallel unit for district heating, whereas at Schwarze Pumpe the removed tars are fired on an entrained flow gasifier. In all cases the energy value of the tars is lost with respect to the biosyngas production.

2.5.2. Fluidised bed gasifiers

Although fluidised bed (FB) gasifiers yield a product gas containing tars, when choosing the right gasification conditions (*i.e.* gasification temperature, use of steam, and special bed material) the amount of tars is limited and acceptable in a product gas that is fired to the gas turbine. The concept of a biomass IGCC has been demonstrated in the Värnamo plant (Sweden) based on a pressurised circulating fluidised bed (CFB) gasifier. Compared to downdraft gasifiers, FB gasifiers are relatively fuel-flexible considering size and biomass composition, but there are serious remaining limitations to the fuels that are acceptable. These limitations are imposed by the fact that FB gasifiers use solid bed material (*e.g.* sand) as fluidisation material and heat carrier. This is an intrinsically weak point, as minerals in the biomass ash tend to react with the bed material forming melts and agglomerates that disturb the fluidisation and result in shutdown of the plant. Frequent replacement of the bed material can prevent agglomeration, however, the consumption and disposal of spent bed material as chemical waste are significant economic cost drivers. Especially, when special and more expensive bed materials are required to suppress tar formation in the gasifier.

Fluidised bed gasifiers are typically operated at 800-1000°C (limited by the melting properties of the bed material) and are therefore not generally suitable for coal gasification,[2] as due to the lower reactivity of coal compared to biomass, a higher temperature is required (>1300°C) [12]. Even for biomass, the carbon conversion is only 90-98% (depending on the temperature and fuel); the unconverted carbon accounts for a significant loss in efficiency. Whereas in fluidised bed gasifiers the bed material imposes limitations on fuels and operation temperatures due to the fact that it may react with the biomass ash to form melts, in entrained flow gasifiers benefit is taken from these phenomena (see below).

2.5.3. Entrained flow gasifiers

Entrained flow (EF) gasifiers typically operate at high temperatures (1300-1500°C) at which the feed is completely converted into syngas, even at the short residence time of only a few seconds. In most cases, EF gasifiers are operated under pressure (typically 20-50 bar) and with pure oxygen and with capacities in the order of several hundreds of MW. For a more extensive technology description see Appendix A. The main technologies for coal-fired slagging EF gasification are characterised by coal-water slurry feedstock or by solid feedstocks of small particles (typically <100 μm), respectively [12]. The Texaco gasifier (since mid 2004: General Electric) is the main representative of the first type, while the Shell/Uhde gasifier (updraft fired) and the Future Energy (formerly: Noell; downdraft fired) are representatives of the second type.

The existing coal-fired large-scale gasification power plants in Europe are based on (slagging) entrained-flow gasification technology of solid feedstock, *i.e.* the Nuon (Buggenum) and Elcogas (Puertollano) plants. Entrained flow (EF) Integrated Gasification Combined Cycle (IGCC) for coal has proven its reliability in these large-scale applications (several hundreds up to a 1000 MW_{th}). In the IGCC gasifiers, coal is converted into a syngas at high temperature, which is fired in a combined cycle after deep cleaning. Gas turbines require a pressurised feed gas; typically a turbine would run at 15 to 20 bar. The gasification gas has to be produced at elevated pressure (*i.e.* by pressurised gasification) or pressurised after gasification. Both approaches have advantages and disadvantages related to investments costs, feedstock pressurisation, gas cleaning, and electricity consumption, but the balance tips in favour of gasifying at the required elevated pressure.

Biosyngas production based on slagging entrained flow gasification meets the defined criteria and has additional technical advantages [13]:

- **Large-scale high-efficiencie biosyngas production**. Several commercial EF gasifiers exist and have proven availability at large-scale (700 MW_{th}). EF gasifiers are operated at sufficient high temperatures (1200-1500°C) to ensure that the biomass is completely converted (>99.5% carbon conversion) and meet the demands of high biomass-to-biosyngas efficiencies. This in contrast to the gasification processes that operate at lower temperatures, which afford a product gas in addition to H_2 and CO containing CH_4, C_2-hydrocarbons, BTX (benzene, toluene, and xylenes), and tars.

2. However, low rank coals and more reactive materials like peat, and lignite can be converted in fluidised bed gasifiers, as they are more reactive than hard coals.

- **Fuel-flexibility**. The slagging entrained-flow gasifier can convert all type biomass materials and the fuel-flexibility is extended as well to the fossil fuels coal and oil residues. EF is suitable for wood, alkaline rich biomass like straw and grasses, high ash streams like sludges and manure, wastes like RDF and plastics, as well as the back-up option to use coal.
- **Simple gas cleaning**. Due to the high temperature in the gasifier, the biosyngas is absolutely free of organic impurities (*i.e.* tars) and can easily be cleaned from small traces of inorganic impurities with conventional proven technologies.
- **Minimum waste & Mineral recycling**. The minerals from the biomass are recovered in the slag and the fly ash. The heavy metals are contained in the non-leachable slag that can be used as construction material; this in contrast to other processes that yield a carbon-containing ash that has to be disposed of as chemical waste. The carbon-free fly ash can be used for mineral recycling and fertilisation of the biomass production areas.
- **Back-end flexible**. In addition to application for liquid fuel production, the biosyngas from entrained flow gasifiers can also be applied for power generation, for hydrogen production, and as feedstock for chemical synthesis.

2.6. Biomass feeding & pretreatment

Due to the high reactivity and volatile content of biomass (compared to coal) complete conversion is easily established at the temperatures typical for entrained flow gasification. The major issue, however, is the pretreatment of biomass and the feeding into the gasifier.

2.6.1. Comparison with coal

Although an entrained flow gasifier can operate both on coal and biomass, the existing coal feeding systems are not unsuitable for biomass. The four issues in feeding are discussed below indicating the differences between coal and biomass handling as well as options for optimisation:

- **Particle size**. Coal feedstock for entrained flow gasification is typically grinded down to 90 • m. Milling biomass to the same size has a five times higher electricity consumption, making this pretreatment economically unacceptable.[3] However, co-gasification tests in the Buggenum plant have shown that wood particles of 1 mm are also completely converted under the same conditions. Therefore, for woody biomass downsizing to 1 mm is sufficient and in this case the electricity consumption is similar to the coal milling [13].
- **Pneumatic feeding**. Coal is transported into the gasifier with a pneumatic feeding system using an inert carrier gas (mostly nitrogen or alternatively CO_2) to create a very dense flow. Milled biomass of 90 • m cannot be transported in a pneumatic system, as due to the fibrous and compressible nature of the material it will aggregate and plug the feeding line. Larger 1 mm biomass particles are not suitable for pneumatic feeding due to their shape.
- **Inert gas consumption**. Purpose of a pneumatic feeding system is to dose a constant and dense flow of coal to the gasifier burner. Even when biomass could be fed with such a system, the consumption of inert gas on energy basis is approximately twice as high for biomass compared to coal due to the lower energy density. This will significantly lower the efficiency of the gasifier, as all the inert gas has to be heated to the gasification temperature,

3. For indication: it can be calculated that although the biomass-to-biosyngas yield is 76% but the overall system efficiency for biosyngas production is only 59%. For definition of the efficiencies see later in text.

and it will result in dilution of the biosyngas. The extra inert gas has also to be compressed, which results in additional electricity consumption.

- **Pressurisation**. An entrained flow gasifier will be operated at elevated pressures (10-30 bar). Pressurisation of biomass in conventional lockhopper systems requires much more inert gas than for coal - similar to what applies for pneumatic feeding. For compression of biomass a piston compressor has been developed in which approximately 50 times less inert gas is consumed.

The major criterion in assessment of different pretreatment and feeding approaches is the impact they have on both the biomass-to-biosyngas and the overall system efficiencies:

- **Biomass-to-biosyngas (B-t-B) efficiency** is the ratio of the chemical energy in the biosyngas and in the biomass;
- **Overall system efficiency** is the sum of the biomass-to-biosyngas efficiency **plus** the net electricity production of the system. The net electricity is the production from process heat recovered in *e.g.* the gas cooler heat minus consumption for (if applicable) fuel pulverization, piston compressor, inert gas compression, syngas compression, and oxygen production (air separation) and compression. The net electricity consumption is calculated back as primary biomass energy consumption assuming 40% efficiency. *N.B. If the system consumes net electricity, the overall system efficiency is lower than the B-t-B efficiency.*

The development of new approaches to biomass feeding and pretreatment is necessary to reach high biomass-to-biosyngas and overall system efficiencies in biomass-fired entrained flow gasifier systems. In Figure 2.2 four possible specific pretreatment and feeding options are shown for different biomass streams. The pretreatment and feeding options are not competitive but complementary or an alternative to each other:

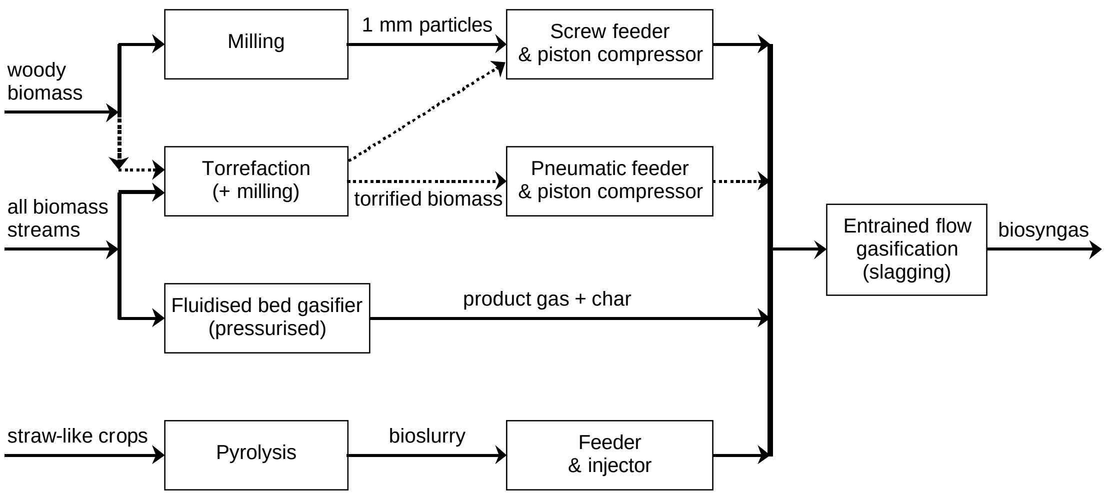

***Figure 2.2**. Different biomass pretreatment and feeding option.*

2.6.2. Torrefaction

Torrefaction can be applied to all biomass streams and in this mild thermal pretreatment process the biomass is converted into a coal-like product. After torrefaction electricity consumption for milling decrease tenfold (compared to fresh wood) while smaller particles are obtained that can be fed with (conventional) pneumatic feeding systems. Therefore, torrefaction is the key step for short-term and direct implementation of biomass (co) gasification in existing coal plants. The overall biomass-to-biosyngas (B-t-B) efficiency of this route is relatively low (*i.e.* 73%), due to the energy loss in the pretreatment step. However, because the electricity consumption is low, the overall system efficiency is as high as 74%. When transport to the gasifier and dosing in the burner can be achieved with a new (screw) feeding system, efficiency will increase to 75% [13].

2.6.3. Milling and screw feeding

The biomass-to-biosyngas and the overall system efficiency can be further optimised when no pretreatment is necessary, *i.e.* as milling wood down to 1 mm wood particles is sufficient to reach complete conversion. Then the electricity consumption is not excessive and no separate pretreatment process is required with the accompanying loss in efficiency and the investment and running costs. (*N.B. this option is not applicable to straw, as the knots in the straw cuttings are not completely converted*). A piston compressor does pressurisation. Development of a new feeding and dosing system is a necessity, as pneumatic feeding is not possible due to the plugging nature of the fibrous biomass. This route affords higher B-t-B energy and system efficiencies (*i.e.* 81 and 84%, respectively) because of the low electricity and inert gas consumption. Therefore, this route is the preferred option, especially for expensive biomass. However, conditionally that (i) the 1 mm biomass cuttings can be fed by a screw to the gasifier and (ii) that sufficient conversion is achieved in the gasifier [13].

2.6.4. Pyrolysis for bioslurry production

For straw and grassy biomass, pretreatment by conversion into bioslurry is the preferred option in most cases. Direct feeding of straw after milling is not possible due to the incomplete conversion of the knots [14] - torrefaction offers an alternative pretreatment. More important, however, is the consideration that straw-like materials are agricultural products or residues that are distributed generated and with large seasonally fluctuations. The energy density of bio-slurry is much higher than of raw biomass and, therefore, cost reductions in transport, transhipment, and storage as well as easy pressurisation more than compensate the lower B-t-B and overall system efficiencies (*i.e.* 69 and 76%, respectively). This route is particularly relevant for <u>cheap biomass</u> that is distributed available. Major advantage of the bio-slurry is that it is a liquid and can easily be pressurised and fed into the gasifier [13].

2.6.5. Fluidised bed gasification (pressurised)

High overall biomass-to-biosyngas and system efficiencies can also be obtained with a system in which a (pressurised) fluidised bed gasifier is used to ‘pretreat’ the biomass (*i.e.* 78 and 85%, respectively). The raw product gas, containing hydrocarbons and tars as well as the unconverted char and some bed material from the bed, is directly fed into the entrained flow gasifier. Upon EF gasification all the organic compounds and char are converted into syngas, therefore, the product gas quality and the carbon conversion of the fluidised bed gasifier are irrelevant. The entrainment of bed material from the fluidised bed gasifier is no problem and even preferred, as it will act as flux for the EF gasifier. Major advantage is that no pretreatment of the biomass is necessary (chips of 5 cm are acceptable) and that all types of biomass can be processed (*i.e.* both woody and straw-like biomass). However, this system is the most challenging, as the EF gasifier requires a very stable feed flow to guarantee safe operation, while a fluidised bed gasifier typically has some variations in the product gas flow [13].

2.7. Summarizing

In summary, the "Biosyngas Vision" can be described in the following lines:

- Biosyngas is an important intermediary for the production of renewable chemicals and fuels.
- Biosyngas will be produced and consumed in large centralised industrial areas, preferable located close to seaports or near larger rivers for effective biomass logistics.
- The optimum gasification technology to establish the required high biomass-to-biosyngas efficiency is entrained flow gasification.
- Wood and straw will be the main biomass feedstocks for biosyngas production.
- Different pretreatment and feeding options have to be applied for the different feedstocks to achieve optimum biomass-to-biosyngas and overall system efficiencies:

Pretreatment option	**Efficiency:**	**B-t-B**	**Overall system**
Torrefaction		73%	75%
Milling and screw feeding		81%	84%
Pyrolysis for bioslurry production		69%	76%
Fluidised bed gasification (pressurised)		78%	85%

- For short term implementation pretreatment by torrefaction is the most promising, as it converts the biomass into a coal-like product that can be applied in conventional coal feeding systems.

3. RESEARCH & DEVELOPMENT APPROACH

The overall objective of the research and development trajectory is to develop the technology for dedicated biomass-fired entrained flow gasification systems for reliable, high-efficient, and cost-effective production of biosyngas from multiple biomass streams. The technology should be proven in a full-scale (>100 MW_{th}) demonstration plant.

3.1. Starting point

Starting point of the development is the existing coal-based gasification technology that will be adapted for biomass firing. In spite of the evident suitability of entrained flow gasification for biomass and the existence of EF plants in operation, it is not such that implementation can commence right now. Biomass as feedstock has different properties than the fuels typically used today in EF gasifiers (*i.e.* in most cases coal or oil residues). Experience with entrained flow gasification of biomass is limited to a small number of co-gasification tests in the Nuon and Elcogas coal IGCC plants and series of short experiments in the pilot gasifier of Future Energy (Freiberg, Germany).

From the co-gasification tests in the EF IGCC plants it is clear that for optimum performance the gasifier should be specifically designed for the biomass properties. Even more important is the issue of biomass feeding, *i.e.* conventional coal feeding systems cannot be applied for biomass and new solutions need to be found. Re-designing the gasifier for biomass firing also holds the opportunity to take advantage of specific biomass properties. Due to higher reactivity of biomass (compared to coal) the gasification temperature might be decreased,[4] resulting in higher efficiencies and lower costs for oxygen.

To bridge the gap between the existing and proven technology for coal and the implementation of biomass-fired entrained flow gasifiers, a research and development trajectory is necessary with focus on four interrelated themes:

1. Biomass pretreatment & feeding;
2. Gasification & burner design;
3. Ash and slag behaviour;
4. Hot gas treatment (cooling, cleaning, and conditioning).

3.2. Description of R&D themes

The four R&D themes cover the complete integral entrained flow gasification system to produce a clean and conditioned biosyngas from multiple biomass feedstocks as shown in Figure 3.1.

4. Typical coal gasification temperatures are 1400-1600°C. For biomass materials to establish complete conversion, while preventing tar formation with minimum CH_4 production, a temperature of 1200°C will be sufficient.

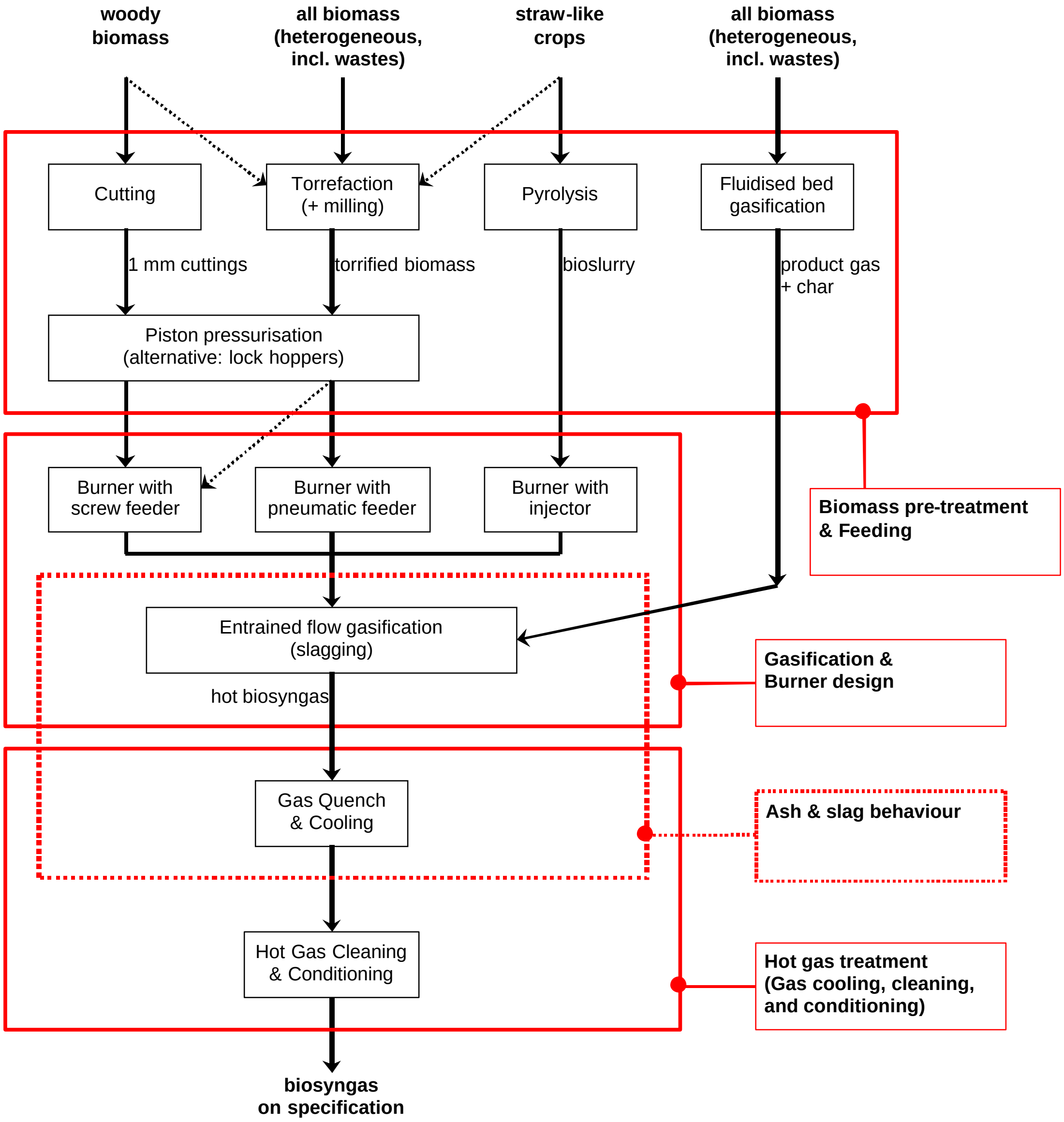

Figure 3.1. *Integral system for entrained flow gasification of multiple biomass feedstocks to produce a clean and conditioned biosyngas.*

3.2.1. Biomass pretreatment & Feeding

Biomass cannot be handled and fed similar to coals, as the biomass properties are completely different (*i.e.* biomass has a fibrous structure and high compressibility). Therefore, either biomass has to be pretreated to make it behave similar to coal or dedicated biomass handling systems have to be developed. The advantage of pretreating the biomass to match coal properties (*i.e.* by torrefaction), is that it allows short-term implementation of biomass firing in existing plants. The efficiency can be improved when a dedicated feeding system for solid biomass is developed. Gasification of solid straw gives rise to problems in the gasifier as the knots are poorly converted [14]. Therefore, for straw materials the route via pre-conversion by pyrolysis into a bio-slurry is applied. An alternative high efficiency pretreatment route is pre-conversion in a fluidised bed gasifier and firing of the raw product gas in the EF gasifier

The main R&D issue is how to feed a variety of biomass materials into the gasifier with minimum pretreatment and inert gas consumption. The four different routes that will be addressed in the R&D are:

1. Milling of (woody) biomass, pressurisation in a piston compressor with negligible inert gas consumption, and feeding to the gasifier burner with a screw system with low inert gas consumption.
2. Pre-conversion of grassy and straw biomass materials into bioslurry by flash pyrolysis; bioslurry is easily pressurised and fed into the gasifier.
3. Pre-conversion by torrefaction, which can be applied to all types of biomass and also homogenises other heterogeneous (waste) streams. The torrefied material is pressurised in a piston compressor and fed either by a screw (preferred) or a pneumatic feeding system.
4. Gasification of the feed material in a fluidised bed gasifier into a product gas that is directly fired on the gasifier.

3.2.2. Gasification & Burner design

The general objective of the R&D on these topics is to determine the optimum burner design for solid biomass feeding and the optimum gasification conditions with respect to maximum efficiency, maximum heat recovery, minimum flux use, minimum inert gas consumption, complete conversion, production of biosyngas with desired quality (*i.e.* low CH_4 and no tars). The gasifier should fulfil the following requirements:

- The heart of the system is a pressurised oxygen-blown slagging entrained flow gasifier;
- Slagging properties are tuned by the addition of ‘flux’ (process control). The flux can be recycled.
- The gasifier is suitable for a large variety of feed materials, varying from wood particles, grass and straw-based bioslurries, and heterogeneous biomass streams after homogenisation by torrefaction.
- The gasifier is operated at lowest temperature possible to obtain high cold-gas efficiencies and oxygen consumption.
- The gasifier produces a tar-free biosyngas with a low nitrogen concentration.
- The gasifier produces no solid waste as the bottom ash is recovered as non-leachable slag with value as construction material, whereas the fly ash can be used for mineral recycling.

Complete conversion of the biomass is required to obtain a high efficiency and a carbon-free slag. To minimise oxygen consumption and heat losses, the lowest gasification temperature must be determined at which complete conversion to the desired products H_2 and CO is achieved. Correlations with the biomass properties and particle size have to be determined.

The critical step in the gasification is the stable operation of the gasifier burners. With respect to burner design the critical issue is to ensure a constant flow of biomass material to prevent dangerous situations of excess oxygen. Furthermore, the atomisation and mixing of the biomass and the gasification gases with the oxygen must be very well. For liquid biomass (*i.e.* the bioslurry) feeding to the burner and injecting with sufficient atomisation is the key challenge. For solid biomass stable feeding with a constant flow and density (*i.e.* mixture of biomass and inert gas) is crucial. Also the inert gas consumption is of importance for the efficiency of the process.

R&D activities comprise: (i) pilot-scale gasification tests (with solid feeding system) to prove conversion, (ii) conversion experiments in lab-scale EF simulators (atmospheric and pressurised) to determine correlations between temperature, particle size, type of biomass, CH_4 (and small amounts of tars) content of the biosyngas, and conversion, and (iii) modelling of gasification hydrodynamics.

3.2.3. Ash and slag behaviour

The theme of ash and slag behaviour is relevant for both the gasifier operation and the hot gas cooling. In a slagging gasifier the ash and flux are present as a molten slag that protects the gasifier inner wall against high temperatures. The slag must have the right properties (*e.g.* flow behaviour and viscosity) at the temperature in the gasifier. It is crucial to have a good understanding of the slag behaviour as function of the gasification temperature, biomass ash properties, and selected flux [15]. Research activities comprise:

- Deposition experiments in lab-scale EF simulators (atmospheric and pressurised) to determine behaviour of ash and slag, and interactions between both, as function of temperature, type of biomass, and selected flux.
- Based on the experimental work thermodynamically modelling is carried out to support the selection of gasification conditions and flux materials.
- Gasification tests in pilot EF gasifier to validate and prove slag and ash behaviour under realistic gasification conditions. In first experiments bio-slurry, with added minerals, is used as biomass feed. The slurry has the same chemical composition as solid biomass, but the advantage of liquid feeding system. Therefore, these tests can be performed independent of the progress in the solid feeding project topic. Later experiments (after installation of a new feeding system) will be carried out with solid biomass feed, to prove the integrated concept for solid biomass.

The biosyngas is cooled to ~800°C by a water or gas quench. The gas is cooled further with a heat exchanger to ~200°C to recover heat. Fouling of the heat exchangers is a major issue to be addressed; this has also been the major problem in co-gasification tests with biomass in the large scale IGCCs. Deposition tests will be carried out in the lab-scale EF simulator at the temperature range of the gas heat exchanger to study fouling phenomena.

3.2.4. Hot gas treatment (cooling, cleaning, and conditioning)

This theme addresses all topics related to the hot gas treatment, *i.e*. gas cooling, gas cleaning, and when necessary gas conditioning. Gas cooling from the gasifier outlet temperature (1000-1300°C) is normally done by a partial gas quench (to 800°C) with recycled clean gas or water injection. A gas quench is preferred considering the higher efficiency and amount of energy that can be recovered. However, it requires a large gas recycle (typically 1:1 to the raw gas) resulting in twice as large gas cleaning section (compared to a system without gas recycle). Therefore, there is a large incentive to develop an innovative hot gas cooler for cooling of the hot gas with energy recovery and to make the recycle superfluous. The biosyngas is further cooled to the level necessary for the gascleaning. R&D activities will focus on the development of a fluidised bed gas cooler.

Biosyngas that will be utilised for chemical processes or liquid fuel synthesis needs to meet the restrictive catalyst specifications [16]. The hot gas cleaning has to remove all components that may be harmful to the catalysts or other parts of the plant by corrosion, erosion or fouling. Preferably the gas cleaning is operated at the same temperature of the downstream gas application to minimise efficiency loss by cooling. Especially, significant efficiency improvements are possible when water is not condensed from the biosyngas, which happens in ‘wet’ gas cleaning (*i.e.* below water dew point). Due to the large spectrum and the broad variety of biomasses taken into consideration for gasification, an efficient gas cleaning at temperatures of about 200°C appears to be necessary. N.B. therefore *warm gas cleaning* is a more appropriate definition and avoids reference to the poor results in the developments of real hot gas cleaning for coal applications (*i.e.* above 500-600°C). Activities comprise lab-scale experiments are carried out to evaluate absorbentia for high temperature gas cleaning from inorganic impurities.

3.2.5. Result of R&D trajectory

The final objective of the R&D trajectory is to define a blueprint (“conceptual design basis”) for a dedicated biomass-fired demonstration biosyngas production plant based on the slagging entrained flow gasification technology. Specific supporting R&D activities comprise:

- Assessment of sociological, economical, and environmental aspects of biomass import and logistics.
- Complete mass and energy balances for selected cases.
- Assessment of quality and value of by-products.
- Life cycle assessment (LCA) of biomass entrained flow technology.
- Operating philosophy for operation of varying biomass load and coal-biomass mixtures.
- Assessment of up-scaling risks and the economic potential of the technology.
- Assessment of the reproduction potential of the technology and definition of implementation plan with business case.

3.3. Time schedule

For the intermediate development trajectory to reach this goal the following phased approach is foreseen:

Phase	Activity Year:	1	2	3	4	5	6-9	>10
1	Research & Development							
2	Proof-of-Principle (lab-scale)							
3	Proof-of-Concept (pilot & co-gasification)							
4	Demonstration plant							
5	Full-scale plant							

Underlying scope of the R&D trajectory comprises phases 1 through 3 (indicated by the thick dotted box), *i.e.* the research & development (R&D), proof-of-principle (POP), and proof-of-concept (POC). In these phases the existing issues are solved resulting in a blueprint for a dedicated biomass-fired demonstration biosyngas production plant (Figure 3.2).

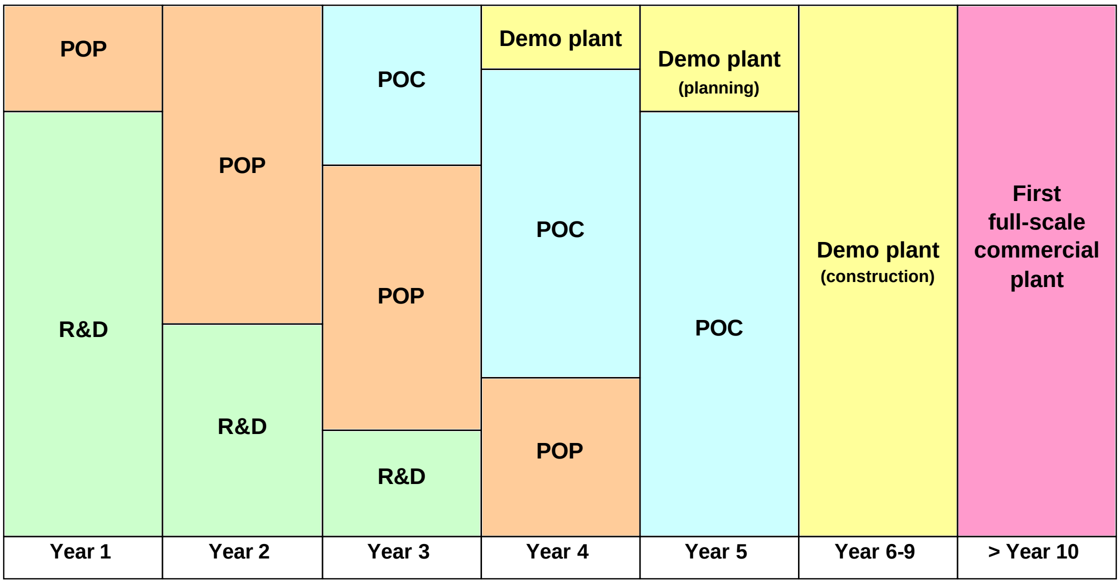

Figure 3.2. *Indicative time schedule of BIOSYNGAS development with different phases and topics indicated.*

The construction of a demonstration plant is foreseen after the R&D phases; planning and engineering can already start earlier. Shortly after ten years the first full-scale plants should come in operation.

4. CONCLUSIONS & CONTINUATION

In this report the necessary research and development (R&D) trajectory is defined to reach implementation of large-scale production of renewable syngas (*i.e.* biosyngas) from biomass and to form a (international) consortium to carry out the activities.

4.1. Conclusions

The "Biosyngas vision" describes the conceptual ideas, choices, and motivation that form the foundation of the R&D trajectory. In summary, the "Biosyngas Vision" can be described by the following statements:

- Biosyngas is an important intermediary for the production of renewable chemicals and fuels.
- Biosyngas will be produced and consumed in large centralised industrial areas, preferable located close to ports for effective biomass logistics.
- The optimum gasification technology to establish the required high biomass-to-biosyngas efficiency is entrained flow gasification.
- Wood and straw will be the main biomass feedstocks for biosyngas production.
- Different pretreatment and feeding options have to be applied for the different feedstocks to achieve optimum biomass-to-biosyngas efficiencies.
- Pretreatment by torrefaction is the most promising for short term implementation as it converts the biomass into a coal-like product that can be applied in conventional coal feeding systems.

A large total installed biosyngas production capacity with large individual plants is required to meet the ambitious renewable energy targets. This requires a robust, fuel-flexible, and high-efficient technology for optimum biomass utilisation and to guarantee availability. Starting point of the phased research and development trajectory is the existing coal-based gasification technology. To bridge the gap between the existing and proven technology for coal and the implementation of biomass-fired entrained flow gasifiers, a research and development trajectory is necessary with focus on four interrelated themes:

1. Biomass pretreatment & feeding;
2. Gasification & burner design;
3. Ash and slag behaviour;
4. Hot gas treatment (cooling, cleaning, and conditioning).

4.2. Continuation

In the December 2004 call of the Sixth Framework (FP6) an international consortium will submit a proposal for a Strategic Targeted Research Project. This project (acronym "POWERGAS") will address "High-efficient IGCC power production from multiple biomass streams via fuel-flexible entrained-flow gasification and biosyngas as intermediary".

Parallel a national Dutch consortium will be formed that will submit and proposal in the January 2004 tender of the EOS programme of SenterNovem. This foreseen project will address the more fundamental and innovative aspects of the integral biosyngas production system that are not included in the POWERGAS proposal.

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APPENDIX A. ENTRAINED FLOW GASIFIERS

Text taken from ECN report C--04-039 (reference [13]).

A.1. Introduction

An entrained flow gasifier (German: Flugstromvergaser, Dutch: stofwolkvergasser) is characterized by fuel particles dragged along with the gas stream. This generally means short residence times (typically 1 second), high temperatures (typically 1300-1500°C) and small fuel particles (solid or liquid, typically <100 μm). Furthermore, entrained flow gasifiers often are operated under pressure (typically 20-50 bar) and with pure oxygen. The capacity often is in the order of several hundreds of MW.

Pulverized solid fuels generally are introduced in the gasifier (after being pressurized, mostly using a lock hopper system) by pneumatic feeding. The powder is moved by inert gas and injected in a so-called burner in the gasifier. The burner intends to realize a good mixing between solid fuel and oxygen. Often vortex flow patterns are created in the burner. Local temperatures in the burner zone can be 2500°C or even higher. In the case of liquid fuels or slurries, pressurizing systems can be simply pumps. The liquid fuel subsequently is atomised and fed to the burner similarly to solid fuel powder.

Since entrained flow gasifiers operate at high temperature, it results in a CO- and H_2-rich gas (and inevitably also CO_2 and H_2O). Depending on the type of fuel, also soot may be formed. Soot formation often is suppressed by adding steam, typically 0.1 kg of steam per kg of oxygen. Two types of entrained flow gasifiers can be distinguished: (1) slagging and (2) non-slagging.

A.2. Slagging entrained flow gasifier

In a slagging gasifier, the ash forming components melt in the gasifier. The molten particles condense on the relatively cold walls and ultimately form a layer being solid close to the wall and liquid on the inner side. This slag layer serves as a protective layer for the wall. The liquid slag is removed from the bottom of the gasifier. In order to generate a liquid slag with the right viscosity at the given temperature, generally so-called fluxing material must be added. For coal-fired plants, this often is limestone or another Ca-rich material. Slagging entrained flow gasifier manufacturers are Shell, Texaco, Krupp-Uhde, Future-Energy (formerly Babcock Borsig Power and Noell), E-gas (formerly Destec and Dow), MHI (Mitsubishi Heavy Industries), Hitachi and Choren (formerly UET).

One example of a large-scale entrained flow gasifier is the 600 MW_{th} coal-fired Shell gasifier in Buggenum, the Netherlands.[5] It is owned by the utility company NUON and produces electricity with a net efficiency of 43%. Tests have been performed with different kinds of biomass like wood, sewage sludge and chicken manure up to approximately 10% on energy basis (corresponding to 18% on weight basis). It is planned to co-fire 25% biomass on energy

5. Zuideveld, P.L.; Graaf, J. de, Overview of Shell global solutions' worldwide gasification developments. In: Gasification Technologies, San Fransisco, October 12-15, 2003.

basis in 2005.[6,7] Shell has signed several contracts to make similar coal gasifiers for fertilizer industries in China.[8] Another example is a 130 MW_{th} gasifier (25 bar) made by Noell (presently Future Energy), operating on waste oil and sludges on the premises of the Schwarze Pumpe in Germany.[9] Figure A.1 shows this gasifier, where the bottom half of the reactor is gas cooler by water quench.

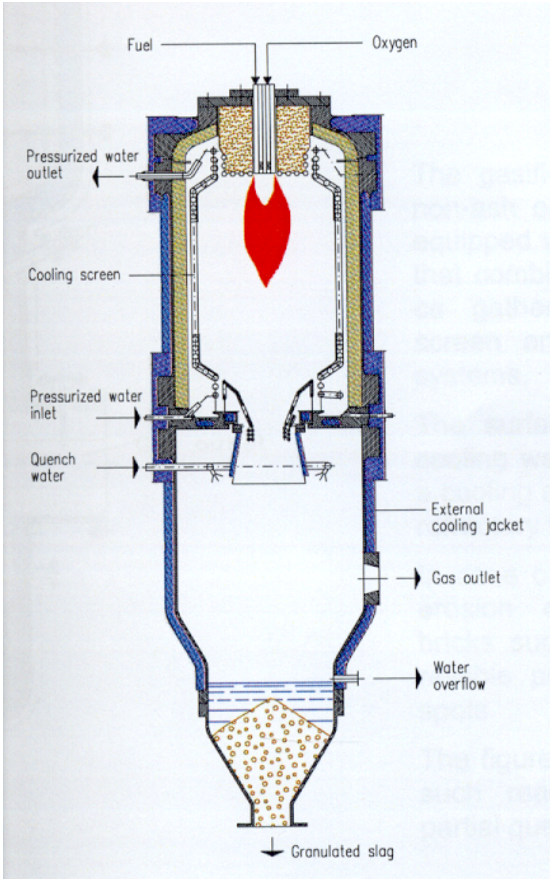

Figure A.1 *Schematic representation of the entrained flow reactor of Noell (presently Future Energy).*[10]

The largest coal-fired entrained flow gasifier is located in Puertollano and owned by the utility company Elcogas.[9] It can produce 320 MW_e. The technology is from Krupp-Uhde (Prenflo) and similar to the Shell technology. Tests have been performed with MBM (Meat and bone meal) up to 4.5 wt%.[11]

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A.3. Non-slagging entrained flow gasifier

In a non-slagging gasifier, slag is not produced. In practice, this means that fuels should contain only little amounts of minerals/ashes. Generally 1% is the maximum allowable ash content. An example of this type of gasifier is the SGP (Shell Gasification Process) on oil residues in Pernis, the Netherlands[5]. A certain amount of soot often is deliberately produced to generate condensation surface in the gas to prevent fouling of the walls.