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# Biomass co-firing in high percentages - Dutch R&D consortium pushing the limits

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## Abstract

In the Netherlands, biomass is envisaged to play a major role in fulfilling national ambitions concerning the reduction of $CO_2$-emissions and the introduction of renewable energy sources. Ambitious targets have been set in the long-term energy research strategy programme of the Dutch Ministry of Economic Affairs, including targets of 25% and 40% biomass co-firing in 2020 and 2040 respectively. These co-firing targets cannot be met with state-of-the-art technology. Therefore, ECN and KEMA, with the assistance of Delft University of Technology, have joined forces to address the biomass co-firing R&D needs. The Dutch power generation sector is closely involved to ensure that the R&D activities are well targeted to market needs and to facilitate the implementation and exploitation of the results. This paper presents an overview of the topics considered.

Keywords: Advanced clean coal technologies, biomass co-firing, full-scale operation, lab-scale experimentation

## Introduction

In the Netherlands, biomass is envisaged to play a major role in fulfilling national ambitions concerning the reduction of $CO_2$-emissions and the introduction of renewable energy sources. Ambitious targets have been set in the long-term energy research strategy programme of the Dutch Ministry of Economic Affairs, including 25% and 40% biomass co-firing levels in 2020 and 2040 respectively and coal+biomass-to-electricity efficiencies of >50%. To achieve this in the said timeframe, not only existing fossil-fuel-fired power plants will have to be considered, but also new plants involving new conversion technologies aiming at higher overall efficiencies and a lower environmental impact. According to the long-term vision of the Dutch power sector, coal-fired power generation capacity in the Netherlands in 2040 will consist of a mix of near-zero and zero emission plants with a high efficiency (>50%) and $CO_2$-emissions comparable to state-of-the-art gas-fired combined-cycle units. Coal gasification with $CO_2$ capture and oxy-fuel coal combustion with Ultra Super Critical (USC) steam conditions and $CO_2$ capture are envisaged to be the most cost-effective technologies.

## R&D needs to meet targets for biomass co-firing

The targets set for biomass co-firing in 2020 and 2040 respectively cannot be met with state-of-the-art technology. New innovative co-firing technology solutions will have to be developed. In line with the long-term vision of the Dutch power generation sector, and based on a detailed assessment of the expected impact of biomass co-firing on power plant performance and of the current technology status, the following technology developments are thought to be required:

1. *Biomass upgrading, pre-treatment and feeding technology*. Apart from their $CO_2$-neutral nature, most biomass types have inferior mechanical and physical properties compared to fossil fuels. This includes low energy density, hydrophylic nature (high water uptake when stored in open air), fibrous structure and tenacity (poor flowability and grindability), susceptibility to biodegradation and heating, and high contaminant levels (especially for biomass residues/waste and mixed streams). Dedicated upgrading/pre-treatment and feeding technology will be required to enable more efficient (also in economical terms) handling, transport and storage and to meet the narrow feedstock specifications set by thermal conversion processes. In this respect, it would be very attractive to develop technology for the upgrading of biomass into standard or "commodity" fuels with properties similar to existing fossil fuels like coal or oil.

2. *Assessment and solution of technical bottlenecks in direct co-firing*. Direct biomass co-firing in coal-fired plants, especially at higher co-firing percentages (>10% on energy basis), involves a range of potential technical bottlenecks. These include: decreased burn-out and flame stability, altered heat distribution, NOx formation and abatement profiles. Also slagging and fouling, (fouling-induced) corrosion and the impact on downstream gas conditioning and the resulting stack emissions need to be addressed. These bottlenecks will have to be brought in chart, and strategies, technology and predictive tools will have to be developed to avoid and overcome them. This holds not only for existing (conventional) pulverised-coal-fired plants, but also for new coal-fired capacity based on advanced coal conversion technologies such as USC combustion, oxy-fuel combustion and entrained-flow gasification.

3. *Indirect co-firing technology*. In coal-fired power plants, the targeted co-firing percentages will likely have to be met through a combination of direct and indirect co-firing. Direct co-firing is most cost-effective, which gives a strong incentive to maximise this option beyond the current levels (typically 5-10% on energy basis). Indirect co-firing technology for both coal-fired and gas-fired plants is insufficiently proven and requires further R&D. This also holds for the smart, cost-effective combination of direct and indirect co-firing.

4. *Process monitoring and control*. The high direct co-firing percentages require more detailed on-line process monitoring and control in order to avoid excessive maintenance cost and unscheduled plant outages.

5. *Residues management*. To ensure sustainable biomass use, proper solutions will have to be found for process residues (e.g., ashes), including ash recycling (for clean biomass) and various utilisation options (for contaminated biomass).

6. *Heat utilisation aiming at higher overall (power plant) efficiencies*. Given the high cost of biomass feedstock and the large share of feedstock cost in the overall power production cost, there is a large incentive to maximise power plant efficiency. A major option is (better) heat utilisation. Concepts should be developed aiming at a proper matching of heat supply and demand, e.g. by combining coal/biomass-fired power stations with heat-demanding biomass upgrading or biomass conversion processes (or other industrial activities). This may involve the upgrading and subsequent co-firing of wet biomass streams, which are not suitable (anymore) for bio-chemical conversion processes, such as residues from primary biomass processing (digestion, ethanol production, bio-chemical bio-refinery).

ECN and KEMA, with the assistance of Delft University of Technology, have formed an R&D consortium to address these biomass co-firing R&D requirements. The Dutch power generation sector is closely involved to ensure that the R&D activities are well targeted to market needs and to facilitate the implementation and exploitation of the results.

## R&D topics addressed by the consortium

Clearly, the consortium cannot address all the R&D topics of interest. Also, much research on biomass co-firing is already being conducted by R&D institutes, universities and industrial parties abroad. Therefore, the consortium in close co-operation with the Dutch power sector has made a careful selection of those R&D topics, which are of particular relevance to the Dutch power sector and where the consortium has clear added value based on available expertise and R&D facilities. Furthermore, the consortium strives for extensive international co-operation, e.g. in the framework of EU R&D programmes, to benefit from relevant, related R&D and experience elsewhere.

The following specific R&D topics have been selected:

1. *Biomass upgrading by means of torrefaction*. Torrefaction is a mild temperature treatment at a temperature level of 250 to 300 °C, at near atmospheric pressure in the absence of oxygen. In combination with pelletisation, it enables energy-efficient and cost-effective production of 2$^{nd}$ generation pellets with superior properties in terms of high energy density (1.5-2x conventional pellets), excellent grindability and water resistant nature (eliminating/reducing biological degradation and spontaneous heating, enabling outdoor storage). Torrefaction can be applied to a broad range of biomass streams, such as wood chips, agricultural residues and various residues from the food and feed processing industry. It is regarded a key technology for the upgrading of biomass into standard (commodity) solid fuels, leading to substantial cost reductions in biomass handling, transport and storage, and improving the compatibility of biomass as a fuel for thermal conversion processes.

2. *Assessment and solution of technical bottlenecks in direct co-firing*. The consortium has a strong international position in this respect based on extensive full-scale experience with co-firing in the Netherlands (several Dutch power producers are in the forefront of biomass co-firing implementation) and the unique lab-scale experimental facilities and high-quality analysis facilities at ECN. Particular focal points are ash behaviour (e.g., slagging, fouling, (trace element) emissions), ash utilisation and corrosion. The R&D is to result in co-firing strategies, fuel blending recipes, design specifications, operating guidelines and predictive tools (models, experimental screening methods).

3. *On-line monitoring and control*. Focus is put on the development of on-line fouling monitoring and control, based on a solid knowledge base on ash behaviour at ECN, specific sensor technology developed by the Dutch firm Hukseflux and soot blowing expertise at Clyde Bergemann.

4. *Indirect co-firing*. Focus is put on fluidised-bed gasification concepts including innovative concepts for low-temperature indirect gasification. In these concepts, pyrolysis and combustion are conducted in two separate, but connected reactors, with sand circulation for heat transfer. They seem especially suitable for biomass types rich in alkalis and chlorine, such as agricultural residues (e.g., straw, grass).

5. *Sustainable ash management*. Building on the extensive experience with the utilisation of coal ashes, the consortium is in a strong position to develop proper solutions for residues from co-firing units as well as stand-alone biomass conversion units.

6. *Conversion-aspects of biomass co-firing in advanced clean coal combustion*. The focal point of this study is USC boiler designs particularly including oxy-fuel combustion

technologies. The knowledge base on the combustion characteristics, including ash formation, slagging/fouling and corrosion, in these new processes and with biomass co-firing is still in its infancy.

7. *Heat utilisation for wet biomass processing*. Interesting options to increase the overall efficiency of coal-fired power plants could lie in combining them with heat-demanding biomass upgrading or biomass conversion processes. For biomass upgrading, this could include the TORWASH concept, under development at ECN [1]. At the heart of this technology lies simultaneous washing and torrefaction at elevated temperature and pressure, followed by a quick drying step (flashing). The combination of the said processes leads to high salt removal efficiencies and relatively low energy requirements. Other biomass conversion processes might include not only digestion and bio-chemical ethanol production, but also innovative bio-refinery concepts.

Torrefaction is addressed by ECN only and the R&D activities have been described in detail in another paper at this conference and in a series of previous papers [2-7]. Also the work on on-line fouling monitoring and oxy-fuel combustion has been describes elsewhere [8,9]. In the following sections, the work on technical bottleneck assessment, indirect co-firing and sustainable ash management will be elucidated.

## Technical bottlenecks in direct biomass co-firing

The assessment of technical bottlenecks and the associated development of co-firing strategies, fuel blending recipes, design specifications, operating guidelines and predictive tools (models, experimental screening methods) generally relies on a combination of three approaches, viz. modelling, lab-scale experimentation and measuring campaigns at full-scale power plants. The three approaches are complementary while each of them has its own merits and limitations. By combining them, a more complete picture can be obtained. Moreover, modelling and lab-scale experiments allow the conditions to be extended beyond those in existing power stations, e.g. to advanced clean coal technologies like USC and oxy-fuel combustion.

**Modelling** comprises both thermodynamic equilibrium calculations using FactSage software and Computational Fluid Dynamics modelling.

The **lab-scale experimentation** is conducted mainly in ECN's Lab-scale Combustion Simulator (LCS), see Figure 1. This apparatus is a flexible facility for the characterisation of solid fuel behaviour under typical pulverised-fuel-firing conditions. The facility comprises a drop-tube reactor in combination with a staged gas burner to simulate a flame/flue gas environment in which the conversion behaviour of fuel particles can be studied as a function of time. An adequate simulation of heating rate, gas temperatures and composition can thus be obtained independently of the test fuel. The main characteristics of the LCS are elucidated in Figure 2.

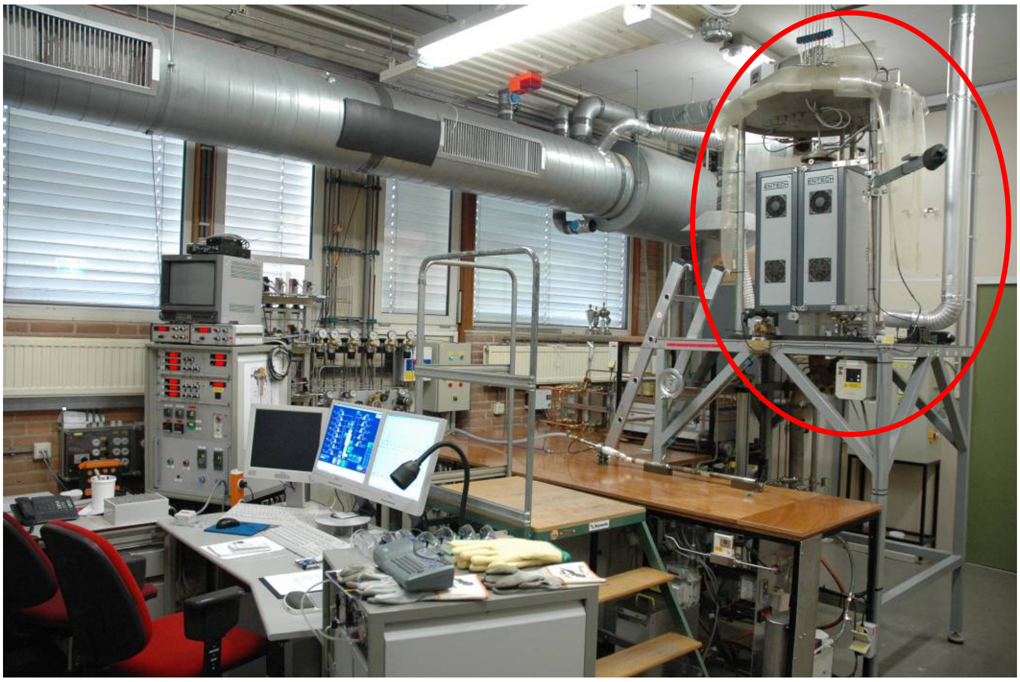


Figure 1: ECN's Lab-scale Combustion Simulator (the red oval indicates the reactor part)

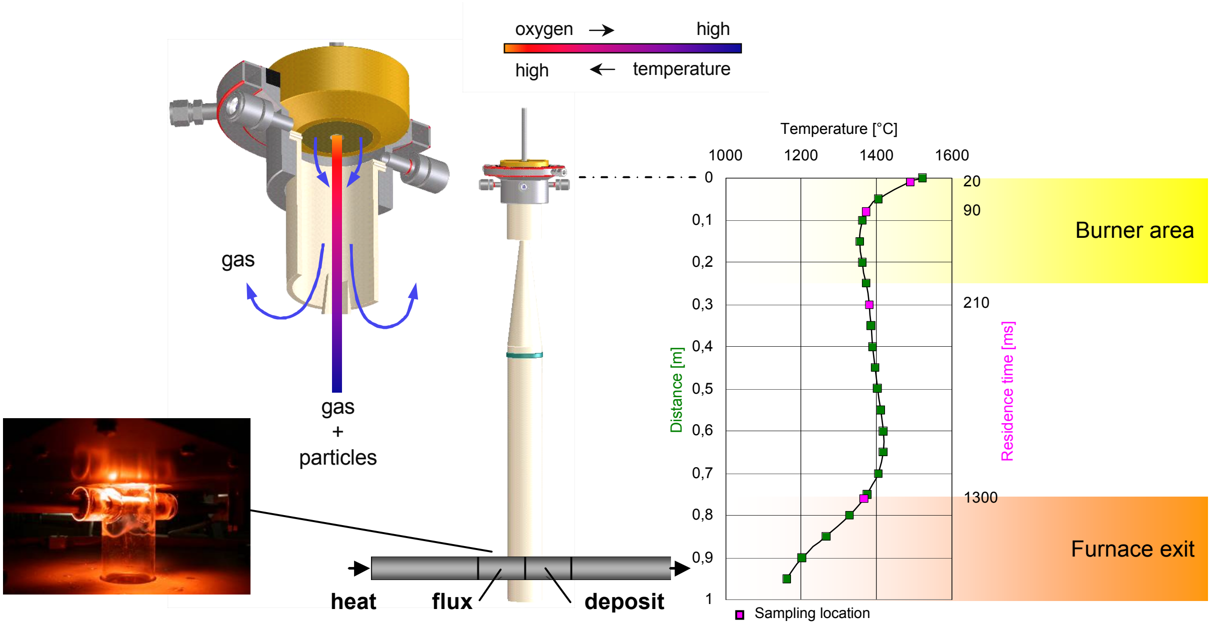



Figure 2: Schematic and main characteristics of the LCS

In the LCS, solid fuel particles are fed through the inner burner and are rapidly heated (>$10^5$°C/s) to the temperature level of, e.g., a coal flame (1400-1650°C). Particle feed rates of 2 g/h are typically used in order to control the gaseous environment of each particle by means of the imposed gas burner conditions. For example, to mimic a low-NOx configuration the primary (inner) burner is supplied with a mixture of $O_2$, $CH_4$, $H_2S$ and $CO_2/N_2$ resulting in an oxygen-lean flame. The outer burner is then supplied with a mixture of $O_2$, $CH_4$, and $N_2/CO_2$ resulting in an oxygen-rich flame. The resulting gas/particle flow enters an alumina reactor tube for complete oxidation of the fuel particles. From a distance of ~130 mm from the burner, the tube is surrounded by two 3.4 kW furnace sections. The flue gas composition is continuously monitored. By using a special tube configuration, residence times can be created of up to 50 ms in the oxygen-lean inner burner zone, up to 1000ms in the devolatilisation zone and up to 3000 ms in the combustion zone. Particles can be sampled at various residence times by inserting a oil-cooled sampling probe in the reactor from the bottom. Alternatively, as shown in Figure 2, boiler tube fouling studies can be conducted using a horizontal probe placed at the burner exit, simulating the gas/particles flow around a single tube in the convective section of a boiler. The probe is fitted with a ring shape heat-flux sensor and a detachable tubular deposition substrate. The probe surface is kept at constant temperature, tuned to the steam conditions in a full-scale boiler. Deposition samples are collected in both the sensor and the detachable probe surface. While the sensor yields on-line data on the influence of the deposit on the effective heat flux through the tube wall, the tubular substrate is used to collect samples for off-line deposit morphology studies (by visual/electron microscopy, combined with EDS).

The LCS has proven to allow a close simulation of actual pulverised-fuel combustion conditions. In fact, a wide range of pulverised-fuel combustion conditions can be simulated, including:
- Unstaged “full NOx”combustion – relevant for older power plant designs, characterised by a very high peak flame temperature, with a relatively low furnace/boiler temperature.
- Air-staged “low NOx” combustion – for some of the existing coal-fired power plants, retrofitted with Low NOx burner, yet without or with limited secondary air-staging facilities (e.g. Borssele 12 plant of EPZ).
- Deep air staged/over fire air conditions – simulating state-of-the-art pf-installations (e.g. Amer 9 of Essent and Hemweg 8 of NUON).
- Oxy-fuel combustion conditions with 20% and 80% flue gas recirculation – for the evaluation of the behaviour in the foreseen oxy-fuel USC power plants.
- Biomass co-firing percentages of 20-45% on energy basis in combination with the above conditions.

Often, modelling and lab-scale experimentation are combined with **full-scale measurement campaigns** for validation purposes. In these campaigns, the multi-purpose probe developed by ECN has proven to be a powerful tool for in-situ measurements and sampling. This probe contains the following measuring devices (see Figure 3):
- A deposition coupon, consisting of a temperature controlled tube-shaped piece on which fly ash may deposit. The coupon is detachable and after embedding/preparation can be further investigated in the lab. The tube material can be chosen freely, thus simulating various stages of the boiler. Materials used so far include SS310/316, several Inconel high alloys as well as USC-capable Alloy 617.
- A fourfold of heat flux/surface temperature sensors, with which the heat transfer to the simulated boiler tube can be measured on-line and in all four axial directions. These sensors are also used to control very precisely the local tube wall temperature, which can be varied between 300 and 750°C.
- A camera equipped with a narrow-angle lens system, with which the accumulation of the deposit can be studied on-line.
- A thermocouple measuring approximate flue gas temperature on location.
- A quenched, isokinetic dust sampling system with which representative furnace/boiler fly ash samples can be collected from the flue gas stream.

The lance, in which the measuring instruments are positioned, has an outer diameter of 60.4 mm. Thus, the probe fits any hole in the boiler wall bigger than 61 mm. A number of mounting flanges/adapter tubes has been developed at ECN in order to allow for a fast and non-invasive installation at the studied boiler/furnace. The lance can penetrate the boiler for up to 2 m depth. The lance itself is water cooled, using a self-contained water circuit with circulation pump and air cooler. The various measurement devices are cooled with compressed air which should be made available in the boiler house. The spent, hot air first cooled by passing through the water-cooled lance and subsequently discharged into the boiler house.

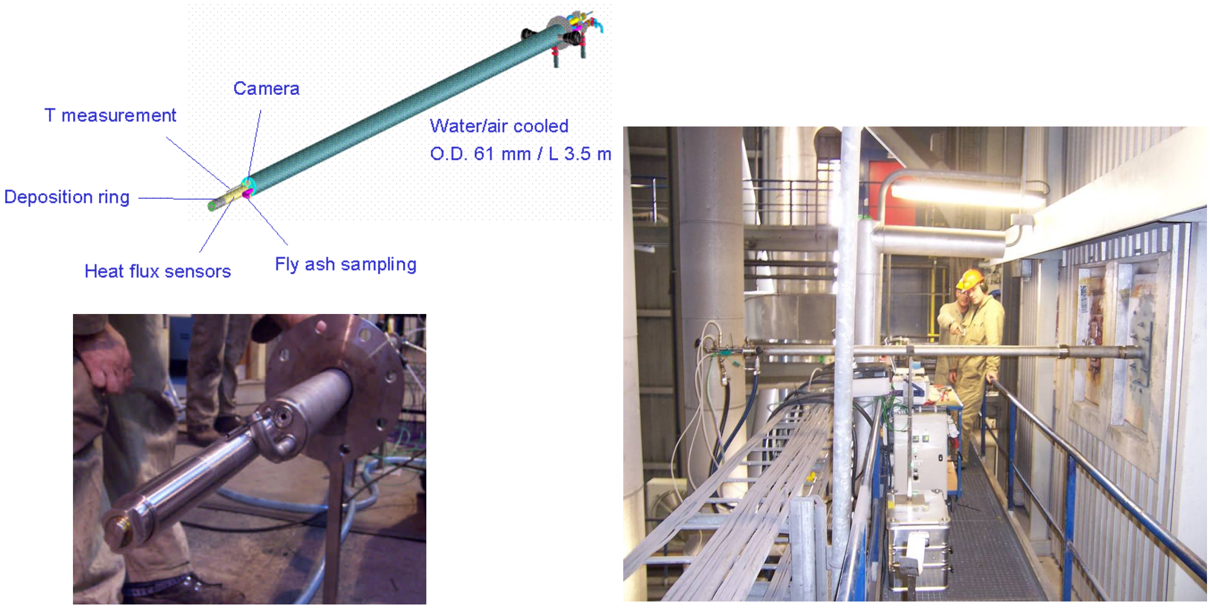



Figure 3: Full-scale sampling using ECN's multi-purpose probe

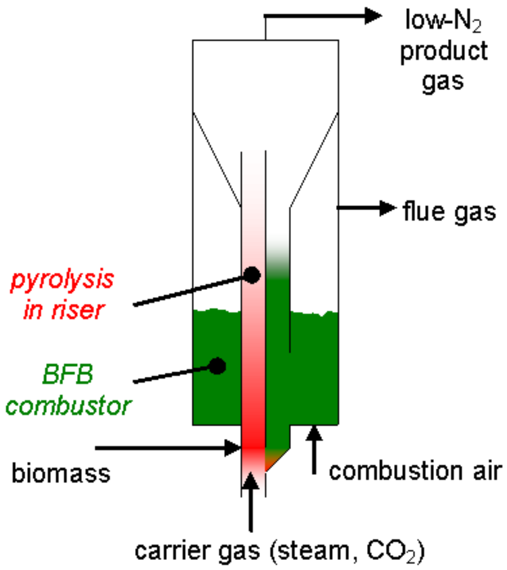
In the consortium R&D programme, particular attention is paid to the fate of trace elements. The behaviour of trace elements in conventional power plants at lower biomass co-firing percentages (up to 5-10% on energy basis) is rather well-known. However, this is not the case for higher co-firing percentages, with biomass containing different trace elements than coal. Nor is it the case for advanced clean coal combustion plants. Furthermore, far less is known about the *speciation* of these elements (i.e. the chemical form in which they occur) and how this depends on the state of oxidation and the related complex building behaviour, especially in flue gas cleaners and scrubbers. What is for instance the influence of temperature, residence time, pH and redox potential?

A combination of the three approaches described above is applied to improve the understanding of trace element speciation and related behaviour to allow the formulation of design and operation guidelines for an adequate control of the emission of critical trace elements. Since trace element behaviour is closely related to the behaviour of macro and micro elements, these will be considered as well. Emphasis is in particular placed on the trace elements relevant to (gaseous) emissions, viz. As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Tl, V. First results of this work will be published in a paper to the US Clearwater conference [10].

## Indirect biomass co-firing

It is expected that a combination of direct and indirect co-firing will be necessary to reach the ultimate target of 40% biomass co-firing, but indirect co-firing is still in its infancy. Only a very limited number of plants are in operation, all with a capacity of approx. 80 $MW_{th}$ and using circulating-fluidised-bed (CFB) technology (Lahti - Finland, Geertruidenberg/Amer – the Netherlands, Ruien - Belgium). Based on recommendations by the Dutch power sector, the consortium will address the further development of fluidised-bed gasification concepts and different ways of integrating the gasification with the main coal-fired boiler. Focus is put mainly on low-cost biomass, which is not suitable for other applications, including direct co-firing, because of ash composition (alkalis, chlorine), moisture content, milling behaviour, etc. The fluidised-bed gasification concepts considered include innovative low-temperature indirect gasification concepts. In these concepts, pyrolysis and combustion are conducted in two separate, but connected reactors, with sand circulation for heat transfer. They seem especially suitable for biomass types rich in alkalis and chlorine, such as agricultural residues (e.g., straw, grass). The low temperature (typically < 650 °C) should limit the evaporation and reactivity of alkalis and chlorine, and thus limit agglomeration in the gasifier itself and fouling and corrosion in the main boiler. The separate combustion step should ensure high burnout, and thus high efficiency. Along these lines, the so-called Low-Temperature Circulating-Fluidised-Bed (LT-CFB) concept is under development in Denmark [11], but also the ECN MILENA gasification technology (Figure 4) is promising for this application as it appears from exploratory tests [12].

Following an extensive desk study, further R&D will be focussed on both further development of selected fluidised-bed concepts and on optimising the gas-side integration of the gasifier with the main (pulverised-fuel) boiler, making use of state-of-the-art full-scale experience with indirect gasification by Electrabel (Ruien, Belgium) and Essent (Geertruidenberg). Activities will comprise CFD-modelling (injection of gasifier product gas in main boiler), system optimisation using the KEMA SPENCE software package and bench-scale experimentation using the ECN fluidised-bed / MILENA test facilities.



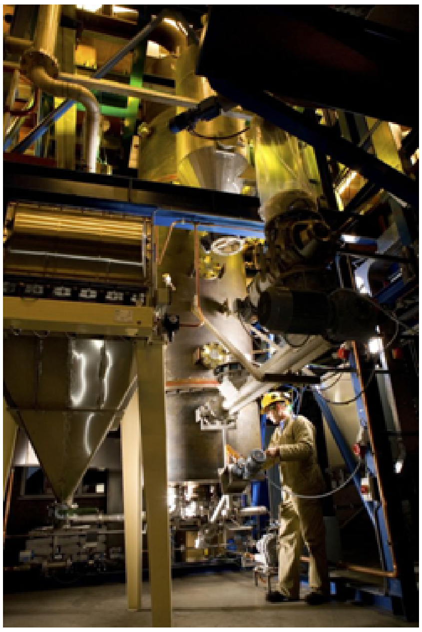



Figure 4: ECN MILENA indirect gasification concept (left) and 800 kWth MILENA pilot plant (right)

## Sustainable ash management

Biomass ashes are physically and chemically different from coal ashes. For the latter, utilisation routes have been well established. In the Netherlands, almost 100% of the coal ashes are used in construction, both directly as building material or in cement and concrete products. For biomass ashes, however, such utilisation options still have to be developed. This applies primarily to ‘pure’ ashes from stand-alone installations and indirect co-firing, but also to mixed ashes from direct co-firing with high biomass co-firing percentages. An important criterion is whether it is possible and desirable from the point of view of sustainability to recycle ashes from imported biomass as fertilizer. In other words, is it a pre-requisite for sustainable biomass utilisation to recycle nutrients and minerals (P, K, Ca/Mg and trace elements) back to the soils where the biomass was harvested in order to close nutrient and mineral cycles? It is unclear whether this is needed or even possible. So far, it has become clear that possibilities depend on biomass production, collection, processing into a fuel and the subsequent conversion technology. Also, it is clear that recycling to soils is not possible for ashes from contaminated biomass fuels. In short, a technical assessment is needed to investigate the possibilities for closing the nutrient and mineral cycles and for the development of alternative utilisations options.

Based on the above, the consortium work is aimed at:
- Development of a database for biomass ash quality as a function of biomass fuel composition, conversion technology and process conditions. This work is connected with the development of the European biomass database BIODAT in the framework of the Phydades project led by ECN [13,14].
- Assessment of the technical necessity and the possibilities for recycling (in order to close nutrient and mineral cycles) of the ash from the main volumes of (imported) biomass fuels. Here, case studies are conducted on, e.g., wood pellets and cacao shells.
- Identification of attractive (new) applications for co-firing and biomass ashes. A list of applications considered is given in Table 1. Well established applications for fly ashes are not included. For each potential application the following items have been assessed: role of the ash in the application (positive and negative), status of technology, market and economy, regulations and sustainability. It is important that a new utilisation option has the potential to create a significant market (bulk application) or a smaller market with a high price (niche application). Bulk application is especially of interest for co-firing ashes. Niche markets appear most attractive for biomass ashes with special chemical compositions.

Table 1 Overview of potential applications for ashes (fly ashes and bottom ashes).

| Application | Function | Sector |
|---|---|---|
| Binders alternative for standard cement | Component | Building industry and civil engineering |
| C-fix | filler | |
| Concrete (products) low quality | Reactive filler | |
| Road Construction material | Binder/Raw material | |
| Sand-lime bricks | Filler | |
| Soil stabilisation | Binder | |
| Synthetic aggregates | Raw material | |
| Fuel | combustion | Energy production |
| Back-filling | Filler | Mining |
| Polymers | Filler | Industry |
| Metals | Filler | |
| Phosphor production | Raw material | |
| Zeolites | Raw material | |
| Metals recovery | Raw material | |
| Mineral fibres | Raw material | |
| Soil improvement / fertiliser | Product / Raw material | Agriculture and fishery |
| Neutralisation of waste acids | Product | Environmental technology |
| Adsorption material | Raw material | |
| Impermeable layer | Raw material | |

## Conclusion

In conclusion, ECN and KEMA with assistance of Delft University of Technology and in close co-operation with the Dutch power generation sector are executing an extensive R&D programme to push the limits of biomass co-firing. Both conventional pulverised-fuel combustion and advanced clean coal technologies such as UltraSuperCritical boiler designs and oxy-fuel combustion with $CO_2$ capture are being considered. Results of the first three consortium years will be published in a range of conference papers and journal articles starting later this year.

## Acknowledgement

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