EMISSIONS REDUCTION THROUGH BIOMASS AND GAS
CO-FIRING - THE BAGIT PROJECT

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ABSTRACT

This paper describes the outcome of work that developed a novel approach to co-firing technology. The work related to utilizing processed biomass and natural gas in CHP systems. The collaborative European project took established technology for biomass pyrolysis and gasification, and developed and assessed technologies for co-utilisation with natural gas.

The project was primarily aimed at two applications:

- The use of biomass and natural gas in the supplementary firing stages of the heat recovery steam generation sections of mid-sized gas turbine-based systems, for CHP systems.
- The joint utilisation of natural gas and biomass in standard boiler/steam turbine systems but with extensions for NOx reduction.

The key aspects of this project included the demonstration of fuel flexibility, emissions reductions and a quantification of the environmental and fiscal benefits for the end-user of the developed technology.

The work comprised the following tasks:

- Laboratory studies of the co-utilisation of biomass and natural gas
- Development of a pyrolysis oil/natural gas burner
- Development of a gasified biomass/natural gas burner with emphasis on applications to supplementary firing systems.
- Pilot-scale testing of the technology
- Development of advanced controls and system integration
- Technical, environmental and social assessment of the technology options.

The results to be presented illustrate that co-utilisation of biomass and natural gas is both feasible and practical, and can be performed using a range of biomass types and technologies.

The future application of the BAGIT concept has the potential to substantially reduce greenhouse gas emissions from small industrial and commercial installations, while contributing to international targets for renewable energy implementation.
# TABLE OF CONTENTS

ABSTRACT

1. INTRODUCTION

2. PROCESSES FOR CO-FIRING OF BIOMASS AND NATURAL GAS
   2.1 Co-firing gasified biomass and natural gas
   2.2 Co-firing bio-oil and propane
   2.3 Co-firing solid biomass and natural gas

3. ENVIRONMENTAL AND OPERATIONAL PERFORMANCE OF THE CO-FIRING TECHNOLOGIES
   3.1 $CO_2$ emissions
   3.2 CO emissions
   3.3 NOx emissions
   3.4 Particulate emissions
   3.5 Corrosion from co-firing

4. COST OF GENERATION OF CO-FIRING SYSTEMS

5. CONCLUSIONS

6. ACKNOWLEDGEMENTS
The BAGIT project was aimed at developing an integrated approach to the joint utilisation of biomass and natural gas for combined heat and power (CHP) applications. The overall project aimed to develop technology for the co-utilisation of natural gas and biomass fuels for electricity and heat generation that is technically, environmentally and financially suitable to meet the energy requirements of a typical medium-sized industrial or commercial plant.

The overall project key aims and objectives were:

- studies to design, develop, test, scale-up and optimise the system with respect to the type of biomass. The types included solid wood-based biomass and processed biomass (wood-derived bio-oil and gasified biomass).
- studies to elucidate the reduction of pollutant emissions when compared with existing fossil fuel fired systems, highlighting the benefits in terms of carbon dioxide, and considering the impact on NOx, SOx and other emissions.
- demonstration of fuel flexibility, including the benefits of biomass for reduction of carbon dioxide emission in CHP systems. This focused on the joint utilisation of biomass and natural gas in the supplementary firing function of heat recovery steam generator systems, and in potential fuel staging applications.
- demonstration of the environmental and fiscal benefits of the technology for the end-user (including the value of carbon trading, carbon tax reductions, and other environmental policy drivers).

In addition to the technical objectives, the BAGIT concept may impact on the sustainable economic growth of the EU and the promotion of bioenergy and CHP. Improving the cost competitiveness of bioenergy and CHP for commercial and industrial users will contribute towards EU targets to double renewable energy demand in the EU by 2010, with bioenergy growing to supply a significant amount of EU primary energy demand. The development of a range of commercial energy products based on co-firing technology will increase EU competitiveness in the renewable energy sector, helping to improve the EU export trade balance with sales of energy services internationally.

The concept of co-utilisation of biomass with fossil fuel has been used extensively in coal-fired power plant. In the UK, several major power generating companies are now co-firing biomass with coal in boilers originally designed to fire coal only. Extending the concept to co-fire biomass and natural gas is a further extension, providing added functionality for power generators.

The technology will assist the EU in moving from reliance on capital intensive and low efficiency centralised electricity generation and distribution to commercially-financed and high efficiency on-site and embedded energy technologies. Introduction of the BAGIT concept will impact on reform of the electricity industry. By encouraging the installation of smaller, distributed or embedded generation units, local to the point-of-use, the losses associated with large-scale generation and transmission can be reduced. This will undoubtedly increase the degree of competition within the electricity market.

In this paper a summary of the results from the BAGIT project is presented. Three forms of bio-fuel (solid, liquid and gaseous) are considered and the co-utilisation with natural gas of each is described.
2 PROCESSES FOR CO-FIRING OF BIOMASS AND NATURAL GAS

Co-firing of natural gas and biomass has been studied in large lab-scale systems to demonstrate the feasibility of combining fuel types and adding fuel flexibility options for users. The work associated with gaining a greater understanding of co-firing has been undertaken by ENEA and Ansaldo (gaseous biomass), BTG (bio-oil) and EST/Setubal (solid biomass).

2.1 Co-firing gasified biomass and natural gas (BAGIT 1)

The feasibility of the using biomass-derived gases in CHP plants is receiving substantial interest and investment. These fuel gases have a relatively low calorific value (containing hydrogen, carbon dioxide and methane together with substantial amounts of nitrogen and carbon dioxide) and a promising application is in the supplementary firing stage of the gas-turbine co-generative systems. The gases are often difficult to use in practical systems due to reduced combustion temperatures, low burning rates and narrow stability limits. In some industrial applications problems are avoided by addition of high-grade fuels to boost the overall calorific value or by using two-stage systems where a high calorific value gas is used for flame stabilisation. Here, a different approach is taken using recirculation of energy between hot products and fresh reactants, so that the overall combustion is under diluted or mild conditions. This is also, known as flameless combustion in some applications.

The effectiveness of mild combustion has been widely demonstrated for industrial furnaces fueled by natural gas. In this work low calorific value gas is combusted under MILD conditions in a novel vortex reactor assembly designed to promote rapid mixing of the fuel and turbine exhaust gas as a supplementary firing system and contain the combustion reaction within the vortex volume.

The ignition delay times for stoichiometric mixture of low calorific value fuel and the turbine exhaust gas have been studied as a function of temperature using chemical kinetic modeling and the values range from 0.1 ms at an initial temperature of 1300 K and 0.83 s at the initial temperature of 850 K. Moreover if we take into account the low adiabatic combustion temperature of the same mixture, the reactants pre-heating through entrainment with the recirculating flue gases, the concept of MILD combustion appears to be an efficient solution for the exploitation of these low calorific value gases.

Experimental measurements have been performed under three different plant load conditions (100%, 80 %, 50 % of the nominal power). A range of measurement techniques have been used to study both the combustion processes with the vortex (TV) burner and the emissions in the flue gas. The experimental studies include CARS (Coherent Anti-stokes Raman Scattering) and LDV (Laser Doppler Velocimetry) to monitor local measurements of velocity and temperature with the vortex burner and natural emission spectroscopy linked to a CCD to establish concentration maps.

In addition, the pollutant emissions (CO and NOx) and CO$_2$ / O$_2$ concentration have been measured at the outlet of the TV burner before the flue stack.

The turbine exhaust gas provides initial reference conditions related to pollutant emissions and values of 33 ppm of NOx (15% O$_2$) and 1 ppm of CO (15% O$_2$) are set. The experimental values, reported in Figure 1, are relative to the measured O$_2$ concentration (12%) and the reference conditions (15% O$_2$) to enable comparison with the input values.

Figure 2 shows the experimentally measured emission trends with load. It is clear that increasing load increases NOx emissions but decreases the CO emissions. It is suggested that these results indicate the sensitivity of the stabilized MILD combustion to temperature and flow rate.
The MILD combustion regime is most stable at the 50% load conditions. The reason for this is that vortex is stable for a specific ratio between the momentum of vitiated oxidant and the vortex momentum. Further design work is required to enable the stabilization of MILD combustion conditions over a wider range of operating conditions.
2.2 Co-firing bio-oil and propane (BAGIT 2)

A bio-oil/propane dual-fuel burner has been developed and optimised. The experimental studies were carried out in a 50 kW\textsubscript{th} combustion chamber, using a dedicated oil atomisation nozzle, enabling air staging: primary air for atomisation, secondary air for combustion and finally tertiary air to complete the combustion process. A large set of data has been obtained, describing the effect on the relevant emission levels of CO, NO/NO\textsubscript{x} and SO\textsubscript{2} and a summary is presented here. A parametric study was performed varying:

- the source of bio-oil, bio-oils derived from switchgrass and from wood;
- the co-firing of propane, on an energy basis varying from 0 to 100%, and
- the stoichiometric ratio between the fuel and the air in the primary, the secondary and/or the tertiary stage, from stoichiometric ratio <1 (gasification) to >2 (complete combustion).

The CO emission levels are mainly dependent on the oxygen concentration in the flue gas and the temperature, whereas, in the majority of tests, the NO\textsubscript{x} emission level in the flue gas is mainly dependent on the nitrogen level in the fuel (fuel-N). The fuel-N (up to 0.35 wt.%) is shown to end up as NO\textsubscript{x} in the flue gas in amounts of 25 to 100 % of the fuel-N. There appears to be an almost linear relationship between the measured NO\textsubscript{x} in the flue gas and the fraction of bio-oil in the fuel, showing the expected link between fuel nitrogen and NO\textsubscript{x}.

Finally, low or zero values of SO\textsubscript{x} emissions are measured in the flue gas. These values are very low (<30 ppm) as the biomass and bio-oil do not contain significant amounts of sulphur.

Figure 3 shows typical results for the NO\textsubscript{x} levels measured as a function of the substitution level of the propane by the bio-oil.

As expected, the NO\textsubscript{x} emission levels increase upon substitution of the propane by the bio-oil, due to the presence of fuel-N in the bio-oil and not in the propane. It was noted that upon feeding the switchgrass and wood-derived pure bio-oil a stable flame was observed under most operating conditions. However, when using high-water content bio-oil (above 35 wt.% water), relatively ‘unstable’ flames were observed. The stability could be improved by addition of small amounts of propane (say in the order of 5 to 10% thermal input). This again shows that improved combustion stability can be promoted through fuel flexibility.
2.3 Co-firing solid biomass and natural gas (BAGiT 3)

The ESTSetúbal study concentrated on the effects of the proportion of biomass used and the impact on the combustion and emissions characteristics. The proportion of biomass used was defined as the solid thermal input/total thermal input ratio (TLR). The study included parametric trials on the combined combustion of different pulverised solids (pine sawdust, pine shell, pine branches and olive stone) and natural gas, as a function of the solids TLR. For comparison purposes, the combined combustion of natural gas and pulverised-coal was also studied. Flue gas emissions data were measured for the main gas phase species (O$_2$, CO$_2$, CO, HC, SOx and NOx), together with the temperature and solid fuel burnout level for five TLR-thermal input ratios. The total thermal input was maintained at 175 kW and excess air fixed at 1.1.

Figures 4 to 6 show flue gas data for all flames studied. The general trends are clear, in that there appears to be increased emissions as the proportion of solid fuel is increased.

**Figure 4 – Carbon monoxide and hydrocarbon emission from natural gas/solid fuel co-combustion**

**Figure 5 - NOx emissions as a function of solid fuel type and the TLR-thermal input ratios**
Figure 4 shows that the CO and HC emissions increase with the increase of the value of the solids TLR. This increase is less accentuated in the case of the pine sawdust and non-existent in the case of the pulverised coal with natural gas firing. The main reason for these observations is related to the larger particle size of the pine shell, pine branches and olive stone.

NOx emissions increase with solids thermal input/total thermal input total (Figure 5). The highest values appear for olive stones and pine branches and suggest a direct correlation with the nitrogen content of the solid fuel. The nitrogen contents (by weight) are 1.86% for olive stone, 1.81% coal, 0.94% pine branches, 0.31% pine shell and 0% pine sawdust. This suggests that the main NOx formation route is the fuel-NOx mechanism.

Figure 6 - Burnout of the solid fuel as a function of TLR-thermal input ratios.

Figure 6 shows that the solid burnout is independent of the solids TLR for most of the solid fuels considered. It can be seen, however, that the pulverised coal with natural gas flames present low values of burnout, as compared with those of biomass with natural gas. This is due to the lower volatile content of the coal, as compared with those of the pine shell and pine sawdust.

3 ENVIRONMENTAL AND OPERATIONAL PERFORMANCE OF THE CO-FIRING TECHNOLOGIES

The three different BAGIT concept processes were investigated (by BIOS) focusing on the overall environmental and operational performance of the technologies when scaled-up from a lab-scale system to a real commercial scale with base case scenarios related to a total electric output of 5 MW<sub>el</sub>. The emissions of CO, CO<sub>2</sub> and NOx as well as particulate emissions are seen as the most important emissions with regard to the environmental impact of the BAGIT system and in terms of operability corrosion of heat transfer surfaces.

3.1 CO<sub>2</sub> emissions

Due to the sustainability of biomass utilisation the CO<sub>2</sub> emitted during the combustion of biomass can be seen as neutral with respect to the greenhouse effect.

Figure 7 shows the CO<sub>2</sub> emissions of the BAGIT processes based on a ratio biomass to total fuel energy input of about 20% (at the burner input) as well as of theoretical 100% natural gas fired applications for comparison purposes. It can be seen, that around 4,500 tons per year of CO<sub>2</sub> can be saved in case of the BAGIT 1 processes, almost 8,100 in case of the BAGIT 2 process and around 7,100 tons per year in case of the BAGIT 3 process. In addition, Figure 7 indicates that the CO<sub>2</sub> emissions of the reference biomass CHP plants would be zero.
3.2 CO emissions

CO emission levels depend on the biomass fuel type, the furnace/boiler technology and the utilisation rate in a co-fired system. The results shown for the gasified biomass (BAGIT 1) indicate that low CO emissions can be maintained, although the emission level is dependent on load.

Data related to CO emissions from tests of the BAGIT 2 process show that the levels are low and suggest that co-firing in a purpose-designed burner should not greatly impact on the overall combustion performance.

The results from the experimental investigations for BAGIT 3 show significant variation depending on fuel type and degree of biomass utilisation. Both for pine sawdust and pine shell the CO levels increase with increasing biomass percentage. However, the increase is less accentuated for pine sawdust. The main reason for this is most probably the larger particle size of pine shell. These results imply that optimisation must be undertaken for the BAGIT 3 processes in order to decrease the CO levels.

3.3 NOx emissions

NOx emissions are both difficult to predict and control. For the BAGIT systems where a high degree of fuel flexibility and fuel quality is possible reflecting the variable nature of biomass in general, NOx emissions may be higher than standard natural gas or dedicated biomass systems. However, NOx emission levels are not excessive.

The BAGIT 1 process does show increased NOx emissions but the MILD combustion process has the capability of producing very low NOx emissions and this method has the potential to enable use of gasified biomass without significantly impacting on NOx levels.

The experimental results related to the BAGIT 2 and BAGIT 3 processes, do show increases in NOx emissions as the proportion of bio-fuel used increases. However, the data suggests that there is a correlation between the NOx emission and the nitrogen content of the biomass, and that NOx emissions are originating from the fuel-NOx mechanism.

3.4 Particulate emissions

The particulate emissions from the three BAGIT systems have not been investigated in detail. For BAGIT 1 and 2 systems the particulate emission is expected to be very low. The BAGIT 1 process utilises exhaust gas from a natural gas fired gas turbine and gasified biomass in a burner. The turbine exhaust gas can be considered as ash free, which covers around 75% of the total fuel energy input. The gasified biomass is expected to have a significantly reduced ash content compared to the biomass, through clean-up of the produced gas. The bio-oil used for the BAGIT 2 processes has ash content below 0.1 wt.% again due to the fuel processing and thus particulate emission is expected to be low.
In case of the BAGIT 3 processes, pulverised solid biomass is directly used in the BAGIT burner. Therefore, the particulate emissions are not expected to be as low as it is expected for the BAGIT 1 and BAGIT 2 processes. However, due to the fact that about 80% of the fuel energy input is covered by ash free natural gas, a certain reduction of the particulate emissions in comparison to a standard biomass CHP plant can be expected.

3.5 Corrosion from co-firing

The corrosion of boiler tube steels is a continuing problem, irrespective of the fuel used, but is acknowledged as a particular problem in coal, waste and biomass fired plant where high levels of sulphur, chlorine and trace metals can exist in combustion gases. The increased use of biomass fuels, such as straw, woodchips and forest residues has increased corrosion problems in many industrial boilers. This is largely due to the high potassium and chlorine content but low sulphur contents of these biomass fuels. The selected biomass-derived fuel used in this study was a bio-oil derived from a clean wood source similar to that produced by BTG. The composition of the bio-oil showed that it is low in sulphur but contains a range of trace metals including sodium and potassium.

Experimental studies at Leeds University have investigated the possible deposition/corrosion effects on a boiler tube steel of co-firing natural gas and a bio-oil at different tube surface temperatures, different stoichiometries and different gas/bio-oil firing ratios. Undertaking experiments of two durations gave some limited data on the kinetics of the degradation. The exposed surfaces were examined by optical and scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDX).

Under oxidising conditions (3% oxygen environment at specimens) the metal loss due to corrosion was doubled when trace metals were present. Metal loss however was found to be unaffected by the rate at which trace metals were added irrespective of the exposure time, stoichiometry or tube temperature. A typical corroded specimen for oxidising conditions is shown in Figure 8.

![Figure 8 - Corroded test specimen (oxidising conditions)](image)

When the furnace was operated under mildly reducing conditions (3% CO at the specimens) there was considerably higher metal loss than for equivalent oxidising conditions. This finding is consistent with previous findings on fireside corrosion in which the flame envelope gives rise to increased corrosion as a result of reducing conditions. Changing the metal temperature from 375 to 425°C produced no noticeable change in metal loss under oxidising conditions. However under reducing conditions a similar increase in metal temperature leads to a significant increase in the metal loss. This positive temperature effect on corrosion has important implications on both expected tube life and selection of tube material. The formation of soot in the flame products leads to an increase in the thickness of the deposit on the surface of the exposed specimen surface, from about 40µm to over 100µm, but had no effect on the extent of corrosion under reducing conditions. Almost identical metal loss was obtained, when soot was generated under reducing conditions to that measured for an equivalent test without soot formation.
The recommended minimum corrosion allowance for a typical carbon steel tube, in a fire tube or waste heat boiler is 0.75mm (BS 2170) for tubes of outside diameters between 38 to 102mm. The metal loss for oxidising conditions is less than 0.1 mm after 5 years and the expected tube life would be well over 40 years for either tube temperature. However for carbon steel tubes exposed continually to reducing conditions the expected tube life for safe operation would be less than 12 years (based on BS 2170) for a tube temperature of 375°C and less than three years for the higher tube temperature of 425°C. In addition even regions exposed to reducing conditions for only 30% of their time, at 425°C, would be at a high risk of a tube failure within 10 years for a carbon steel tube. Clearly a carbon steel tube is unsuitable for regions of a boiler known to be operating under reducing conditions. In this case, the tubes would need to be of a material known to have a relatively high resistance to corrosion, e.g. an austenitic steel (type 310) that has been used extensively in coal-fired boilers in regions at high risk of fireside corrosion.

A further consideration must also be the fact that the corrosion study in this project was restricted to a bio-oil, derived from a clean wood (as agreed by all the partners). A clean wood bio-oil implies no chlorine, which, however is known to be present in many biomasses. Chlorine in association with trace metals, especially potassium and sodium, gives rise to corrosion conditions that are likely to be significantly more aggressive under reducing conditions than in this project. Hence the metal loss rates would be expected to be greater than those measured for the clean wood bio-oil. This has important implications on the selection of suitable corrosion resistant metals for use in co-fired boilers utilising a bio-fuel containing chlorine.

4 COST OF GENERATION OF CO-FIRING SYSTEMS

Figure 9 shows the specific energy generation costs and their composition for different plant capacities of the BAGIT 1 processes. It can be seen, that the specific energy generation costs are dominated by the specific capital costs and the specific consumption costs. The specific consumption costs are in about the same range for all three plant capacities investigated, because these costs are dominated by the fuel costs, which do not decrease significantly with increasing plant capacities. The main cost reduction potential is therefore given by the specific capital costs.
5 CONCLUSIONS

Co-combustion of natural gas and biomass can be undertaken with a range of biomass types, solid, liquid and gaseous. Processing the solid biomass to produce a liquid or gaseous fuel can expand the range of technologies that can be used and enable higher efficiency.

Co-combustion of biomass with natural gas presents a significant benefit in reducing fossil CO$_2$ emissions, compared to fossil fuel fired plant.

The NOx emission in co-combustion of biomass products with natural gas depends on the fuel-Nitrogen level in the biomass. It appears as though the most significant source of NOx is via the fuel-NOx mechanism. Co-combustion of bio-oil or solid phase biomass, both containing some fuel-Nitrogen, lead to an increase in the NOx emission. Technologies such as air staging or reburning may be used to reduce NOx levels below legislated emission limit values.

Carbon monoxide and hydrocarbon emissions vary with co-firing technology. Emissions can be higher in the co-firing systems than for single fuel technologies but the levels are generally low.

The burnout of char particles (solid phase) is better with biomass than with coal, due to the higher volatile content of the biomass. However, compared to natural gas fired plant there is an increase in the particulate loading in the flue products when co-firing and this may result in non-compliance depending on the plant type. Co-fired systems using liquid or gaseous bio-fuel essentially give no particulate emission.

SOx emissions are significantly reduced by the use of biomass compared to fuel oil and coal due to the low sulphur content in the biomass composition. This is biomass-dependent and may be an issue if a plant is converted from solely natural gas firing to co-firing.

The corrosion impact on boiler tubes requires careful consideration. Plant designed for natural gas use only may not sufficient tube corrosion resistance characteristics and operating conditions for co-firing with biomass may result in tube failure. If the plant was designed for coal combustion then the boiler tubes will probably be resistant to corrosion from biomass combustion, but this may be both biomass type and plant technology dependent.

The developed BAGIT concepts provide a range of techniques for co-firing of natural gas and biomass. The methods described could be applied to either new build or retro-fit applications and cover a range of sizes of plant. In this way the successful conclusion of this EC part-funded project provides good opportunities for plant owners and operators to consider co-firing technologies as a method of reducing emissions.

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Further details of the BAGIT project can be viewed on the EU CORDIS web-site: http://www.cordis.lu/en/home.html