DEBCO - Demonstration of Large Scale Biomass Co-Firing and Supply Chain Integration

Energy 2: Renewable Electricity Generation
ENERGY 2.2: Biomass
ENERGY 2007 2.2.4: Large-scale co-firing

DEBCO

DEmonstration of Large Scale Biomass CO-Firing and Supply Chain Integration

D7.10 Advanced Biomass Co-Firing Guidebook

ENEL – S. Gasperetti, P. Leoni
GdF SUEZ – L. Smeeths
USTUTT – A. Fuller, J. Maier, E. Miller
LABORELEC – Y. Ryckmans
CERTH – M. Karampinis
DOOSAN – B. Livingston
VGB – U. Langnickel, S. Zimmerling

Collaborative project

15.03.2013
15.03.2013
01.01.2008
Duration: 60 months

DEBCO Consortium

http://www.debco.eu

<table>
<thead>
<tr>
<th>Dissemination Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU Public</td>
</tr>
<tr>
<td>PP Restricted to other programme participants (including the Commission Services)</td>
</tr>
<tr>
<td>RE Restricted to a group specified by the consortium (including the Commission Services)</td>
</tr>
<tr>
<td>CO Confidential, only for members of the consortium (including the Commission Services)</td>
</tr>
</tbody>
</table>

Project co-funded by the European Commission within the Seventh Framework Programme

Date: 15.03.2013
Page 1 (79)
Acknowledgements

The authors of the present Guidebook on Advanced Biomass Co-Firing wish to thank all of the DEBCO Partners for their contribution to the accomplishment of this challenging project.

With particular regard to the Guidebook writing, the authors gratefully acknowledge the help provided by: H.-J. Feuerborn, L. Müller, U. Schirmer, A. Wecker (VGB); H. Pawlak-Kruczek (Wroclaw University of Technology); L. Barta (MATÚZ); J. Kalivodova (ECN); V. Fantini (RSE); F. Sissot (Agriconsulting).
Executive Summary

The co-firing of biomass materials or Refuse Derived Fuels (RDF) in large coal-fired power stations can lead to significant reductions in CO₂ emissions, and if combined with carbon dioxide capture and storage, it is possible to generate electricity with substantial negative CO₂ emissions. The flexibility of operation of coal plants is very attractive in future energy generation scenarios involving further development of the wind and solar energy, which are intrinsically less constant and predictable.

The DEBCO project has involved an extensive program of research, component testing and demonstration work aimed at the further development of the co-firing of biomass and RDF with coal as a mean for using renewable fuels in the near term. DEBCO (DEmonstration of large scale Biomass CO-firing and supply chain integration) is a collaborative research and technical development project included in the European Commission framework program FP7, and involves seventeen Partners from eight different EU countries.

The general objectives of the DEBCO project have been achieved through a program of research activities, large-scale demonstrations and long-term monitoring of the key co-firing options.

This Guidebook is intended to provide a summary of the key results and experiences of the DEBCO project with a particular focus on:

- The economical aspects, including the political and regulatory framework, the market structure, the local and international fuel supply chains and the main economic factors which may affect co-firing projects;
- The technical aspects, including the fuel characteristics and storage/handling requirements, the plant modifications required for co-firing, the boiler and air pollution control device performance, the utilisation/disposal of the ash and other discards from the power plants.

The principal outcomes and findings of the DEBCO project were obtained through the successful completion of the four main project activities:

- The detailed assessment of three large-scale biomass co-firing demonstration activities, which were selected to represent different technical and socio-economic circumstances in a European context, i.e. at Fusina PP (Italy), at Kardia PP (Greece) and at Rodenhuize PP (Belgium);
- R&D activities concerned with the details of the co-firing impacts on the performance and integrity of six power plants;
- The performance of a number of feasibility studies of the technical and economic aspects of both new and ongoing co-firing activities in Poland and Hungary, with a view to increasing the co-firing ratio;
- The development of the technical know-how and experience of the project Partners, including power utilities, equipment suppliers, SMEs, research centres and universities, in a subject area of increasing importance worldwide.
## INDEX

1 Introduction ................................................................................................. 9
   1.1 Purpose of the Guidebook ................................................................. 11
   1.2 Overview of the co-firing power plants studied within DEBCO ........ 12

2 Economical aspects .................................................................................. 15
   2.1 Political framework and market structure ....................................... 15
   2.2 Economic indicators ......................................................................... 19

3 Technical aspects ..................................................................................... 24
   3.1 Fuel quality and composition ......................................................... 24
   3.2 Safety, handling and storage ........................................................... 26
   3.3 Feeding and milling system .............................................................. 29
   3.4 Boiler modification and performance ............................................. 32
      3.4.1 Boiler modification ................................................................. 32
      3.4.2 Combustion and boiler performance ...................................... 33
      3.4.3 Slagging/touling and corrosion .............................................. 34
   3.5 Air pollution control device performance ....................................... 35
   3.6 Ash utilisation ................................................................................. 37
      3.6.1 Rodenhuize - co-firing of wood pellets ................................... 41
      3.6.2 Rodenhuize - combustion of 100% wood pellets ...................... 41
      3.6.3 Fusina - co-firing of RDF ...................................................... 42
      3.6.4 Kardia - co-firing of cardoon biomass .................................... 42

4 Conclusions ............................................................................................... 43

5 References ................................................................................................ 45

6 Appendix A – DEBCO project power plants .............................................. 46
   6.1 Rodenhuize Power Plant ................................................................. 46
      6.1.1 Retrofitting ............................................................................ 46
      6.1.2 Combustion and boiler performance ...................................... 53
      6.1.3 Air pollution control devices ................................................... 54
      6.1.4 Utilisation of residues ............................................................. 55
   6.2 Kardia and Meliti Power Plants (agricultural biomass/lignite co-firing) .. 56
      6.2.1 Handling, storage and milling .................................................. 57
      6.2.2 Boiler modification .................................................................. 58
      6.2.3 Combustion and boiler performance ...................................... 60
      6.2.4 Air pollution control devices .................................................... 61
6.2.5 Utilisation of residues ................................................................. 62
6.3 Fusina Power Plant (RDF co-firing) ................................................. 63
  6.3.1 Handling, storage and milling ................................................. 63
  6.3.2 Combustion and boiler performance ....................................... 65
  6.3.3 Air pollution control devices ................................................... 67
  6.3.4 Utilisation of residues ............................................................. 68
6.4 Dorog and Mátra Power Plants (agricultural biomass co-firing) .......... 69
  6.4.1 Handling, storage and milling ................................................. 69
  6.4.2 Combustion and boiler performance ....................................... 70
6.5 Rokita (biomass co-firing) ............................................................ 71
7 Appendix B - New findings ................................................................. 72
  7.1 Erosion and corrosion laboratory tests ......................................... 72
  7.2 Large-scale corrosion monitoring of pure wood-dust firing ............ 74
  7.3 Lab-scale and pilot-scale deposition tests .................................... 76
  7.4 Lab-scale combustion behaviour ............................................... 76
  7.5 Modelling activities ................................................................. 76
  7.6 Lab-scale pyrolysis tests ........................................................... 77
  7.7 Lab-scale additive testing ......................................................... 79
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>CO2 €/tonne % for different technologies.</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Comparison of the biomass break-even prices.</td>
<td>22</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Options for direct and indirect co-firing of solid biomass or RDF.</td>
<td>29</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Biomass storage milling unit (1/3).</td>
<td>47</td>
</tr>
<tr>
<td>Figure 5</td>
<td>a) after conversion to coal; b) Advanced Green, wood dust firing @ rows 2 &amp; 3; c) Max Green wood dust firing @ rows 1,2 &amp; 3.</td>
<td>49</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Overview of the boiler installed at Kardia PP.</td>
<td>57</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Boiler geometry of Kardia PP and schematic representation of simulated burner geometry.</td>
<td>58</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Scheme of the MSW management process.</td>
<td>64</td>
</tr>
<tr>
<td>Figure 9</td>
<td>RDF reception area at Fusina PP.</td>
<td>65</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Dorog PP fuel handling and feeding system.</td>
<td>70</td>
</tr>
<tr>
<td>Figure 11</td>
<td>The location and arrangement of burners in PC OP-130 boiler and temperature measurements level by suction pyrometry probe.</td>
<td>71</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Innovative erosion test rig developed by RSE.</td>
<td>72</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Comparison of the erosion rates of the tested materials</td>
<td>73</td>
</tr>
<tr>
<td>Figure 14</td>
<td>SEM-BSE pictures of the ferritic sample after 90 hours’ exposure at 535 °C, windward (left) and lee side (right).</td>
<td>75</td>
</tr>
<tr>
<td>Figure 15</td>
<td>SEM-EDX element mappings of the Alloy 617 after 90 hours’ exposure at 660 °C, windward side.</td>
<td>75</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Scheme of the analytical procedure.</td>
<td>77</td>
</tr>
</tbody>
</table>
DEBCO

LIST OF TABLES

Table 1: Overview of the PPs studied within DEBCO. 13
Table 2: Political framework and market structure analysis for different European countries. 16
Table 3: IWPB sustainability principles (2). 18
Table 4: Summary of the assumptions for the calculations of the biomass break-even price. 21
Table 5: The six evaluated configurations. 24
Table 6: Average composition of the analysed biomass. 25
Table 7: Average composition of the main analysed fuels. 25
Table 8: Performance summary of the fuel handling systems. 28
Table 9: Performance summary of the fuel milling and feeding systems. 31
Table 10: Emission limits of IED for new power plants with permit after 07.01.2013. Emission limits are given as monthly average values and for co-firing as daily average in mg/Nm³ @ 6% O₂. 36
Table 11: Emission limits of IED for existing power plants and power plants with permit before 27.11.2002. Emission limits are given as monthly average values and for co-firing as daily average in mg/Nm³ @ 6% O₂. 37
Table 12: European standards for fly ash requirements. 39
Table 13: Requirements on fly ash for use in cement and in concrete. 40
Table 14: Physical requirements for fly ash in accordance with EN 450-1. 41
Table 15: Long-term corrosion monitoring campaign. 67
Table 16: Erosion rate estimation in co-firing + USC steam cycle conditions. 73
Table 17: Ranking of the erosion/corrosion seriousness in PPs. 74
Table 18: Alloying composition of the exposed materials. 75
Table 19: Composition of pyrolytic gases from wood biomasses. 78
Table 20: Composition of pyrolytic gases from agro-biomasses. 78
Table 21: Composition of pyrolytic gases from RDF. 78
Table 22: Composition of pyrolytic gases from fuel blends. 79
ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>APCD</td>
<td>Air Pollution Control Device</td>
</tr>
<tr>
<td>AOI</td>
<td>Angle Of Impact</td>
</tr>
<tr>
<td>BAT</td>
<td>Best Available Technology</td>
</tr>
<tr>
<td>BFG</td>
<td>Blast Furnace Gas</td>
</tr>
<tr>
<td>DEBCO</td>
<td>Demonstration of large scale Biomass CO-firing and supply chain integration</td>
</tr>
<tr>
<td>CAPEX</td>
<td>CAPital EXpenditure</td>
</tr>
<tr>
<td>CCP</td>
<td>Coal Combustion Product</td>
</tr>
<tr>
<td>CIF</td>
<td>Cost, Insurance and Freight</td>
</tr>
<tr>
<td>CRF</td>
<td>Capital Recovery Factor</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>ESP</td>
<td>ElectroStatic Precipitator</td>
</tr>
<tr>
<td>ETA</td>
<td>European Technical Approval</td>
</tr>
<tr>
<td>ETS</td>
<td>Emissions Trading System</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FGD</td>
<td>Flue Gas Desulphurisation</td>
</tr>
<tr>
<td>GC</td>
<td>Green Certificate</td>
</tr>
<tr>
<td>IED</td>
<td>Industrial Emission Directive</td>
</tr>
<tr>
<td>IFR</td>
<td>Isothermal Flow Reactor</td>
</tr>
<tr>
<td>IWPB</td>
<td>Initiative Wood Pellet Buyer</td>
</tr>
<tr>
<td>LCP</td>
<td>Large Combustion Plant</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
</tr>
<tr>
<td>LNCFS</td>
<td>Low NOx Concentric Firing System</td>
</tr>
<tr>
<td>LOI</td>
<td>Lost Of Ignition</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
</tr>
<tr>
<td>OPEX</td>
<td>OPERating EXpenditure</td>
</tr>
<tr>
<td>PC</td>
<td>Pulverised Coal</td>
</tr>
<tr>
<td>PP</td>
<td>Power Plant</td>
</tr>
<tr>
<td>RDF</td>
<td>Refuse Derived Fuel</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research &amp; Development</td>
</tr>
<tr>
<td>RTD</td>
<td>Research and Technical Development</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reactor</td>
</tr>
<tr>
<td>SGS</td>
<td>Société Générale de Surveillance</td>
</tr>
<tr>
<td>SME</td>
<td>Small Medium Enterprise</td>
</tr>
<tr>
<td>UBC</td>
<td>UnBurned Carbon</td>
</tr>
<tr>
<td>USC</td>
<td>Ultra Super Critical</td>
</tr>
</tbody>
</table>
1 Introduction

The European Commission wishes to increase the share of renewable energy in the overall energy consumption in Europe to 20% by 2020. This was set as a binding target by the European Commission in spring 2007. At the end of 2010, renewable energy sources accounted for 12.5% of overall energy consumption. In order to meet the targets, the share of electricity generation from renewable energy sources must increase from 19.8% in 2010 to around 34% in 2020.

It was considered that wind energy and biomass, in particular, will make the most significant contributions to the achievement of these targets. The EC Biomass Action Plan, which was published at the end of 2005, encourages the EU member States to harness the potential of all cost-effective forms of electricity generation from biomass. The co-firing of biomass is considered to be one of the most promising technologies.

The co-firing of biomass in coal boilers is an important technology for CO₂-neutral electricity generation. As is illustrated in the bar chart below, in a number of countries biomass co-firing, particularly as a retrofit to existing power plants, is one of the most economic ways to reduce CO₂ emissions. The co-firing of biomass is practiced in numerous plants, especially in Denmark, Belgium, The Netherlands, Poland, Italy and United Kingdom.

![Bar chart showing CO₂ emissions for different technologies](image)

**Figure 1**: CO₂ €/tonne % for different technologies.

The government subsidy schemes and other financial instruments that provide national incentives for biomass co-firing vary significantly within the European Union.

Typical co-firing plants in the power plant sector are in the electrical output range of 50-700 MWₑᵣ. The majority of the plants are equipped with pulverized coal firing systems, although, biomass co-firing is also applied in fluidized bed systems (bubbling and circulated) and in other boiler designs.

The key advantages of biomass co-firing include:

- the utilisation of existing capital equipment, with modest costs and fairly short project times for plant conversion;
- the biomass fuel flexibility, particularly at low co-firing ratios;
- the relatively high overall power generation efficiencies from biomass that apply when co-firing in large coal-fired power plants.

The co-firing of biomass materials or Refuse Derived Fuels (RDF) in large coal-fired power stations can lead to significant reductions in CO₂ emissions, and if combined with carbon dioxide capture and storage, it is possible to generate electricity with substantial negative CO₂ emissions. The flexibility of operation of coal plants is very attractive in future energy generation scenarios involving further development of the wind and solar energy, which are intrinsically less constant and predictable.

The combustion of pulverised fuel in the existing boiler of a coal power plant is the most effective technology in terms of CAPEX and OPEX for the combustion of dry biomass. For storage and transport purposes, it is normally most convenient and cost-effective to handle, transport and store the biomass in a milled and pellet form. In terms of CAPEX, this approach normally allows the reuse of much of the fuel feeding and firing system and the boiler pressure parts in the furnace and boiler, with suitable modifications where necessary.

The DEBCO project has involved an extensive program of research, component testing and demonstration work aimed at the further development of the co-firing of biomass and RDF materials with coal as a mean for using renewable fuels in the near term. DEBCO (DEmonstration of large scale Biomass CO-firing and supply chain integration) is a collaborative RTD project included in the EC framework program FP7, and involves seventeen Partners from eight different EU countries.
1.1 Purpose of the Guidebook

The objectives of the DEBCO project have been achieved through a comprehensive program of research activities, large-scale demonstrations and long-term monitoring of the key co-firing options.

This research and testing has provided key insights into the following areas:

- The reliability and sustainability of biomass supply chain and quality of biomass;
- The retrofit and optimisation of biomass co-firing technologies to existing pulverised coal-fired boilers;
- The measurement of the key boiler performance parameters of power boilers when co-firing biomass;
- The measurement of the performance of the air pollution control devices when co-firing biomass;
- The characteristic and utilisation/disposal of the ash discards from coal boiler co-firing biomass.

In this Guidebook, the key results and experiences of the DEBCO project are described in order to provide relevant information to project developers, combustion and boiler engineers and plant operators interested in co-firing technologies. Particular focus is placed on:

- The economical aspects, including the political and regulatory framework, the market structure, the local and international fuel supply chains and the main economic factors which may affect co-firing projects;
- The technical aspects, including the fuel characteristics and storage/handling requirements, the plant modifications required for co-firing, the boiler and air pollution control device performance, the utilisation/disposal of the ash and other discards from the power plants.

The principal outcomes and findings of the DEBCO project were obtained through the successful completion of the four main project activities:

- The detailed assessment of three large-scale co-firing demonstration activities, which were selected to represent different technical and socio-economic circumstances in a European context, i.e. at Fusina PP (Italy), at Kardia PP (Greece) and at Rodenhuize PP (Belgium);
- R&D activities concerned with the details of the co-firing impacts on the performance and integrity of six power plants;
- The performance of a number of feasibility studies of the technical and economic aspects of both new and ongoing co-firing activities in Poland and Hungary, with a view to increasing the co-firing ratio;
- The development of the technical know-how and experience of the project Partners, including power utilities, equipment suppliers, SMEs, research centres and universities, in a subject area of increasing importance worldwide.

The key of the DEBCO project are summarised in the following sections and are based on the experience with six co-firing configurations employing different plant configurations and coals, a variety of biomass types and a range of co-firing levels. More detailed descriptions of the biomass co-firing demonstration activities are presented in Appendix A. The key findings of the research and development activities are summarised in Appendix B.
1.2 Overview of the co-firing power plants studied within DEBCO

The key features and main results of the six co-firing projects are presented in Table 1. These include:

- **Rodenuhize PP**, located in Belgium and owned by GDF Suez SA, has a 285-MWₚₘₖ steam generator and was the host site for a demonstration of wood pellet co-firing at increasing share up to 50% and, then, 100% thermal input, with a de-rating of the maximum power output to about 65% of the maximum output on coal firing. The unit started up on 100% biomass firing in May 2011, and it has been routinely operated in this way since September 2011.

- **Kardia PP**, located in Greece and owned by the Public Power Corporation SA (PPC), consists of four units: Units 1 and 2 (built in 1974 and 1975) with an installed capacity of 300 MWₚₘₖ, and Units 3 and 4 (built in 1980 and 1981) with an installed capacity of 325 MWₚₘₖ. Each unit consists of a supercritical Benson type once-through boiler with single reheating designed for lignite. A program of co-firing tests with cardoon and olive kernel biomass was performed at biomass thermal input up to 10%.

- **Meliti PP**, located in Greece and owned by PPC, consists of one unit with an installed capacity of 330 MWₚₘₖ. Commissioned in 2004, it is the newest and one of their most efficient lignite-fired power plants. Unusually, Meliti PP was designed for the co-combustion of xylite/lignite, with the percentage of the former being up to 32%. Xylite is a brown coal of similar rank to lignite.

- **Fusina PP**, owned by Enel SpA, is located in North-Eastern Italy, in the Venice area. The power plant consists of four pulverised coal (PC) fired units: two 160-MWₚₘₖ boilers (Units 1 and 2), and two 320-MWₚₘₖ boilers (Units 3 and 4). Units 3 and 4 are tangentially fired dry-bottom boilers, equipped with a Low NOₓ Concentric Firing System (LNCFS) designed by Alstom Combustion Engineering (formerly ABB), a Selective Catalytic Reactor (SCR) for final NOₓ reduction, an electrostatic precipitator (ESP) and a flue gas desulphurization (FGD) system. RDF/coal co-firing tests were performed at up to around 5% on a thermal input basis.

- **Dorog PP**, located in Hungary and owned by Dalkia Energia Zrt, is a co-generation plant producing hot water for district heating, process steam and electric energy. There are 3 operating boiler (Units 3, 5 and 6), and 1 boiler (Unit 4) is on reserve. Units 3 and 4 are tangential fired, natural circulation, lignite boilers with a nominal steam capacity of 50 t/h, 430 °C and 35 bar ab. The design coal was of low heating value (12 MJ/kg) and of high ash content (25-30 %). Units 5 and 6 were originally designed identical to Unit 4, but later redesigned for natural gas firing. The biomass/coal co-firing tests were performed up to 75% thermal input of biomass.

- **Rokita PP**, located in Poland and owned by PCC Rokita SA, is a combined heat and power plant (100 MWₚₘₖ, 22 MWₚₘₖ) with tangential combustion boiler. The biomass/coal co-firing tests were performed up to 36% thermal input of biomass (wood, agricultural residues and different bio-liquids).
Table 1: Overview of the PPs studied within DEBCO.

<table>
<thead>
<tr>
<th>Owner</th>
<th>GDF Suez SA</th>
<th>Enel SpA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>Rodenhuize</td>
<td>Fusina</td>
</tr>
<tr>
<td>Capacity</td>
<td>285 MWₑₑ (180 MWₑₑ / Max Green) / 560 MWₑₚ</td>
<td>320 MWₑₑ / 820 MWₑₚ</td>
</tr>
<tr>
<td>Boiler type</td>
<td>PC dry-bottom boiler</td>
<td>PC dry-bottom boiler</td>
</tr>
<tr>
<td>APCDs</td>
<td>Advanced Green: ESP</td>
<td>High-dust SCR, ESP, wet FGD</td>
</tr>
<tr>
<td></td>
<td>Max Green: high-dust SCR, ESP</td>
<td></td>
</tr>
<tr>
<td>Design fuel</td>
<td>Hard coal / blast furnace gas</td>
<td>Hard coal</td>
</tr>
<tr>
<td>Co-firing fuel</td>
<td>Wood pellets</td>
<td>RDF (biofraction &gt; 60%)</td>
</tr>
<tr>
<td>Co-firing rate</td>
<td>2009: increase from 25 to 50%</td>
<td>Increase from 2.5 to 5%</td>
</tr>
<tr>
<td></td>
<td>2012: demonstration for 100% (Max Green)</td>
<td></td>
</tr>
<tr>
<td>Milling</td>
<td>Separate</td>
<td>Separate</td>
</tr>
<tr>
<td>Injection</td>
<td>New low NOx burners</td>
<td>RDF is injected directly into the pulverised coal pipes</td>
</tr>
<tr>
<td>Co-firing trials</td>
<td>Light Green: 2005 wood</td>
<td>RDF up to 5% thermal input</td>
</tr>
<tr>
<td></td>
<td>Advanced Green: 2009 wood</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Owner</th>
<th>Public Power Corporation SA</th>
<th>Public Power Corporation SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>Kardia</td>
<td>Meliti</td>
</tr>
<tr>
<td>Capacity</td>
<td>300 MWₑₑ / 856 MWₑₚ</td>
<td>330 MWₑₑ / 870 MWₑₚ</td>
</tr>
<tr>
<td>Boiler type</td>
<td>PC dry-bottom boiler</td>
<td>PC dry-bottom boiler</td>
</tr>
<tr>
<td>APCDs</td>
<td>ESP</td>
<td>ESP, wet FGD</td>
</tr>
<tr>
<td>Design fuel</td>
<td>Lignite</td>
<td>Xylite / lignite</td>
</tr>
<tr>
<td>Co-firing fuel</td>
<td>Cardoon</td>
<td>Wood pellets, maize residue pellets</td>
</tr>
<tr>
<td>Co-firing rate</td>
<td>Increase from 0 to 10%</td>
<td>Increase to 3.3%</td>
</tr>
<tr>
<td>Milling</td>
<td>Together with the coal</td>
<td>Together with the coal</td>
</tr>
<tr>
<td>Injection</td>
<td>Together with the coal</td>
<td>Together with the coal</td>
</tr>
<tr>
<td>Co-firing trials</td>
<td>Cardoon, olive kernels</td>
<td>Wood pellets, maize residue pellets</td>
</tr>
<tr>
<td>Owner</td>
<td>Dalkia Energia Zrt</td>
<td>PCC Rokita SA</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Plant</td>
<td>Dorog</td>
<td>Rokita</td>
</tr>
<tr>
<td>Capacity</td>
<td>40 MW&lt;sub&gt;el&lt;/sub&gt; / 160 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>22 MW&lt;sub&gt;el&lt;/sub&gt; / 100 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Boiler type</td>
<td>2 PC and 2 combined cycles</td>
<td>PC/ Combined heat and power</td>
</tr>
<tr>
<td>APCDs</td>
<td>ESP</td>
<td>ESP</td>
</tr>
<tr>
<td>Design fuel</td>
<td>Hard coal</td>
<td>Hard coal</td>
</tr>
<tr>
<td>Co-firing fuel</td>
<td>Saw dust, sunflower hull, sunflower pellets, wood chips</td>
<td>Wood, rape, glycerol</td>
</tr>
<tr>
<td>Co-firing rate</td>
<td>75%, 100%</td>
<td>10%, 36%, 40%, 80%</td>
</tr>
<tr>
<td>Milling</td>
<td>Beater mill coal and biomass milled separately</td>
<td>Together with the coal</td>
</tr>
<tr>
<td>Injection</td>
<td>Multi-fuel burners, injection of coal and biomass separately, using external fuel recirculation for unburned fuel</td>
<td>Together with the coal</td>
</tr>
<tr>
<td>Co-firing trials</td>
<td>straw like material, grain sorghum, sunflower hull, ground corn stem</td>
<td>Barley pellets, ground corn stem, grain sorghum briquettes, sunflower hull</td>
</tr>
</tbody>
</table>
2 Economical aspects

The evaluation of the economic aspects was focused on the following issues:

- the political framework and market structure for biomass in the participating countries,
- the different fuel supply chains (local, international, woody biomass, agricultural biomass, etc.),
- the characteristics of different biomass fuels,
- the sustainability requirements for solid biomass fuels.

The public deliverable D3.6 “Indicators and guidelines for future implementation of fuel supply chains” (1) is available on the DEBCO website (http://www.debco.eu). This document provides a detailed description of the activities performed within this aspect of the DEBCO project.

2.1 Political framework and market structure

The key results of the political framework and market structure analysis are summarised in Table 2.

The results of the analysis of policy framework show that the economic and environmental potential of biomass co-firing is not adequately recognised in the legislation of all of the European countries. In a number of countries, biomass co-firing is not included in the renewable energy incentive system. The national regulations are also subject to regular modification, and this is not conducive to market stability. The legal definitions of biomass and renewable energy are poorly described, and the uncertainties in the sustainability criteria, across Europe, leads to a lack of security for investment in large scale biomass co-firing projects.

A common approach across Europe, at least for financial incentives and binding sustainability criteria, as pointed out by EURELECTRIC would lead to an improved level of security for investment, and a higher propensity for the private sector to become involved in the development of fuel supply chains and of biomass co-firing projects.

The analysis of the market potential shows clearly that there is significant potential growth in the European and international market for solid biomass fuels, without significant interference with food supply, wood process industry or land use issues. It is also considered that the stimulation of local markets for biomass fuels will help secure employment in the power sector, and create new jobs in the agricultural and transport sectors.

It is clear from the work on the demonstration of the supply chains that the creation of local markets for biomass fuels is a big challenge, requiring coordination and co-operation between the agricultural sector and the power producers. This cannot be achieved without security of investment for both the local farmer and the power producer.

The cardoon supply chain for Kardia PP could only be established to provide biomass fuel for a longer test campaign, because the cultivation of cardoons was financially supported by local authorities. A fuel supply chain based on maize residues for Kardia PP was established, with two companies operating as intermediates between PPC and farmers, which facilitated business operations and the handling of contracts. The supply chain for straw at Meliti PP could not be established on a large-scale basis, due to the inability to find a local business entity that could collect, store and deliver the biomass to the power plant.
Table 2: Political framework and market structure analysis for different European countries.

<table>
<thead>
<tr>
<th>Type of support scheme</th>
<th>Belgium / Flanders</th>
<th>Belgium / Wallonia</th>
<th>Greece</th>
</tr>
</thead>
<tbody>
<tr>
<td>RES quota 6% Penalty: 125 €/MWh in 2011, 118 €/MWh in 2012, 100 €/MWh in 2013 Market: 90 €/MWh Guaranteed: 85 €/MWh</td>
<td>Green certificate</td>
<td>Green certificate</td>
<td>Feed-in tariff</td>
</tr>
<tr>
<td>Co-firing support</td>
<td>50% of GCs if biomass &lt; 60%</td>
<td>no GCs granted → only 100% biomass combustion supported</td>
<td>Yes, based on biomass thermal share in fuel mixture</td>
</tr>
<tr>
<td>Other characteristics / restrictions</td>
<td>Traceability criteria GCs granted according to energy balance of supply chain and reference CCGT</td>
<td>Sustainability must be proven GCs granted according to CO₂ balance of supply chain and reference CCGT</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Co-firing in NREAP / Policy direction</td>
<td>Yes Policy supports higher biomass shares</td>
<td>Yes Policy supports large-scale dedicated biomass combustion</td>
<td>Not considered No national framework, only regional support</td>
</tr>
<tr>
<td>Sustainability considerations</td>
<td>No sustainability criteria Traceability of supply chain and energy balance considered in GCs Laborelec verification scheme</td>
<td>Sustainability criteria GC granted according to GHG balance of supply chain Laborelec verification scheme</td>
<td>No sustainability criteria</td>
</tr>
<tr>
<td>Biomass markets</td>
<td>Low availability of local biomass sources / Restrictions in the use of wood (Flanders) Import of pellets &amp; wood chips</td>
<td></td>
<td>Undeveloped, will be based on agrobiomass</td>
</tr>
<tr>
<td>Socio-economics &amp; other considerations</td>
<td>Job retention in retrofitted power stations</td>
<td></td>
<td>Importance of co-firing schemes in retention of regional income Job creation in agricultural sector</td>
</tr>
</tbody>
</table>
### Table: Support Schemes

<table>
<thead>
<tr>
<th>Type of support scheme</th>
<th>Hungary</th>
<th>Italy</th>
<th>Poland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed-in tariff</td>
<td>Depending on capacity For &gt; 50 MW Peak time: 29.56 Ft/kWh (98.5 €/MWh) Valley time: 26.46 Ft/kWh (88.2 €/MWh) Deep valley: time 10.8 Ft/kWh (36 €/MWh)</td>
<td></td>
<td>RES quota 10.4% Penalty: PLN 267.95/MWh</td>
</tr>
<tr>
<td>Co-firing support</td>
<td>Eligible only if biomass is &gt;70% of thermal share (both monthly and yearly) If fossil fuel fraction &gt; 50% feed-in tariff fraction reduced by 10%.</td>
<td>Yes, no restrictions</td>
<td>Yes, Obligatory composition of agrobiomass in fuel mixture</td>
</tr>
<tr>
<td>Other characteristics / restrictions</td>
<td>Efficiency &gt;30% for dedicated biomass combustion &gt; 32% for co-firing</td>
<td>GC multiplier before 2013: 1.8 for traceable biomass supplied within 70 km radius or within frameworks agreements, 1.3 for other cases. Starting from 2013: see Ministerial Decree (14).</td>
<td>Exemption of RESe from excise duty: PLN 20/MWh No distinction between RES technologies</td>
</tr>
<tr>
<td>Co-firing in NREAP / Policy direction</td>
<td>Yes Pushing to agrobiomass utilisation Invest in dedicated biomass boilers &lt; 20 MWel or Retrofit old units to 100% biomass combustion</td>
<td>Considered and supported Policy favors local supply chains</td>
<td>Considered and supported Favors utilisation of agricultural biomass</td>
</tr>
<tr>
<td>Sustainability considerations</td>
<td>No sustainability criteria Forest biomass must originate from maintainable forest cultivation Biomass fuel must not be edible by humans</td>
<td>No sustainability criteria Traceability criteria for higher GC multiplier</td>
<td>No sustainability criteria High quality wood excluded Biodegradability must be proved</td>
</tr>
<tr>
<td>Biomass markets</td>
<td>Developed, issues with pricing in the past</td>
<td>Developed market for imports in heating sector Power sector is developing on domestic resources</td>
<td>Developed market with domestic resources Concerns of fiber board, furniture and pulp &amp; paper industries increasing share of agrobiomass</td>
</tr>
<tr>
<td>Socio-economics &amp; other considerations</td>
<td>Job creation in agricultural sector Job retention in retrofitted power stations</td>
<td>Job creation in agricultural sector</td>
<td>Job creation in agricultural sector</td>
</tr>
</tbody>
</table>

There are countries within Europe without any sustainability criteria, and countries with rather rigid criteria. There are some agreements between local authorities and electricity producers. In either case, if sustainability requirements are established they are generally reliant on the national or local forest and agricultural regulations.

The Initiative of Wood Pellet Buyers (IWPB) (2) has proposed sustainability principles for the sourcing and trading of woody biomass among its members. This is a working panel including representatives of the major European utilities involved in the firing or co-firing of...
wood pellets in large power plants, and of the key regulators such as the SGS (Société Générale de Surveillance) and Control Union. This proposal builds on the EURELECTRIC position paper (3), which was prepared in reaction to the recommendations of the European Commission. In this document, binding principles on the sourcing and trading of woody biomass are proposed.

An overview of the key principles of fuel sustainability that the IWPB plans to apply in the sourcing and trading of woody biomass (2) is provided in Table 3.

Table 3: IWPB sustainability principles (2).

<table>
<thead>
<tr>
<th>IWBP SUSTAINABILITY PRINCIPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principle 1: GREENHOUSE GAS BALANCE (GHG)</strong></td>
</tr>
<tr>
<td>The greenhouse gas (GHG) savings along the entire life-cycle, taking into account the whole supply chain including production, processing, transport and end-use are at least 60% with respect to reference fossil fuels.</td>
</tr>
<tr>
<td><strong>Principle 2: CARBON STOCK</strong></td>
</tr>
<tr>
<td>Production of woody biomass does not take place at the expense of significant carbon reservoirs in vegetation and soil.</td>
</tr>
<tr>
<td><strong>Principle 3: BIODIVERSITY</strong></td>
</tr>
<tr>
<td>Production of woody biomass may not take place in areas with high biodiversity value, unless evidence is provided that the production of that raw material did not negatively interfere with nature protection purposes.</td>
</tr>
<tr>
<td><strong>Principle 4: PROTECTION OF SOIL QUALITY</strong></td>
</tr>
<tr>
<td>Production of woody biomass should maintain or improve the soil quality.</td>
</tr>
<tr>
<td><strong>Principle 5: PROTECTION OF WATER QUALITY</strong></td>
</tr>
<tr>
<td>Production of woody biomass should not exhaust ground and surface water and should avoid or significantly limit negative impacts on water.</td>
</tr>
<tr>
<td><strong>Principle 6: PROTECTION OF AIR QUALITY</strong></td>
</tr>
<tr>
<td>Production of woody biomass should avoid negative impact or significantly reduce impact on air quality.</td>
</tr>
<tr>
<td><strong>Principle 7: COMPETITION WITH LOCAL BIOMASS APPLICATIONS</strong></td>
</tr>
<tr>
<td>Production of woody biomass should not endanger food, water supply or subsistence means of communities where the use of this specific biomass is essential for the fulfilment of basic needs.</td>
</tr>
<tr>
<td><strong>Principle 8: LOCAL SOCIO-ECONOMIC PERFORMANCE</strong></td>
</tr>
<tr>
<td>Production of woody biomass should respect property rights and contribute to local prosperity and to the welfare of the employees and the local population.</td>
</tr>
<tr>
<td><strong>Principle 9: ETHICS</strong></td>
</tr>
<tr>
<td>Ethical issues that the organization should uphold include at least health &amp; safety, respect of internationally proclaimed human rights, freedom of association and the right to collective bargaining, elimination all forms of forced and compulsory labour, effective abolition of child labour, elimination of discrimination in respect of employment and occupation, promotion of greater environmental responsibility, high standards of business integrity, including the work against corruption in all its forms.</td>
</tr>
</tbody>
</table>
Several documents from IWPB utilities were examined, including:

- the Green Gold Label developed by Essent and Control Union in the Netherlands (4);
- the corporate approach developed by Drax Power Ltd. in the UK for biomass sustainability;
- the agreement of Vattenfall with the Senate of Berlin for the use of biomass as a sustainable fuel (5);
- the verification procedure developed by Laborelec and SGS in Belgium for the grant of green certificates with sustainable solid biomass.

2.2 Economic indicators

For a biomass co-firing retrofit or repowering project, the power utility has to consider the integration of the biomass supply chain and the impact of biomass utilisation in the business model. In most cases, there is a significant difference between the delivered fuel cost of coal and the biomass fuel under consideration. This is typically covered by the provision of additional financial support to the power production from biomass through a feed-in tariff scheme or the grant of green certificates. The level of support for bio-energy varies widely among EU members states and, in some cases, co-firing is not considered eligible for support.

Within the DEBCO project, a simplified economic indicator was developed for the estimation of the biomass break-even price at the plant gate. This price is compared with typical or expected biomass prices in order to evaluate whether a particular biomass type can be considered as an economic option and whether it has the potential to generate additional revenue to the power plant to justify the capital investment involved in the conversion of the plant to biomass firing or co-firing. The calculations are performed on the basis that the coal power production set-up is economically neutral to the plant operator.

The biomass break-even price is a function of three components:

The baseline price, which consists of the price of coal replaced minus the annualised investment cost per unit of biomass fuel energy:

\[ p_{\text{bio, base}} = p_{\text{coal}} - \frac{\alpha \cdot \eta \cdot CRF}{\text{Availability}} \]  

(1)

where:

- \( p_{\text{coal}} \) is the coal price (€/GJ),
- \( \alpha \) is the specific investment (€/kW \text{el} of net capacity retrofitted),
- \( \eta \) is the unit net efficiency,
- CRF is the capital recovery factor, which is multiplied by the total investment in order to calculate the annualised investment cost.

The CRF value is given by the following equation:

\[ CRF = \frac{k \cdot (1 + k)^i}{(1 + k)^i - 1} \]  

(2)

where \( k \) is the project duration (yr) and \( i \) is the discount rate.

As can be seen from equation (1), the baseline price increases with the cost of coal and availability, while it decreases as the specific investment and efficiency increase, since a more efficient power plant utilises less biomass for the production of the same amount of electricity. Moreover, the baseline price decreases as the project duration is decreased, due to the effect of the CRF.
It should be noted that the baseline price is independent of the biomass thermal share, provided that the specific investment cost remains the same. Typically, for low biomass shares an optimal techno-economic level of substitution can be found, which minimises the specific investment.

The CO₂ saving price, which takes into account the fact that biomass is considered as CO₂ neutral for the purposes of the European ETS. By displacing coal combustion co-firing biomass results in a decreased cost of CO₂ emissions. This is calculated by the equation:

\[ p_{\text{bio,CO₂}} = p_{\text{bio,base}} + \frac{e_f \cdot p_{\text{CO₂}}}{LHV_{\text{coal}}} \]  

(3)

where:
- \( e_f \) is the emission factor of coal i.e. the mass of CO₂ emitted per unit mass of coal,
- \( p_{\text{CO₂}} \) is the market price of CO₂ (€/tonne),
- \( LHV_{\text{coal}} \) is the lower heating value of the coal.

The biomass support price, which takes into account the effect of the support scheme for bio-energy and co-firing in particular. It is calculated as:

\[ p_{\text{bio,feed-in}} = p_{\text{bio,CO₂}} + \eta \cdot p_{\text{sup}} \]  

(4)

where \( p_{\text{sup}} \) is the level of support for biomass power production from co-firing or large-scale power production (€/MWhₑ).

This depends on the market value of the Green Certificates or the difference between the feed-in tariff and the system marginal price, depending on the type of the support scheme, and on any price modifiers that may apply.

A summary of the assumptions used for the calculations of the biomass break-even price is presented in Table 4.

Five cases are compared:
- The Rodenhuize PP in Flanders, Belgium, in the Advanced Green operation (co-firing of wood pellets at 50% thermal share);
- The Rodenhuize PP in Flanders, Belgium, in the Max Green operation (repowered for 100% wood pellet firing);
- One hard-coal PP in Italy, retrofitted for co-firing at thermal shares of around 10%, biomass sourcing for “short” distances (< 70 km);
- One hard-coal PP in Italy, retrofitted for co-firing at thermal shares of around 10%, biomass sourcing for “long” distances (>70 km), e.g. imported wood pellets;
- One lignite PP in Greece, retrofitted for co-firing at thermal shares of around 10%.

An electrical efficiency of 35% and availability of 7500 hours has been assumed for all cases. In addition, a CO₂ emission cost of 10 €/tonne is used.
Table 4: Summary of the assumptions for the calculations of the biomass break-even price.

<table>
<thead>
<tr>
<th>Bioenergy support</th>
<th>Belgium, Flanders</th>
<th>Italy</th>
<th>Greece</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_coal (€/GJ)</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>α (€/kW_a)</td>
<td>330 for co-firing 700 for biomass repowering</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>LHV_coal (MJ/kg)</td>
<td>25</td>
<td>25</td>
<td>5.4</td>
</tr>
<tr>
<td>Emission factor (tn CO_2/tn coal)</td>
<td>2.29</td>
<td>2.29</td>
<td>0.667</td>
</tr>
</tbody>
</table>

GC: 100 €/MWh_e
GCs granted according to energy balance of supply chain (~ 80 % for wood pellets made of residues, 75% from round wood)
Since 2011:
- 50 % of GCs if biomass < 60 %
- 70% of GCs if biomass = 100%
- 89% of GCs for Rodenhuize, Max Green (grandfathering)
From 2013 on:
- case by case banding> 20 MW_e
- Power plants in operation before 2013
- GC: 90 €/MWh_e
- Multiplier:
  - 1.3 for supply chains > 70 km
  - 1.8 for supply chains < 70 km and framework agreements
- From 2013: incentives based on a bid mechanism are planned (14).
- Feed in tariff 150 €/MWh_e + 15 % if no public funding for investment
- System marginal price ~ 70 €/MWh_e

The results of the estimation of the biomass break-even prices are presented in Figure 2.

The following estimated delivered fuel costs for relevant biomass supply chains are assumed to apply:

- Imported wood pellets with a typical cost of 8 €/GJ CIF Rotterdam, as estimated from the Endex Wood Pellets (6). This is considered to be typical of the biomass costs for power plants in Belgium, which typically have easy access to port facilities and low cost bulk transportation, e.g. via barges.
- Imported wood pellets with a typical cost of 10.9 €/GJ CIF Thessaloniki, Greece. A further increase of 0.7 €/GJ to the fuel cost at the plant gate is imposed by harbour tax, handling costs and transport costs with truck from Thessaloniki harbour a lignite-fired power plant. The total cost is thus estimated at about 11.6 €/GJ.

This represents an increase of 45% for the biomass fuel delivered cost in Greece compared to that for plants in Belgium. It is considered that the main reason is the lack of an established market for biomass pellets in Greece, hence the low bulk volume trade, and the higher shipping costs estimation.
As can be seen, the break-even biomass price for the Advanced Green operation of Rodenhuize PP would be below the wood pellet cost CIF Rotterdam as a result of the low level of the support for bioenergy from co-firing at thermal shares below 60%. It should be noted that the Max Green retrofit was possible due to a special agreement between the plant operator and the Flemish authorities that granted 89% of the GCs instead of the standard 70% for repowered plants. At 70%, the profit margin would have been very small.

Greece and Italy have a higher biomass break-even price than the repowering case in Flanders and the wood pellet cost CIF Rotterdam. However, in both countries there are some critical issues to consider:

- For Greece, the biomass break-even price is marginally higher than the estimated wood pellet costs at the plant gate. The development of a market for the power sector and the establishment of long-term contracts could bring about a decrease of the cost for the imported wood pellets. On the other hand, the current fiscal uncertainty could result in a feed-in tariff decrease for co-firing power plants, and the case of co-firing was not explicitly considered by the Greek NREAP. As a result, plant operators in Greece are currently focussing on developing supply chains from domestic biomass sources, with lower fuel costs.

- Italy is a major importer of wood pellets for domestic heating (7). The total consumption in 2012 was 1.9 million tonnes, the majority of which was imported (8). Since imported wood pellets can claim higher prices in the domestic heating sector, it is unlikely that co-firing initiatives will be based on wood pellet imports. Other traditional biomass sources, such as forest residues and agro-industrial residues, are already being utilised in other sectors, such as domestic heating, or for existing power plants and are unlikely candidates for co-firing fuels. Instead, it appears that potential biomass fuels for co-firing will be currently under-utilised biomass sources, such as olive prunings in the South of Italy, or new energy crops, such as Short Rotation

![Figure 2: Comparison of the biomass break-even prices.](image-url)
Coppice in the North. A major incentive for such initiatives is the increase of the GC multiplier used in the case of short supply chains (transport distance < 70 km) to 1.8.

It should be noted without financial support for bio-energy and considering only the CO₂ saving price, it is only possible to consider biomass fuels with a cost range of 2.7 – 3.5 €/GJ. In order to consider biomass prices of 8 €/GJ, the emission costs for CO₂ would have to increase to more than 50 €/tonne. Co-firing with lignite would benefit more from such a scenario, due to the higher emission factor of lignite over hard coal.

Overall, provided that a reliable biomass fuel supply can be secured and that the financial support scheme is stable, co-firing can be a low risk investment for utilities. Economic evaluations for Meliti PP indicated a pay-back of one year for the implementation of a co-firing scheme at low biomass thermal shares.

The above analysis does not cover the case of RDF co-firing. The biomass faction of RDF may not be considered eligible for financial support in some EU member states. However, RDF co-firing may still be economically profitable for the power plant operator due to the gate fee available for disposal of the waste.
3 Technical aspects

The co-firing of biomass and RDF materials present some potential technical risks to the performance and integrity of the power plant, including fuel compatibility and handling/storage logistics, combustion and boiler impacts, boiler efficiency, environmental control, ash quality and utilisation.

The main comments and observation presented below are based on the six biomass co-firing configurations employing different shares of biomass firing as well as different fuels, as described in Table 5.

Summaries of the adopted solutions and a commentary on those issues that still need to be resolved are presented below. A more detailed description of the results of each co-firing demonstration is provided in Appendix A.

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Main fuel</th>
<th>Secondary fuel (Biomass/RDF)</th>
<th>% thermal input secondary fuel</th>
<th>Appendix A paragraph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodenhuize</td>
<td>Hard coal</td>
<td>Wood pellets</td>
<td>50</td>
<td>6.1</td>
</tr>
<tr>
<td>Rodenhuize</td>
<td>-</td>
<td>Wood pellets</td>
<td>100</td>
<td>6.1</td>
</tr>
<tr>
<td>Kardia</td>
<td>Lignite</td>
<td>Cardoons, Olive kernels</td>
<td>10</td>
<td>6.2</td>
</tr>
<tr>
<td>Fusina</td>
<td>Hard coal</td>
<td>RDF</td>
<td>5</td>
<td>6.3</td>
</tr>
<tr>
<td>Dorog</td>
<td>Hard coal-lignite</td>
<td>Saw dust, sunflower hull, sunflower pellets, wood chips</td>
<td>&gt; 50</td>
<td>6.4</td>
</tr>
<tr>
<td>Rokita</td>
<td>Hard coal</td>
<td>Wood, agriculture by-products as rape seed and liquid biomass-crude glycerol and SRF were used</td>
<td>36-50</td>
<td>6.5</td>
</tr>
</tbody>
</table>

3.1 Fuel quality and composition

A high level of control of the delivered fuel quality and composition is essential for efficient power plant operation. Binding quality standards and stringent quality control are required for the delivered biomass and RDF fuels.

The most important physical properties of the delivered fuels are the moisture content, calorific value and ash content. These physical properties are employed to control fuel payments, but they also have an influence on the design of the handling and storage systems and the modifications to the power plant equipment.

The chlorine and the sulphur contents are also important for emissions in that these elements may have an impact on the performance of the emissions control equipment and may help to increase the rates of corrosion of boiler components (9).

For RDF, quality standards are already in effect for different industry sectors, and can be either directly applied or adapted for co-firing applications.

For international traded biomass fuels, IWPB has defined standards for wood pellets that could be adapted for other types of biomass. The IWPB standards could also be a template to define quality standards for local biomass supply chains.
The impact that a biomass fuel has on plant operation will be dependent also on the range of coals with which the biomass is to be co-fired. An overview of the physical average properties of fuels, analysed by Partners within the project, is given in the following Table 6 and Table 7.

**Table 6: Average composition of the analysed biomass.**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Standard</th>
<th>Moisture [wt %, a.r.*]</th>
<th>LHV [MJ/kg, a.r.*]</th>
<th>Ash [wt %, d.b.**]</th>
<th>Cl [wt %, a.r.*]</th>
<th>S [wt %, a.r.*]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardoon I</td>
<td>EN 14918</td>
<td>8.3</td>
<td>14.70</td>
<td>9.45</td>
<td>1.84</td>
<td>&lt;0.3*</td>
</tr>
<tr>
<td>Cardoon II</td>
<td>EN 14918</td>
<td>13.8</td>
<td>15.20</td>
<td>7.73</td>
<td>0.19</td>
<td>0.22</td>
</tr>
<tr>
<td>Cardoon</td>
<td>EN 14918</td>
<td>15.4</td>
<td>14.67</td>
<td>8.63</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Cardoon Pellets</td>
<td></td>
<td>6.8</td>
<td>14.33</td>
<td>9.50</td>
<td>1.0</td>
<td>0.11</td>
</tr>
<tr>
<td>Straw</td>
<td>EN 14918</td>
<td>6.68</td>
<td>16.19</td>
<td>7.07</td>
<td>0.25</td>
<td>0.00</td>
</tr>
<tr>
<td>Straw Pellets</td>
<td>EN 14918</td>
<td>5.95</td>
<td>17.38</td>
<td>9.60</td>
<td>0.14</td>
<td>0.03</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>EN 14918</td>
<td>6.48</td>
<td>16.08</td>
<td>6.74</td>
<td>0.04</td>
<td>0.28</td>
</tr>
<tr>
<td>Willow</td>
<td>EN 14918</td>
<td>6.25</td>
<td>18.41</td>
<td>1.93</td>
<td>0.02</td>
<td>0.34</td>
</tr>
<tr>
<td>Poplar</td>
<td>EN 14918</td>
<td>2.66</td>
<td>17.41</td>
<td>1.71</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Paulownia</td>
<td>EN 14918</td>
<td>8.15</td>
<td>16.55</td>
<td>0.93</td>
<td>0.01</td>
<td>0.26</td>
</tr>
<tr>
<td>Wood Pellets BE I</td>
<td>EN 14918</td>
<td>9.0</td>
<td>16.80</td>
<td>0.64</td>
<td>0.01</td>
<td>&lt;0.3*</td>
</tr>
<tr>
<td>Wood Pellets BE II</td>
<td>EN 14918</td>
<td>-</td>
<td>-</td>
<td>2.30</td>
<td>0.03</td>
<td>&lt;0.3*</td>
</tr>
<tr>
<td>Wood Pellets</td>
<td>EN 14918</td>
<td>6.4</td>
<td>17.56</td>
<td>1.73</td>
<td>0.03</td>
<td>0.21</td>
</tr>
<tr>
<td>RDF GR</td>
<td>EN 15400</td>
<td>22.7</td>
<td>12.32</td>
<td>16.22</td>
<td>0.78</td>
<td>&lt;0.36*</td>
</tr>
<tr>
<td>RDF IT</td>
<td>EN 15400</td>
<td>-</td>
<td>-</td>
<td>22.10</td>
<td>0.94</td>
<td>0.27</td>
</tr>
<tr>
<td>RDF</td>
<td>EN 15400</td>
<td>3.0</td>
<td>17.56</td>
<td>15.27</td>
<td>0.55</td>
<td>0.13</td>
</tr>
<tr>
<td>RDF Fusina</td>
<td>ASTM</td>
<td>8-20</td>
<td>17-23</td>
<td>15-20</td>
<td>0.7-0.9</td>
<td>0.2-0.4</td>
</tr>
</tbody>
</table>

Analysed performed by: IFK – Institut für Feuerungs- und Kraftwerkstechnik (D3.3); CERTH – Centre for Research & Technology, Hellas (D3.3); Enel Engineering and Research.
PS IE – Pellet study, Institute for Energy and Environment (Institute for Energy and Environment (IE), 2006)
*a.r. – as received; **d.b. – dry basis

**Table 7: Average composition of the main analysed fuels.**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Standard</th>
<th>Moisture [wt %, a.r.*]</th>
<th>LHV [MJ/kg, a.r.*]</th>
<th>Ash [wt %, d.b.**]</th>
<th>Cl [wt %, a.r.*]</th>
<th>S [wt %, a.r.*]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Coal</td>
<td></td>
<td>2.7 – 14.0</td>
<td>20 - 32</td>
<td>1 - 15</td>
<td>0.03-0.3</td>
<td>0.6-1.4</td>
</tr>
<tr>
<td>Lignite</td>
<td></td>
<td>50 - 60</td>
<td>2 - 10</td>
<td>3.6 - 18</td>
<td>0-0.08</td>
<td>0.3-3.9</td>
</tr>
<tr>
<td>Fusina Coal</td>
<td>ASTM</td>
<td>3-9</td>
<td>26</td>
<td>6.5-15</td>
<td>0.005-0.01</td>
<td>0.56-0.64</td>
</tr>
<tr>
<td>Kardia Lignite</td>
<td>ASTM</td>
<td>53.9</td>
<td>5.43</td>
<td>29.32</td>
<td>-</td>
<td>1.05</td>
</tr>
<tr>
<td>Kardia Lignite</td>
<td>DIN</td>
<td>52.25</td>
<td>5.25</td>
<td>35.22</td>
<td>-</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Analysed performed by: IFK – Institut für Feuerungs- und Kraftwerkstechnik (D3.3); CERTH – Centre for Research & Technology, Hellas (D3.3); Enel Engineering and Research.
PS IE – Pellet study, Institute for Energy and Environment (Institute for Energy and Environment (IE), 2006)
*a.r. – as received; **d.b. – dry basis
3.2 Safety, handling and storage

The long-term storage and the handling of large amounts of biomass fuel present a number of significant new challenges to the power plant operators.

Unlike coal, most biomass fuels should not be stored outside on the coal yard. Most biomass materials tend to absorb water when exposed to the weather, and this can affect their physical properties. There is also a tendency for organic compounds to be dissolved in the leaching liquors from large open stockpiles of biomass. Many biomass materials contain significant levels of fines, and these can give rise to fugitive dust emissions from fuel reception and storage/handling facilities.

Biomass materials in stock piles also have a tendency to self-heating. This occurs especially at higher moisture contents and is caused by exothermal processes whose heat of reaction cannot be dissipated. These processes can be promoted by:

- an elevated temperature during/before storage;
- long storage times;
- high storage volume;
- high altitude of the stock;
- inappropriate ratio of stock volume and surface;
- storage of mixed fuels;
- forming of rat-holing or arching in fuel silos.

Stored biomass may emit certain gases like CO, CO₂, CH₄, etc. These can form explosive gas/air mixtures, and at a certain concentration can be harmful to the operating personnel. In addition biomass dust can form explosive mixtures with air, especially during transportation, conveying and moving the fuel within storage buildings. ATEX measures and zoning are mandatory when firing dry dusty biomass like wood pellets.

The ignition and explosion characteristics of biomass fuel may exceed the known limits of more familiar solid fuels, and special attention and additional equipment may be necessary. In either case, the ignition and explosion limits of the biomass fuel have to be known in order to adapt the safety measures.

For the biomass fuel and its deposited dust these are:

- inflammability and flammability;
- smouldering temperature;
- spontaneous ignition temperature.

And for its suspended dust:

- explosiveness (explosion limits);
- ignition temperature;
- minimum ignition energy;
- maximum explosion overpressure;
- maximum rise in explosion pressure.

Recommendations on the prevention of self-ignition, on the storage of biomass and the equipment for prevention of fire and explosions can be found in the VGB-Standards “R108: Fire Protection in Power Plants” (10), “Fire and Explosion Protection in Biomass Fired Power Plants” (11) as well as in “Health and Safety Aspects of Solid Biomass Storage, Transportation and Feeding” (15) and “The Pellet Handbook” (16).

Biomass refining can help to overcome some of these challenges. “Refining” is a generic term for different fuel processing technologies like torrefaction, steam explosion or hydrothermal carbonisation. The products of these processes show more “coal-like” properties and may be easier to handle and store in large quantities. The energy density of
the refined materials tends to be higher, and they may be more brittle in nature and easier to mill than the raw biomass material.

The commercial availability of the refined biomass fuels is still limited. Further R&D is needed to support the development of refined biomass fuels to become an alternative solid fuel for co-firing at industrial scale.

There are several possibilities of fuel handling considered within DEBCO are summarised in Table 8.

The handling of the fuel needs much attention. The key fuel properties are the grain size, the grain form and aspect ratio, the bulk and particle density, the moisture content, the pouring and flow properties.

In most instances, the biomass and RDF materials will have specific handling and storage requirements. It is possible, in some circumstances to make use of the existing coal handling, bunkering, feeding and milling systems, with appropriate modifications, particularly if the fuel is in pellet or other densified form.
Table 8: Performance summary of the fuel handling systems.

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Measure</th>
<th>Results</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodenhuize</td>
<td>The ship unloading activities and long storage. The pellets are unloaded by means of a Grab crane and stored in a large automated warehouse. From the warehouse, the pellets are conveyed by covered belt conveyor to the day silos at the Max Green milling installation. For risk mitigation, it is recommended that the necessary pre-cleaning devices are installed upstream of the main storage facility to avoid tramp and oversize material entering the storage.</td>
<td>All buildings, installations and equipment shall be provided with all the necessary devices to protect, detect and fight explosion. ATEX compliant installation.</td>
<td></td>
</tr>
<tr>
<td>Kardia</td>
<td>No changes for short term test wanted.</td>
<td>The existing secondary fuel handling system is capable of handling biomass fuels with characteristics similar to olive kernels. The existing, not for biomass optimised fuel handling system, has little difficulties with olive kernels. The fuel weighting takes place after the mixing and may not be really accurate.</td>
<td>For long term operation with olive kernels little difficulties. For long term operation with cardoons individual solution is necessary.</td>
</tr>
<tr>
<td>Fusina</td>
<td>RDF is received at the station, and sent to two large storage silos. The RDF is then fed out of the silos and conveyed through ferrous and non-ferrous metal separation units to four high speed hammer mills.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorog</td>
<td>The pellets were transported to the plant by a truck and handled very similarly to coal.</td>
<td>The proper feeding rate was worked out by determining the heating value of the fuels and weighed amount of coal and biomass was separately fed conveyed into the bunkers. Feeding of biomass was not always continuous due to the inhomogeneous mixture. Wood-chips tended to form craters in the bunker and for avoiding plugging, mechanical agitation of the material was necessary.</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Feeding and milling system

There are basically five options for direct and indirect combustion of solid biomass or RDF in a pulverised-fuel boiler (Figure 3).

1. When the proportion of biofuel is relatively low, generally less than 10% by mass, it can be fed together with coal to the coal mills (co-milling) and then be burned together with coal through the existing coal burners. In principle, this is the simplest option and involves the lowest capital investment costs and shortest project implementation times. This approach also carries the highest risk of malfunction of the fuel feeding systems.

2. The second option involves separate handling, metering and comminution of the biofuel, normally using hammer mills, and injection into the pulverised fuel upstream of the burners or at the burners (co-injection). This option requires the installation of a number of biomass transport pipes across the boiler front, and integration of the biomass feeding systems with the existing boiler control systems, for process control and safety reasons.

3. The third option involves the separate handling and comminution of the biofuel with combustion through a number of dedicated burners. This approach normally has relatively high capital costs, but can be applied at elevated co-firing levels.

4. The fourth approach involves the gasification of the fibrous raw material and injection of the syngas and char in the main boiler as a substitute for coal.

5. The fifth approach is similar to option 1, but involves the utilisation of torrefied biomass to permit operation at higher co-milling ratios.

![Figure 3: Options for direct and indirect co-firing of solid biomass or RDF.](image-url)
Within the DEBCO project, only the first three options were investigated:

- co-milling at Kardia PP;
- separate milling, injection in PC lines, combustion in PC burners at Fusina, Dorog and Rokita PPs;
- separate milling and firing in dedicated burners at Rodenuize PP.

In all cases, it is essential that the size distribution of the milled fuel fed to the boiler is suitable for firing in a suspension flame. The injection of coarser material will result in an unstable flow of fuel, poor combustion conditions and increased levels of unburned carbon (UBC) in the fly and furnace bottom ashes.

At low co-firing ratios, up to 5-10% on a heat input basis, a wide range of biomass materials in pellet or granular forms may be co-milled successfully with coal in vertical spindle coal mills or lignite beater mills. At higher biomass and RDF shares, dedicated milling equipment, normally based on hammer mills, is required.

This technology may not be suitable for very wet biomass materials which may blind the outlet screen and adhere to internal surfaces of the mill body. This can lead to poor product quality, higher power consumption and lower throughput. For this reason, drying prior to milling is strongly recommended.

Hammer mills also require regular routine maintenance, i.e. replacement of the hammers and screens, to maintain good performance and an acceptable mill product quality.

The experience gained within the DEBCO project and elsewhere has indicated that coal handling and feeding systems can be unsuitable for handling and feeding baled and straw-like herbaceous biomass. Continuous feeding is not assured, and there is a tendency for fuel to block and accumulate in the feeding system.

Two solutions are suggested to overcome the problem of feeding herbaceous biomass in PC plants:

- Build a new facility for handling and feeding (expensive solution);
- Pelletise the material at the source.

For the pneumatic conveying of the milled fuel to the boiler burners, the use of dedicated blowers for each conveying line has been most popular. This approach has a number of important advantages:

- Reduced blockage risk, because there are no splitter in the biomass conveying lines;
- Good dust/air ratio control;
- Constant and controllable fuel flow rates.

The dust/air ratio is an important parameter, which is controlled to ensure proper operation of the burners. Excessive dust/air ratios can cause pulsations and can have a negative impact on the combustion prices.
## Table 9: Performance summary of the fuel milling and feeding systems.

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Process</th>
<th>Adaptations</th>
<th>Results</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodenhuize</td>
<td>Milling and feeding</td>
<td>A dedicated system was installed. Fast rotating mills were selected. A pneumatic conveying system is used to transport the milled wood dust.</td>
<td>After a few weeks of operation the efficiency of grindability of the hammer mills decreased dramatically and the worn out material had to be replaced.</td>
<td>Regular routine maintenance of the mills is necessary to maintain good performance and non to increase the unburned particle fallout into the bottom ash hopper of the boiler.</td>
</tr>
<tr>
<td>Kardia</td>
<td>Milling</td>
<td>No changes for short term test wanted.</td>
<td>No explosions or temperature increases in the mills were detected. The temperature values were within the usual range of mill operation and well within safe operation limits.</td>
<td>No accumulation of olive kernels in the mills.</td>
</tr>
<tr>
<td>Kardia</td>
<td>Feeding</td>
<td>No changes for short term test wanted.</td>
<td>Cardoon accumulation in the feeding system was not initially observed, but during a maintenance, significant cardoon quantities were found in several places along the feeding line, remaining practically blocked.</td>
<td>Physical properties of olive kernels (small particle size, grindability) are similar to fossil fuels but not to herbaceous biomass.</td>
</tr>
<tr>
<td>Fusina</td>
<td>Milling</td>
<td>RDF is milled in dedicated high-speed blade-type coal mills.</td>
<td>Owing to a gradual wear of hammers and screens, the RDF milling performance has been observed to decrease significantly over the time if hammer mills are used.</td>
<td></td>
</tr>
<tr>
<td>Fusina</td>
<td>Feeding</td>
<td>Milled fuel conveyed pneumatically to Units 3 and 4, and the RDF is injected directly into the PC pipes, at a location just upstream of the primary air fans.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4 Boiler modification and performance

3.4.1 Boiler modification

The injection of biomass or RDF into the furnace of a pulverised coal-fired boiler can have a significant impact on plant performance and integrity. Depending on the co-firing ratio and the nature of the biomass, the installed equipment will require modification. For low co-firing ratios, major modifications are not required. This has been demonstrated at Fusina and Kardia PP, with 5-10% thermal input. For higher co-firing ratios, significant modifications to the fuel handling and firing system are normally required, e.g. at Rodenhuize PP, with 50-100% thermal input.

Within the DEBCO project, CFD modelling has proved to be of value for the assessment of the modifications to the boiler and firing systems. The activities have included calculations of velocity and temperature fields, as well as the flue gas composition. The CFD simulations should preferably be validated with experimental measurements, e.g. velocity, temperature, chemical species concentrations.

As stated above, at high biomass co-firing levels and 100% biomass firing significant modification of the fuel handling and firing systems are normally required, as at Rodenhuize power plant to 50% co-firing (advanced green) and 100% wood pellet combustion (max green). At Rodenhuize, the existing burners have been modified significantly for biomass firing. The inlet section of the primary air annulus has been redesigned with a hexagonal cross section with the internal surfaces completely covered with ceramic tiles. It is considered that this shape has several advantages:

- The kinetic energy of the wood dust particles at the inlet is partly absorbed by the side of the hexagon which is perpendicular to the wood dust flow,
- The hexagonal shape contributes to the generation of an even distribution of the wood dust all around the primary air tube,
- The primary air tube can be turned in order to extend its lifetime by presenting another side to the inlet wood dust flow.

The wood dust is transported in dense phase independently from the primary air and is injected in a concentric way inside the primary pipe about one meter upstream of the inlet to the burner.
Another challenge was to ensure efficient combustion of the milled biomass without any support fuel. During the operation at 50% biomass/coal co-firing, biomass was injected together with coal through a number of the burners. In this operating condition, the coal combustion was well controlled, and the biomass combustion was supported by the pulverised coal flames. It is considered, however, that the wood particle velocities within the flame were too high, and the larger wood particles were hitting the opposite membrane walls without completely burning out.

After retrofitting the firing system for operation at 100% biomass, the burner was modified, based on the results of experimental tests, to obtain a self-sustaining stable flame. The main modifications were to the primary air temperature and flow rate, the secondary air flow rate and the secondary air swirl level.

3.4.2 Combustion and boiler performance

The impacts of biomass co-firing on the performance and integrity of PC boilers depends upon the details of the combustion system and the boiler, and the general operating regime of the plant.

From a general point of view, the impact of the co-firing of biomass and RDF material at up to 5-10% on thermal basis, e.g. at Kardia and Fusina PP, on the performance of the boiler has been negligible.

For the Advanced Green project at Rodenhuize the existing coal burners and part of the pulverized coal transport system were used for wood co-firing. In order to avoid pulsing and sedimentation in the fuel lines, the primary air flow rates and velocities in the pulverised coal pipework had to be kept very high, at 30 m s\(^{-1}\), or even faster. This resulted in high primary air velocities at the burner outlets, causing the flame to be unstable and not well attached to the burner. There was evidence of flame impingement on the opposite and side walls and high levels of UBC in the bottom and fly ashes. There was also evidence of increased slag and fouling deposit formation in the furnace and the inlet to the convective section. The burnout was not complete at the 43 metre level and it is known that secondary combustion of coarse fuel particles on heat transfer surfaces can create local reducing zones that favour slag formation.

After changing the burners and modifying the boiler for the Max Green configuration, the combustion was much more stable, lower levels of UBC in the ashes, no significant flame impingement on the furnace surfaces, and much less slagging.

At Kardia PP, the boiler efficiency was not influenced by co-firing biomass at a co-firing level of 10%. The mean values of the flue gas temperatures at various positions in the the boiler, as well as after the ESPs, were measured. No significant changes were observed during co-firing. The flue gas volumes decreased by only around 2% during the co-firing tests.

The only noticeable difference was a doubling of the UBC levels in the bottom ashes during cardoon co-firing compared to those for 100% lignite firing.

At Fusina PP, an assessment study has been carried out on the basis of 11 tests in different operational conditions, at RDF thermal input varying from 0 to 5% and average unit load levels in the range 301-307 MW\(_{el}\). The boiler data, i.e. the flue gas flow rates and the measured flue gas temperatures in the convective section indicated that there was no variation in the boiler performance at the different RDF co-firing levels.

The measured superheater spray flow rates, which are best indicator of the heat absorption performance of the furnace, show no significant variation. This indicates that there is no evidence to suggest that the co-firing of the RDF material had any significant impact on the furnace performance.
No major differences appear in the gas composition downstream of the economiser, i.e. the (NO\textsubscript{x}, O\textsubscript{2} and CO concentrations were within the normal range of fluctuation experienced without co-firing. The UBC levels in the fly ashes were also unchanged when co-firing RDF.

The only measurable differences in boiler performance were an increase in the heat absorption in the convective section of the boiler due to the sootblowing cycle frequency being increased during the co-firing tests, in anticipation of increase fouling. This was within the normal boiler operating envelope and the increase in the steam consumption for the sootblowing was negligible.

3.4.3 Slagging/fouling and corrosion

The inorganic constituents of biomass materials, and the ashes produced in combustion and other thermal processes, are of particular interest for plant designers and operators. These materials are very different in a number of important respects from coal ashes. They are not alumino-silicate systems, and commonly comprise mixtures of a limited number of relatively simple inorganic compounds, principally silica, and the oxides, sulphates, chlorides and phosphates of the alkali and the alkaline earth metals. In general terms, therefore, the biomass ashes are relatively rich in elements that are effective fluxes for coal ash systems and that tend to be volatile at elevated temperatures in combustion and other thermal processes.

The overall result is that many of the potential impacts of the co-firing of biomass materials in coal combustion and other thermal processing plants are associated with the changes in the ash composition and the ash behaviour that occur when co-firing. The principal ash-related impacts on plant operation and integrity that may be affected by biomass co-firing include:

- The formation of fused or partly-fused ash deposits on surfaces in furnaces and reactors;
- The formation of bonded ash deposits on convective section heat exchangers;
- The formation of aggressive ash deposits on high temperature surfaces, resulting in accelerated metal wastage;
- The formation of aggressive ash deposits on surfaces at saturated steam temperature, resulting in accelerated metal wastage in the area from the burner to the first convective heat exchangers;
- The formation and emission of fine inorganic aerosols and fumes;
- The impact on the performance of flue gas cleaning equipment;
- The impact on the handling and the utilisation/disposal of the ash discards from thermal processes.

These impacts are dependent on a number of factors, including the chemistry and behaviour of the coal and the biomass ashes, the co-firing ratio and the plant configuration. The ability to assess these risks and to minimise the impacts on plant performance are of key importance to the industry.

The industry has a suite of laboratory test procedures and other methods for the analysis and characterisation of coal ashes, and these have been applied, with appropriate modification where necessary, to biomass ashes and the ashes from co-firing.

To date, the industrial experience has been principally with the co-firing of clean biomass materials in large pulverised coal boilers at relatively low co-firing ratios. Currently, however, the range of biomass materials of industrial interest is expanding rapidly, and the co-firing ratios are increasing. These trends will tend to result in an increase in the risks of significant ash-related impacts on the performance and integrity of the thermal processing equipment.

In all of the demonstration plants, the slagging, fouling and corrosion tendency has been evaluated with appropriate short-term measurement campaigns. In Fusina PP, where RDF materials were being co-fired, long-term deposition and corrosion monitoring campaigns...
were carried out. The evidence from Fusina indicated that there was a long term trend towards higher levels of slag formation on furnace surfaces when co-firing the RDF compared to coal firing alone.

No significant influence of cardoon/ignite co-firing at 10% biomass thermal share has been observed on the slagging behaviour at Kardia. At higher biomass co-firing levels, an increase in the slagging and fouling in the combustion chamber as well as at the convective part inlet is anticipated.

In summary, the experience with waste to energy plants and biomass power plants has indicated that the following measures against boiler corrosion may be helpful:

- The online-cleaning of tubes and membrane walls can reduce the risk of circular reactions underneath the deposits.
- The introduction of curtain air at the furnace walls may help to maintain oxidising conditions at the furnace walls can help to control fireside corrosion rates.
- The testing results suggest that the application of fireside additives for corrosion reduction is a complex matter. Only a few tests were a little successful, e.g. with the application of pyrogenic silica. The application of SO$_3$ or SO$_3$-forming compounds similar to the so called “Chlor-out”® procedure may be more promising.

### 3.5 Air pollution control device performance

The impact of biomass and RDF co-firing on the performance of the Air Pollution Control Devices (APCDs) was assessed during long term monitoring of emission values as well as by the performance analysis of the selective catalytic reduction (SCR) unit and of the electrostatic precipitator.

The future legal requirements of the Industrial Emission Directive (IED – Directive 2010/75/EU (12)) are listed Table 10 and Table 11 for new and for existing power plants respectively.

Demonstrations showed that for biomass co-firing or 100% biomass combustion in Large Combustion Plants (LCP) originally designed for PC a flue gas cleaning system is needed to meet the emission limits. That means DeNOx, de-dusting and de-sulphurization steps. With this equipment it is possible to respect the emission limits for new power plants in accordance with the Industrial Emission Directive. Depending on the fuel constituents (e.g. lignite, wood), in some cases the de-sulphurisation step can be omitted, of course without forgetting to carefully verify the respect of the heavy metal emission limits.

It has been noted that without DeNOx equipment (Kardia PP) there is no chance to satisfy the emission requirements of the IED. The values of Rodenhuize PP before retrofitting, and therefore before installing high-dust catalyst, show that without DeNOx equipment the NOx-values are far above the emission limits. It could be shown that a high-dust SCR device combined with a high Cl-content in the fuel is able to oxidise elemental mercury to the ionic form, which can be captured in the wet Flue Gas Desulphurisation (FGD) system. This oxidation potential can however decrease with deactivation of the catalyst, which is faster during biomass co-firing because of the higher amount of alkali salts in the fly ash.

With regard to the ESP, the results show that the dust particle size distribution changes with co-firing. With high amount of biomass, the amount of fine particles increases and the dust concentration decreases. This indicates that, if the ESP is well designed for coal-firing, it also can be used for biomass firing. It is no problem to remove fine particles with d $2.5 < d < 10 \mu m$, while finer particles (with d $< 2.5 \mu m$) can pass the ESP. To have the same dust removal efficiency as for coal-firing, a well-designed ESP or a combination of ESP and wet FGD is needed. However, the emissions of fine dust $< PM \ 2.5$ cannot be prevented.
PC/RDF co-firing up to 5% RDF thermal input resulted not to affect the macro-pollutant and micro-pollutant emissions of the PC power plant. The measurement highlighted values fairly below the maximum lawful limits.

**Table 10:** Emission limits of IED for new power plants with permit after 07.01.2013. Emission limits are given as monthly average values and for co-firing as daily average in mg/Nm³ @ 6% O₂.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Thermal input (MW)</th>
<th>IED emission limits for new plants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coal, Lignite</td>
</tr>
<tr>
<td>SO₂</td>
<td>50 - &lt;100</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>100 - 300</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>&gt;300</td>
<td>150/200</td>
</tr>
<tr>
<td>NOₓ</td>
<td>50 - &lt;100</td>
<td>300/400</td>
</tr>
<tr>
<td></td>
<td>100 - 300</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>&gt;300</td>
<td>150/200</td>
</tr>
<tr>
<td>Dust</td>
<td>&lt;50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 - &lt;100</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>100 - 300</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>&gt;300</td>
<td>10</td>
</tr>
<tr>
<td>CO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cd, Tl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V</td>
<td>0.5/6</td>
<td>0.5/6</td>
</tr>
<tr>
<td>Dioxins+Furans</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3) Fluidised bed firing
5) Value for waste incineration daily average
6) Average values over the sampling period of a minimum of 30 minutes and a maximum of 8 hours
7) ng/Nm³, average value measured over the sampling period of a minimum of 6 hours and a maximum of 8 hours
### Table 11: Emission limits of IED for existing power plants and power plants with permit before 27.11.2002. Emission limits are given as monthly average values and for co-firing as daily average in mg/Nm³ @ 6% O₂.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Thermal input (MW)</th>
<th>IED emission limits for existing plants</th>
<th>IED emission limits for co-firing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1)Coal, 2)Lignite</td>
<td>Biomass</td>
</tr>
<tr>
<td>SO₂</td>
<td>50 - &lt;100</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>100 - 300</td>
<td>250</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>&gt;300</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>NOₓ</td>
<td>50 - &lt;100</td>
<td>300¹/450²</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>100 - 300</td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>&gt;300</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Dust</td>
<td>&lt;50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 - &lt;100</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>100 - 300</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>&gt;300</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>CO</td>
<td></td>
<td></td>
<td>50⁵</td>
</tr>
<tr>
<td>Cd, Tl</td>
<td></td>
<td>0.05⁶</td>
<td>0.05⁶</td>
</tr>
<tr>
<td>Hg</td>
<td></td>
<td>0.05⁶</td>
<td>0.05⁶</td>
</tr>
<tr>
<td>Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V</td>
<td></td>
<td>0.5⁶</td>
<td>0.5⁶</td>
</tr>
<tr>
<td>Dioxins+ Furans</td>
<td></td>
<td>0.1⁷</td>
<td>0.1⁷</td>
</tr>
</tbody>
</table>

¹ Fluidized bed firing
² Value for waste incineration daily average
³ average values over the sampling period of a minimum of 30 minutes and a maximum of 8 hours
⁴ ng/Nm³, average value measured over the sampling period of a minimum of 6 hours and a maximum of 8 hours

#### 3.6 Ash utilisation

The utilisation of CCPs from coal-fired power plants has developed over decades. The basic technical, physical and chemical properties of the ashes are addressed in product and application standards and regulations. In general terms, the DEBCO project has demonstrated that the solid by-products generated during the co-firing in dedicated plants at low co-firing ratios can also be utilised as construction materials.

The co-firing of specific biomass materials is already covered by the European Standard EN 450-1 for fly ash for concrete. The biomass properties and the co-firing levels are limited to guarantee that the key properties of the fly ash materials do not change significantly.
In order to extend the co-firing of biomass to higher levels, the utilisation paths of by-products need to be analysed and the impact of co-firing need to be assessed. The intention is to minimise the quantities of material that need to be sent to disposal to land.

For the use in or as construction materials, the requirements in European standards, which have to be considered for the placing on the market of coal ash, as well as national standards, for the application in the countries, have to be considered. The possible uses of CCPs could be:

- In cement;
- In concrete;
- Road constructions;
- Aggregates.

The specific technical and other requirements for fly ashes for different applications are established by European standards, and these are listed in Table 12.

The requirements for fly ash for the use as a constituent of blended cements and of concrete established in the European Standards are given in Table 13. For the use in concrete, some additional physical parameters are defined in EN 450-1:2005 and listed in Table 14.

For the evaluation of the impact of co-firing of different biomass / materials on the properties of ashes it is recommended to consider the following issues:

- If the ash from co-firing is to be used for the same purpose as the ash from coal, the impact on the chemical and physical properties should be minimal or negligible.
- Different biomass materials have different chemical compositions and will have different impacts on the chemical compositions of the ashes resulting from co-firing with hard coal or lignite. The results of the work carried out within the DEBCO project show significant variability in the ash chemistry even when co-firing relatively well-defined wood pellets.
- The lower the ash content of the co-firing material, the lower the impact on the resulting ash. For wood pellets, the ash content is commonly less than 2.5% by mass.
- If the ash from co-firing is to be used for specific fields of application, special physical or chemical requirements may have to be met, and this may have an impact on the biomass specification or the co-firing ratio. In general, terms, it is normally desirable to minimise the UBC levels for most applications.
### Table 12: European standards for fly ash requirements.

<table>
<thead>
<tr>
<th>In cement</th>
<th>EN 197-1 “Cement – Part 1: Composition, specifications and conformity criteria for common cements” (For the definition of fly ash - and therefore also regarding co-firing - the standard refers to EN 450-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregates</td>
<td>EN 12620 “Aggregates for concrete” (for lightweight aggregates for concrete, mortar and grout: EN 13055-1 “Lightweight aggregates for concrete, mortar and grout”)</td>
</tr>
</tbody>
</table>
### Table 13: Requirements on fly ash for use in cement and in concrete.

<table>
<thead>
<tr>
<th>Loss on ignition</th>
<th>Use in cement EN 197-1</th>
<th>Use in concrete EN 450-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>W1</td>
<td>W2</td>
</tr>
<tr>
<td>siliceous fly ash</td>
<td>category A: ≤ 5.0% by mass</td>
<td>≤ 5.0% by mass</td>
</tr>
<tr>
<td></td>
<td>category B: 2 - 7% by mass</td>
<td>2 - 7% by mass</td>
</tr>
<tr>
<td></td>
<td>category C: 4 - 9% by mass</td>
<td>4 - 9% by mass</td>
</tr>
<tr>
<td>Chloride</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sulphuric anhydrite (SO₃)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reactive calcium oxide</td>
<td>≤ 10% by mass</td>
<td>10 – 15% by mass</td>
</tr>
<tr>
<td>Free calcium oxide</td>
<td>≤ 1% by mass</td>
<td>2.5% by mass</td>
</tr>
<tr>
<td>Reactive silicon dioxide</td>
<td>≥ 25% by mass</td>
<td>-</td>
</tr>
<tr>
<td>Silicon dioxide, aluminium and iron oxide</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alkalis (Na₂O equivalent)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Soluble phosphate</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Compressive strength at 28d</td>
<td>≥ 10 N/mm²</td>
<td>-</td>
</tr>
<tr>
<td>Expansion</td>
<td>≤ 10 mm</td>
<td>-</td>
</tr>
</tbody>
</table>

1) LOI of up to 7 or 9 % by mass is allowed provided requirements at the place of use regarding durability are met
2) CaO_{mass} = total CaO reduced by fraction calculated as CaCO₃ and CaSO₄
3) CaO_{free} = amount up to 2.5% by mass accepted when soundness is given (see 5)
4) SiO₂_{react} = fraction of SiO₂ which is soluble after treatment with HCl and boiling KOH-solution
5) mortars with ground fly ash as binder, amount < 40µm between 10 and 30% by mass
6) mixture of 30 % by mass ground fly ash, 70% by mass cement
7) if the amount of free calcium oxide exceed 1.0% by mass soundness have to be proven
8) requirement to be fulfilled for fly ash obtained from co-combustion
Table 14: Physical requirements for fly ash in accordance with EN 450-1.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Category N</th>
<th>Category S</th>
</tr>
</thead>
<tbody>
<tr>
<td>fineness (residue on 45 µm mesh sieve)</td>
<td>≤ 40% by mass</td>
<td>≤ 12% by mass,</td>
</tr>
<tr>
<td>fineness variations 1) (deviation from declared value)</td>
<td>≤ ±10% by mass</td>
<td>≤</td>
</tr>
<tr>
<td>density variation</td>
<td>1) ± 200 kg/m³</td>
<td></td>
</tr>
<tr>
<td>soundness2)</td>
<td>max. 10 mm (30/70/3)</td>
<td></td>
</tr>
<tr>
<td>activity index4)</td>
<td>≥ 75%</td>
<td></td>
</tr>
<tr>
<td>after 28 days after 90 days</td>
<td>≥ 85%</td>
<td></td>
</tr>
<tr>
<td>initial setting time</td>
<td>≤ 120 min more than cement paste with test cement 4)5)</td>
<td></td>
</tr>
<tr>
<td>water demand</td>
<td>category N: not valid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>category S: ≤ 95% of that for the test cement alone</td>
<td></td>
</tr>
</tbody>
</table>

1) average value as declared by the producer
2) required only if amount of CaOfree is > 1% by mass
3) to be determined with a paste made from 30% by mass of fly ash and 70% by mass of cement
4) to be determined with a paste made from 25% by mass of fly ash and 75% by mass of cement
5) requirement is assumed to be met for fly ash produced by combustion of pure coal

3.6.1 Rodenhuize - co-firing of wood pellets

At Rodenhuize PP the amount of wood pellet co-firing was increased from 25 to 50% (Advanced Green) and later 100% wood pellet was fuelled (Max Green). Wood pellet fuels of the type fired at Rodenhuize have a fairly wide range of chemical compositions, normally depending on the level of bark present. The wood pellets have much lower ash contents than most coals and, as a consequence, the co-firing of wood pellets normally has only a modest impact on the chemistry of the mixed ash produced. In most systems, the control of the UBC levels in the ashes can be controlled by the maintenance of acceptable combustion conditions. The industry has already agreed on a quality scheme for wood pellets which help to maintain adequate control over the ash levels in the wood fuels. These standards will normally permit the ash quality standards for the products of the co-firing of these fuels to be met under normal combustion conditions.

At present, the standard for fly ash for concrete EN 450-1 (13) restricts the amount of co-firing to 20% by mass. However, due to the experience with co-firing over the past few years, the level of co-firing will be increased to 40% by mass, and 50% by mass in case of green wood. The results of the ash tests for wood pellets co-firing within DEBCO are consistent with this revision of the standard.

3.6.2 Rodenhuize - combustion of 100% wood pellets

With 100% wood pellet combustion, the ash residues differ significantly from those originating from coal combustion and from co-firing. The ashes are rich in calcium- and magnesium oxide, alkali metals, phosphate and sulphur. The levels of silica, alumina and iron oxide are lower, as would be expected for wood ash. For utilisation of this material as a constituent of cement, it will be the task of the cement producer to decide about the ratio of this ash in his raw meal mix.
The ash may be used as a lime or an alkali agent. and its use as a low grade fertiliser can be considered. These applications may be restricted by trace elements contents, and these need to be considered for a specific country or region and for the respective national and/or regional requirements.

### 3.6.3 Fusina - co-firing of RDF

At Fusina PP the co-firing of refuse derived fuel (RDF) up to 5% (thermal) was investigated. At these co-firing levels, the ranges of the concentrations of the main ash constituents are similar to those for coal ashes. RDF materials, however, are not covered by the definition of co-firing materials in EN 450-1.

The RDF used for the co-firing trials had a biomass fraction of more than 60% by mass, and an ash content of about 15 to 22% by mass.

Compared with pure bituminous coal combustion, the analyses of the ashes sampled during 5% RDF co-firing showed a slight increase in the concentrations of same trace elements (Cu, Fe, Zn), alkalis and chlorides. The trace elements need to be taken into account in light of the future requirements for the product standards as well as in light of the existing national application rules.

The main conclusion of the fly ash characterisation is that RDF co-firing up to 5% thermal input has slightly increased the trace element contents but not affected the main oxide composition and, therefore, the use as concrete addition could be possible provided an ETA (European Technical Approval) for co-firing of RDF is granted.

### 3.6.4 Kardia - co-firing of cardoon biomass

At Kardia PP, co-firing was tested up to 10% cardoon thermal share. The main fuel of the plant is lignite from nearby lignite mines. A number of different lignite types are fired and a relatively wide range for the ash chemical parameters have to be considered. The cardoon biomass used for the tests is characterised by an ash content ranging from 9.5 to 14.5% by mass. The impact of co-firing on the ash quality was modest and, in general terms, the co-firing of the biomass resulted in a more consistent ash chemical composition than for the normal lignite fuel diet.

As the investigated ashes from lignite are not covered in the fly ash standard for concrete and as the chemical composition of these ashes is varying widely for a use as construction material, as e.g. filling material, the physical properties have to be considered more intensively as well as the trace element concentration, especially for the leaching limit values. If the co-firing is combined with lignite from a specific seam, also ash qualities for the use in cement and concrete may be obtained.
4 Conclusions

The DEBCO project has involved an extensive program of research, component testing and demonstration work aimed at the further development of the co-firing of biomass and RDF materials with coal as a mean for using renewable fuels in the near term. DEBCO (DEmonstration of large scale Biomass CO-firing and supply chain Integration) is a collaborative RTD project included in the EC framework program FP7, and involves seventeen Partners from eight different EU Countries.

The general objectives of the DEBCO project have been achieved through a program of research activities, large-scale demonstrations and long-term monitoring of the key co-firing options.

This Guidebook is intended to provide a summary of the key results and experiences of the DEBCO project with a particular focus on:

- The economical aspects, including the political and regulatory framework, the market structure, the local and international fuel supply chains and the main economic factors which may affect co-firing projects;
- The technical aspects, including the fuel characteristics and storage/handling requirements, the plant modifications required for co-firing, the boiler and air pollution control device performance, the utilisation/disposal of the ash and other discards from the power plants.

The co-firing of biomass in coal boilers is an important technology for CO$_2$-neutral electricity generation. Different government subsidy schemes, as well as other financial instruments, provide a range of national incentives for biomass co-firing within the European Union.

The key advantages of biomass co-firing include:

- the utilisation of existing capital equipment, with modest costs and fairly short project times for plant conversion;
- the biomass fuel flexibility, particularly at low co-firing ratios;
- the relatively high overall power generation efficiencies from biomass.

The main technical results illustrated in the present Guidebook are based on six co-firing configurations employing different shares of biomass firing and different fuels.

The analysis of the member state policy framework shows that the economic and ecological potential of biomass co-firing is not adequately recognised in the legislation of all of the European countries. A common approach across Europe, at least for incentives and binding sustainability criteria, would lead to an improved level of security for investment, and a higher propensity for the private sector to invest.

The analysis of the market potential shows clearly that there is significant potential growth in the European and international market for solid biomass fuels, without significant interference with food supply, wood process industry or land use issues. It is also considered that the stimulation of local markets for biomass fuels will help secure employment in the power sector, and create new jobs in the agricultural and transport sectors.

Biomass and RDF co-firing, at low and high levels, face some technical issues such as fuel compatibility and logistics, boiler efficiency, environmental control, ash quality and utilisation.

The impacts of biomass/RDF co-firing on the performance and integrity of the installed plant depend on the share of biomass or RDF co-fired. At up to 5-10% thermal input, the impacts are modest and, in many cases with clean biomass materials, the impacts are negligible. At higher co-firing levels, the impacts are more significant, and it may be necessary to limit the range of fuels fired, modify the existing equipment or install new equipment.
The main conclusions from the demonstration activities carried out under the DEBCO project are:

- The maintenance of a high level of control of the quality and composition of the delivered fuel is essential for the power plant operation, and binding quality standards are required for large scale biomass utilisation;
- The long-term storage and the handling of large amounts of biomass fuel presents a number of significant new challenges to the power plant operators, particularly related to plant safety, and biomass storage conveying, milling and feeding;
- The co-firing ratio and the mode of introduction of the biomass into the pulverised coal boiler have a influence on the performance of the combustion system and the boiler. It is normally necessary to modify plant operations to permit co-firing, and it may be necessary to modify the installed equipment to accommodate the new fuel mix.
- The experience of the PC power plant operation gained during the project indicates that capital-expensive boiler modifications are generally not required for co-firing at low biomass or RDF levels as at Fusina and Kardia. More significant modifications including modification of fuel handling feeding and firing system and of the boiler may be required for higher co-firing levels as at Rodenhuize PP.
- For biomass co-firing and 100% biomass combustion in large combustion plants, it is necessary to have a flue gas cleaning system that meets the requirements for best available technology (BAT). This normally involves a NOx control, de-dusting and de-sulphurisation equipment. With suitable equipment it is possible to meet the emission limits for new power plants according to the Industrial Emission Directive. Depending on the fuel constituents it may be possible to operate without de-sulphurisation.
- The utilisation of the ashes resulting from co-firing of different materials in coal-fired power plants can be achieved in some cases, however the chemical composition of the fuels and that of the specific mix of co-firing material have to be considered in detail.
5 References

(1) DEBCO website (http://www.debco.eu), Deliverable D3.6 “Indicators and guidelines for future implementation of fuel supply chains”


(4) http://www.greengoldcertified.org/

(5) Vereinbarung zwischen dem Land Berlin und der Vattenfall Europe AG über Kriterien zur Nachhaltigkeit der Beschaffung von holzartiger Biomasse,” Berlin, 2009


(8) http://www.pellet.org/home/24-italys-increasing-demand

(9) M. Born, “Cause and Risk Evaluation for High-temperature Chlorine Corrosion,” VGB PowerTech 5, 2005

(10) VGB Powertech e.V., VGB-R 108: Fire Protection in Power Plants, Essen, 2009

(11) VGB Powertech e.V., “Fire and Explosion Protection in Biomass Fired Power Plants”, Essen, expected in 2012


(14) Italian Ministry for the Economic Development, Ministerial Decree 06.07.2012


6 Appendix A – DEBCO project power plants

6.1 Rodenhuize Power Plant

One of the key case studies on the power plant and boiler modifications for biomass co-firing is the Rodenhuize Advanced Green and Max Green project, which involved all of the engineering and other activities specific to the co-firing and firing of wood pellets.

Main information on Rodenhuize Unit 4:

- **Type:** Opposed wall fired outdoor water-tube boiler with natural circulation and gastight walls.
- **Make:** Brouhon under Riley licence
- **Year of construction:** 1974
- **Design fuel:** BFG and HFO
- **Power:** 745 MW\textsubscript{in} / 285 MW\textsubscript{el} (original design)
- **Conversions:**
  - 1989 converted to coal firing
  - 2005 converted to 65 MW\textsubscript{el} pellet co-firing with coal (“Light Green”)
  - 2008 converted to 135 MW\textsubscript{el} pellet co-firing with coal (“Advanced Green”)
  - 2011 converted to 560 MW\textsubscript{in} / 195 MW\textsubscript{el} 100% wood pellet firing (“Max Green”)

- **Max Green fuel:** Industrial wood pellets

The conversion of the unit 4 to 100% biomass firing was a stepwise process with a gradual increase of the biomass co-firing rate.

The biomass milling plant consists of three more or less identical systems, each comprising:

- A buffer silo of 2,000 m\textsuperscript{3};
- 4 fast rotating hammer mills of 10-13.5 t/h each
- Pneumatic transport system for wood dust transport to the burners.

6.1.1 Retrofitting

**Biomass handling and storage**

The ship unloading activities and long storage of the pellets is subcontracted to the Ghent Coal Terminal (GCT), and takes place on land adjacent to the power plant site. The pellets are unloaded by means of a Grab crane and stored in a large warehouse.

From the warehouse, the pellets are conveyed by covered belt conveyor to the day silos at the Max Green milling installation. The wood dust emissions to the environment are reduced to a minimum by means of an adequate de-dusting/extraction system (Lysair) on chutes and discharge points.

For risk mitigation, it is recommended that the necessary pre-cleaning devices are installed upstream of the main storage facility to avoid tramp and oversize material entering the storage.
Main storage

For the Max Green project, pellets are stored in a large automated warehouse. Large silos could also be considered for large scale biomass storage.

The key points of attention for such facilities are:

- The installation of explosion panels to prevent further damage to the silo by venting the overpressure, in case of an explosion;
- CO/CO\textsubscript{2} detection and monitoring is advised for the early detection of the presence of smouldering material or auto-combustion in the biomass;
- The possibility of inerting with CO\textsubscript{2} or N\textsubscript{2} in the case of a smouldering fire in the silo should be considered;
- The possibility for fast evacuation of the content of the silo via access doors for wheel loaders, should be considered,
- The installation of fire detection and fire fighting system is required;
- The limitation of horizontal surfaces inside the storage where dust can settle is recommended to reduce the risk of secondary explosions;
- The prevention of water infiltration and the formation of condensation is recommended to keep the fuel as dry as possible and minimise the risks of microbial respiration.

![Figure 4: Biomass storage milling unit (1/3).](image)

Day storage

The on-site day storage for the pellets consists of 3 x 2,000 m\textsuperscript{3}, i.e. around 32 hours buffer storage capacity, in conic bottom, steel silos, with a rotary fuel reclaimer mounted at ground level. From the day silo, a chain conveyor transports the pellets to a small buffer silo of 50 m\textsuperscript{3} capacity located on top of the hammer mill building, from where the pellets are distributed to the four mills. The chain conveyor has a maximum incline of 45°.
**Milling**

The hammer mills are located in a separate concrete building to reduce noise emissions. Each mill is located in a separate room to reduce fire propagation and to allow separate maintenance. The building is equipped with all necessary accessories to ensure good working and maintenance conditions.

To reduce fire and explosion risk and to increase the lifetime of the hammers, additional cleaning equipment is installed upstream of each mill:

- A vibrating screen for separation of oversize material,
- A ferromagnetic drum separator, and
- An air classifier to remove heavy particles.

The amount of UBC in the ash discards was not considered as a major consideration for Max Green, a once-through milling system, without wood dust oversize screening and re-milling, was adopted.

For Max Green, fast rotating mills by Sprout Matador, were selected. Each mill has a nominal throughput capacity of 10 t/h. The product particle size distribution and the throughput depend the mill screen size. At Rodenhuize, a hammer mill product with a 2.5-3 mm topsize results in a sufficient fineness taking into account boiler impact and UBC amount.

**Feeding**

A pneumatic conveying system is used to transport the milled wood dust from the 12 hammer mills to the 24 burners of the boiler. Based on experiences from other projects, each blower feeds a single pneumatic conveying pipe. Despite the higher investments costs, this solution has important advantages:

- No splitting of the biomass stream in the pneumatic conveying ducting, which reduces the risk of blockage,
- Good control over the dust-air ratio
- Constant and controllable wood dust flows.

The dust/air ratio is an important parameter, which is controlled to ensure proper operation of the burners. Excessive dust/air ratios might cause pulsations and have a negative impact on the combustion prices.

**Boiler modification**

Rodenhuize Unit 4 also serves as back-up for a new, dedicated Blast Furnace Gas (BFG) unit located on the Arcelor-Mittal site. The boiler was retrofitted to operate on the following fuels and capacities:

- 560 MW<sub>n</sub> on BFG
- 200 MW<sub>n</sub> on natural gas (only during start-up)
- 560 MW<sub>n</sub> on biomass (industrial wood pellets)

The emission requirements (at 11% O<sub>2</sub>, dry) are:

- NO<sub>x</sub>: &lt;60 mg/Nm<sup>3</sup> (BAT)
- SO<sub>x</sub>: &lt;50 mg/Nm<sup>3</sup>
- Dust: &lt;10 mg/Nm<sup>3</sup>

Light Green: Co-firing of pulverised wood pellets at row 2 (40 t/h)

Advanced Green: Co-firing of pulverised wood pellets at row 2+3 (80 t/h)

Start-up fuel changed from HFO to NG
Max Green: Co-firing of pulverised wood pellets at row 1+2+3 (120 t/h)
BFG burners level 5 to level 2.

The major system modifications, in the framework of Max Green, have been:
- NOx abatement system in the flue gas line to meet the BAT emission limits for NOx
- Retrofit of the ESP to increase its lifetime and to meet the dust emission limit;
- Renewing electrical motors for the ID fans
- Modifications to CW pump to improve efficiency
- New FW pump (incl. Motor and VSD) with higher efficiency
- New DCS/Control system

**Figure 5:** a) after conversion to coal; b) Advanced Green, wood dust firing @ rows 2 & 3; c) Max Green wood dust firing @ rows 1,2 & 3.

**BFG burners/NG burners**

The BFG burners are out of service most of the time, and the cooling of the large furnace openings, of greater than 1.2 m in diameter), has to be ensured properly, while minimising the negative impact of the cooling air flow on the biomass combustion zone. As shown in Figure 5, a number of the BFG burners are located at the same level as the biomass burners. It was decided, after several CFD studies, to use low temperature re-circulated flue gas, taken after air heater and ESP, as the cooling medium, because of its lower oxygen content compared to combustion air. This tended to limit the disturbance of the biomass flame controlled by undesired air entrance into the boiler. Thereby, the re-circulated flue gas circuit has been completely modified to ensure the effective cooling of the BFG burners.

To create the optimal conditions for the biomass combustion, i.e. ensuring good flame stability without support fuel and minimising the NO and CO emissions, it is necessary to match the combustion air supply closely to the fuel flow. The NG burners are combined with the biomass burners on levels 1 and 3 to reduce the number of new furnace penetrations, and hence minimise air in-leakage.

The position of the burners for biomass, NG and BFG has been studied extensively using CFD modelling techniques. The furnace heat fluxes, the flue gas temperatures and temperatures of heat exchangers have all been studied in detail to help avoid damage and accelerated ageing of the existing boiler pressure parts. The results of the CFD studies led to the relocation of the BFG burners, among other modifications.
**Burner modifications**

The selected technology for biomass combustion within the Max Green project is pulverized fuel firing into the existing boiler furnace. This is the most effective in terms of CAPEX and OPEX for the combustion of biomass in dry pellet form. In terms of CAPEX this technology allows the reuse of the pressure parts in the furnace and boiler, except for the modification of the burners and OFA ports.

In terms of OPEX this technology allows high combustion efficiency in comparison to the fluidized bed technology which operates at lower furnace temperature. This results in a measured boiler efficiency in excess of 90%.

The existing coal burners have been modified significantly in order to cope with the new type and quantity of biomass fuel.

New materials have been used on the most critical parts of the burner to minimise the erosion rates. The first section of the primary air pipe has been completely covered by ceramic tiles. The shape of the first section of the primary air is hexagonal. This particular shape has several advantages:

- The kinetic energy of the wood dust particles is partly absorbed by the edge of the hexagon which is perpendicular to the wood dust flow at the entrance of the burner.
- The hexagon shape allows a good distribution of the wood dust all around the primary air tube.
- Finally because the hexagon is a symmetric shape the primary air tube can be turned by 180° in order to extend the lifetime of the primary air tube by presenting another side to the inlet wood dust flow (the side of the hexagon directly impacted is obviously exposed to the highest erosion rate).

The wood dust is transported in dense phase independently from the primary air and is injected in a concentric way inside the primary pipe about one meter upstream of the inlet to the burner. From the injection point of the wood dust inside the primary air pipe every parts of piping subject to erosion have been covered by ceramic tiles. The inner side of the secondary air pipe in contact with the wood dust has been protected from erosion by using hard-facing by welding.

Another challenge was to ensure efficient combustion of the milled biomass without any support fuel. Prior to the Max Green project, Unit 4 at Rodenhuiize was co-firing up to 50% biomass with coal through a number of the burners. In this operating condition, the coal combustion was well controlled, but the biomass combustion was more erratic, and was supported by the pulverised coal flames. It is considered that the wood particle velocity was far too high and the wood particles were hitting the opposite membrane walls without burning.

During the Max Green project the burners have been converted for 100% biomass combustion. The combustion parameters have been modified, based on the results experimental tests, to obtain a self-sustaining stable flame at the outlet of each burner. The main parameters influencing the combustion process were the primary air temperature and flow, the secondary air flow and the secondary air swirl.

The boiler start-up is carried out with natural gas support. The current start-up procedure is designed to minimise the requirement for natural gas support, before the establishment of a stable flame on 100% biomass. A complex combustion air regulation sequence during start-up has been implemented to reduce the start-up period using natural gas.

The installed sootblowing system was not modified for the Max Green project. It is considered, however, that improved sootblowing systems in the convection and radiation part
of the boiler may be required in cases where more severe slagging and fouling is expected after conversion to 100% biomass firing.

**Dust abatement**

The existing electrostatic precipitator of the Rodenhuize 4 was designed for the treatment of flue gas issued from the coal combustion and for dust concentration at the stack of 80 mg/Nm³ at 6% O₂, dry gas. The future emissions values for this plant are 15 mg/Nm³ at 6% O₂, dry gas.

In the framework of the Max-Green project, the existing ESP filter was retrofitted:

- To increase the remaining lifetime of the filter,
- To improve the dust capture efficiency to meet the new emission level.

The performance of the ESP filter depends, among other things, on the contact time between the flue gases and the collector electrodes of the filter, and the performance of the filter can be improved by increasing the surfaces of the collecting plates.

The experience from Rodenhuize indicates that for 100% wood dust firing a dust emission level around 7-8 mg/Nm³ requires a contact time of 27.5 seconds.

The particle contact time is dependent on the flue gas flow rate which is different for biomass firing. Although the biomass materials have relatively low ash contents, the ash particles tend to be smaller than coal fly ash and are more difficult to capture.

The optimisation of the ESP filter consisted of moving the insulators to the filter top casing to increase by about 20% the length of the collector plates. This design optimisation involved:

- Replacement of the discharge electrodes (DE) of the filter.
- Modification of the ESP filter top casing to put the insulators on top.
- Modification of the collector plates, to increase width of passage from 300 mm to 400 mm (now standard) increase length (horizontal) of the collector plates;
- The installation of a new rapping system.
- In case the space in between the CE plates would be increased from 300 mm to 400 mm, the secondary voltage (HS Trafos) has to be increased accordingly.

An alternative solution for the increase of the dust capture performance is a so called “Hybrid system”, which has a fabric filter installed in the last fields:

- the first field remains ESP;
- the ESP fields 2-4 are replaced with a fabric filter.

Normally such a modification can be carried out within an existing casing of an ESP filter. However, this has to be evaluated case by case.

**DeNOx**

The combustion process releases NOₓ, which mainly result from the oxidation of the molecular nitrogen N₂ contained into the combustion air, and chemically bound nitrogen N contained into the fuel. A third reaction exists, the reaction of molecular nitrogen N₂ with hydrocarbon radical, but its incidence on NOₓ formation is minimal.

The factors which affect the NOₓ emissions are the fuel specification, the combustion chamber temperature and the flame temperature, the residence time, the excess air level, and the fuel particle sizes.

As a primary NOₓ reduction measure, low NOₓ burners have been installed, combined with an OFA system, which provide low excess air combustion at burner level, for NOₓ control with acceptable burnout levels.
To achieve the required NOx emission limits of 90 mg/Nm³ at 6% O₂ secondary NOx reduction measure were required. The installation of a Selective Catalytic Reduction system was proposed. This technology is well known in case of coal combustion, but there was no experience with the 100% wood pellets pulsed boiler with high-dust SCR system at the beginning of the Max Green project.

The main first challenge was to define the catalyst and SCR design parameters, i.e. the catalyst formulation, catalyst geometry, reactor sizing, design temperature, NH₃ slip design and SO₂ conversion, in order to make it suitable for the requirements of the Max Green project.

Based on the test results from a high-dust SCR pilot installation of Laborelec on a 100% wood pellet boiler, it was possible to choose all the design parameters to maximise the catalyst lifetime and to get all the typical guarantees for such a SCR retrofit. The performance of the SCR system designed for the Max Green project represents therefore a technical significant achievement for Electrabel, Laborelec and Tractebel Engineering.

The most relevant flue gas parameters are:

**Flue gas composition:**

- The combustion of wood pellets results in flue gas with the higher concentrations of some volatile poisonous components for the catalyst, principally the alkali metals and some of the trace elements. These elements can have a direct impact on the life time of the catalyst, and therefore on the catalyst formulation and SCR design.
- The flue gas from biomass combustion contains lower fly ash concentrations but higher levels of alkali metals, leading to a different catalyst geometry and different NH₃ slip design.
- The SO₂ concentrations in the flue gas with 100% wood combustion are very low. This has an impact on the SO₂ conversion level and the SCR design.

**Flue gas temperature:**

- The experience has been that the conversion from coal to 100% wood resulted in lower flue gas temperature after the economiser. In combination with the low SO₂ concentrations in the flue gas, the lower working temperature of the DeNOx catalyst allows adaptation of the catalyst formulation in order to increase its activity, without the risk of SO₃ related problems in the DeNOx reactor and in the air pre-heater. To increase the catalyst activity, the concentrations of the active catalyst elements (vanadium, tungsten, molybdenum) are typically increased.
- There has been a significant CAPEX decrease resulting from the absence of the requirement to split the economiser surface to maintain the SCR temperature at part load.

**Flue gas flow:**

- The SCR reactor is designed to ensure an allowable performance when firing BFG, i.e. higher flue gas flow rates and no SCR by-pass.
- This design also ensures an advantageous area velocity for the biomass mode, not taking into account the requirement for flue gas recirculation on the burner levels to cool the BFG burners.

Taking into account these project specific factors for the Max Green project, a 3+1 catalyst layer SCR reactor was installed in order to ensure the required NOx reduction and acceptable catalyst life time.

At the Rodenhuize power station a 24.5% NH₄OH solution is evaporated and directly injected in the flue gases, without first mixing with hot air. This solution reduces the consumption of
auxiliary steam or electricity and limits the loss of efficiency due to steam extraction on the turbine.

A second challenge was linked to the integration of the SCR reactor in the already very congested flue gas duct area. The SCR reactor is located above the air pre-heaters, between the furnace chamber and the ESP. A substantial steel structure of about 1,000 tonnes supporting the 400-tonne reactor had to be installed and supported by substantial foundations, in order to reach the boiler outlet duct located at an elevation of 70 m.

**DeSOx**

Because of the low sulphur content in the industrial wood pellets, the SO₂ concentrations in the flue gases remain below the emission limit without the requirement for additional deSO₂ equipment in the flue gas system.

### 6.1.2 Combustion and boiler performance

**Boiler performance at 50% biomass thermal input**

During the Advanced Green phase, wood pellets were fired on the boiler rows 2 and 3. The lower row 1 was used for coal. The existing coal burners and part of the pulverized coal transport system were reused for wood. The wood combustion was problematic in the Advanced Green configuration. Owing to the large size of the biggest particles, the worse particle size distribution and the irregular shape of wood particles compared to PC particles, the fuel feeding resulted rather difficult, especially where the pipes bend. In order to avoid pulsing and sedimentation in the fuel lines and to overcome the pressure losses, the feeding velocity had to be kept very high (30 m/s or even faster). This resulted in a too high velocity at the burner outlet, causing the flame to be very unstable and not attached to the burner. The pulverized wood was even "projected" in the boiler, which caused flame impingement to the opposite and side walls, a bad combustion with a large amount of UBC in the bottom and fly ash, post-combustion in the convective part and increased slagging and fouling in the combustion chamber as well as at the convective part inlet. The burnout was not complete at 43 meters and it is known that secondary combustion of coarse particles on heat transfer surfaces can create local reducing zones that favour slagging.

**Boiler performance at 100% biomass input**

After changing the burners and modifying the boiler for the Max Green configuration as described in chapter 3, the combustion resulted much more stable, with much less slagging, UBC in the ashes, no flame impingement.

**Slagging and fouling**

As main conclusion of the deposit analyses on the probes, it came out that there was a spread of molten salts which causes a sulphate layer on the metal surface, with cracks and loss of the oxide layer as a consequence. The particles were large and sintered, and problematic to clean. The recommendations were to maintain a stable and constant firing system, to avoid fluctuating temperatures, and to be sure that the protective oxide layer on the tubes was good before co-combustion of biomass.

Another finding was the confirmation of the post-combustion of particles in the convective part. The burn-out was not complete at 43 meters and it is known that secondary combustion of coarse particles on heat transfer surfaces can create local reducing zones that favour slagging.

The ash fusion temperature, more specifically the initial deformation temperature of the wood ashes at that time, was about 1150 °C, which is low compared to coal.

After the first months of Max Green operation, slagging has increased considerably, resulting in stops for manual cleaning. The origin of the slagging is probably a decreased pellet
quality, but also combustion problems can be at the origin. In order to analyse and remediate the problem, following action scheme is set up:

- Follow up the pellet quality more frequently and accurately;
- Install a 2D temperature mapping, as knowing the temperature profile is necessary to keep the combustion process under control and to reveal potential problems;
- Optimise the sootblowing system (the most recent developments such as “intelligent sootblowing” systems are examples of strongly optimised sootblowing with much better results and less medium consumption than former systems);
- Follow up the post-combustion in the convective part, as this can also lead to increased slagging;
- Optimise the air repartition (swirl, secondary/tertiary air, etc.).

### 6.1.3 Air pollution control devices

**Evaluation of SCR performance**

Biomass combustion reduced the NOx emissions. The NOx reduction was about 55% in average. The slightly more than half reduction may indicate the need to improve the performance of the catalyst by operational controls and the ammonia distribution or flow.

Measures of NH3 slip after catalyst have shown very low concentrations. The stoichiometry between NH3 and NOx were estimated below or near 1 in all the investigated periods. This shows that the ammonia flow for the NOx reduction was not high enough to reach optimal conditions in the catalyst. This also would explain the low NOx conversion.

**Evaluation of ESP performance**

The dust composition during Max Green tests after retrofitting showed that the CaO, SiO2 and K2O contents are the major compounds. This implicates that most of the alkali and sulphur of the biomass ends up in the fly ash. A high amount of UBC in the fly ash (14%) shows that the incineration of the biomass particles was not satisfying.

There was a big influence of dust removal efficiency before and after retrofitting of ESP. Higher dust emissions before ESP have been measured during 50% co-firing scenario compared to 100% wood firing, due to higher ash content in the fuel. Nevertheless the dust emissions after ESP to stack were similar for both firing scenarios. Before and after the boiler retrofit, PM1 fraction after the ESP (emitted to stack) represents 70% by weight of the total dust load.

The composition of the fine fractions during 100% wood and 50/50 wood/coal scenario is similar. While the coarse fraction contains mainly alumina silicates which have been separated in the ESP, the fine fraction is composed mainly by salts KCl, NaCl, K2SO4, CaSO4.

**Evaluation of gas emissions**

NOx emissions are in a small range and the SO2 emissions are mostly low and can be attributed to a low amount of sulphur in the biomass and the neutralization effect of the fly ash with high alkali- and calcium oxide content. Only some peaks are detected. The peaks for the CO emission are much stronger and can be attributed to the soot blowing activities. The dust emission was very low due to the fact that the ESP was retrofitted with enhancements to the flow pattern and electrical part and is oversized because of the higher ash content of the coal for which it was designed.
6.1.4 Utilisation of residues

At Rodenhuize PP the amount of wood pellet co-firing was increased from 25 to 50% (Advanced Green) and later 100% wood pellet was fuelled (Max Green). Wood pellet fuels of the type fired at Rodenhuize have a fairly wide range of chemical compositions, normally depending on the level of bark present. The wood pellets have much lower ash contents (0.6-2.3%) than most coals and, as a consequence, the co-firing of wood pellets normally has only a modest impact on the chemistry of the mixed ash produced. In most systems, the control of the UBC levels in the ashes can be controlled by the maintenance of acceptable combustion conditions. The industry has already agreed on a quality scheme for wood pellets which help to maintain adequate control over the ash levels in the wood fuels. These standards will normally permit the ash quality standards for the products of the co-firing of these fuels to be met under normal combustion conditions.

At present, the standard for fly ash for concrete EN 450-1 (13) restricts the amount of co-firing to 20% by mass. However, due to the experience with co-firing over the past few years, the level of co-firing will be increased to 40% by mass, and 50% by mass in case of green wood. The results of the ash tests for wood pellets co-firing within DEBCO are consistent with this revision of the standard.

100% wood pellet combustion

With 100% wood pellet combustion, the ash residues differ significantly from those originating from coal combustion and from co-firing. The ashes are rich in calcium- and magnesium oxide, alkali metals, phosphate and sulphur. The levels of silica, alumina and iron oxide are lower, as would be expected for wood ash. For utilisation of this material as a constituent of cement, it will be the task of the cement producer to decide about the ratio of this ash in his raw meal mix.

The ash may be used as a lime or an alkali agent, and its use as a low grade fertiliser can be considered. These applications may be restricted by trace elements contents, and these need to be considered for a specific country or region and for the respective national and/or regional requirements.
6.2 Kardia and Meliti Power Plants (agricultural biomass/lignite co-firing)

All the information related to agricultural (olive kernel, cardoon) biomass/lignite co-firing is based on experimental tests performed on Kardia PP and Meliti PP.

The results related to biomass/lignite co-firing are based on experimental campaigns performed on the Unit 1 of Kardia PP with cardoon as biomass at 10% thermal share (3% by weight).

The chemical analysis of lignite, cardoon and the mixture shows a difference especially in nitrogen, sulphur and chlorine content. However, other chemical analysis show a broad variation in the lignite itself, which can affect the values of the mixture in larger amount than cardoon at 10% thermal share actually does.

Kardia power plant is located in the Region of West Macedonia, near the cities of Ptolemaida and Kozani and utilises indigenous low-rank coal (lignite) from the nearby Kardia open-cast mine. Kardia consists of four units: Units 1 and 2 (built in 1974 and 1975) with an installed capacity of 300 MW<sub>el</sub>, Units 3 and 4 (built in 1980 and 1981) with an installed capacity of 325 MW<sub>el</sub>. Each unit consists of a supercritical Benson type once-through boiler with single reheat. After passing through the convective section of the boiler, the flue gas is led to the air pre-heater before passing through the ESPs and the stack. Figure 6 presents an overview of the boiler.

The plant is fuelled with lignite from the nearby Kardia mine, which is transferred via a conveyor belt system and unloaded to a storage space or distributed to the belts of the coal handling.

No DeNOx unit is installed at the Kardia PP. Furthermore, due to the high content of calcium in the fuel ash, flue gas desulphurization is not required.

The Meliti PP is located in the Region of Western Macedonia, near the city of Florina and close to the border with FYROM (Former Yugoslav Republic Of Macedonia).

The Meliti PP consists of one unit with an installed capacity of 330 MW<sub>el</sub>. Commissioned in 2004, it is the newest and one of the most efficient lignite-fired power plants of PPC. In contrast with the other lignite-fired power plants operating in Greece, Meliti PP was designed for combustion of xylite / lignite, with the percentage of the former being up to 32%. Xylite is a brown coal of similar rank with lignite. However, the lignite is a lithotype with a matrix coal derived from marsh reeds, sedges, etc., which are rich in cellulose, while the xylite is a lithotype rich in woody material with over 10% stems and rich in lignin.

This required special considerations in the design of the boiler and the milling system. In addition, in order to conform to the increasing stricter environmental regulations in the EU, the Meliti PP was designed as a supercritical boiler, with maximum steam parameters of 235 bar / 543 °C, and with integrated measures of emission control, such as Over-Fire Air (OFA) as a primary measure for NOx reduction and a Flue Gas Desulphurization (FGD) unit to minimise SOx.

Co-firing tests have been performed in order to identify technical problems that should be avoided during the permanent operation with secondary fuels, planned until 2022. Public Power Corporation (PPC) organised and carried out the co-firing trials in the older 300-MW<sub>el</sub> lignite-fired units, while CERTH contributed to the evaluation of results, as regards to operational malfunctions. The tested biomass fuels have been separately olive kernels and cardoons. The biomass was loaded to the feeding system and mixed with lignite before the crushers. The plant was tested at 255-290 MW<sub>el</sub> with 10% biomass thermal share.
6.2.1 Handling, storage and milling

The existing secondary fuel handling system of Kardia PP is capable of handling biomass fuels with characteristics similar to olive kernels (small particle size, grindability comparable to fossil fuels and not herbaceous biomass). On the contrary, it is unsuitable for handling baled biomass, since constant feeding is not assured. Accumulation of biomass appears to be the main issue, while suitable particle size reduction is not guaranteed. The mill recirculation system can be bypassed even by quite large biomass particles. This might be a risk factor.

The existing, not for biomass optimised, fuel handling system has little difficulties with olive kernels.

Feeding system. No material accumulation was attested in any part of the feeding system during co-firing with olive kernels, whereas significant cardoon quantities were found practically blocked in several places along the feeding line when baled biomass was used. The feeding of a homogenized mixture of chopped cardoons and lignite at Kardia PP and of pellets and lignite at Meliti PP did not cause any feeding issues; however, it required significant planning on the part of the coal yard operator and increased expenditures for the fuel mixing.

Mills. No mill energy increase correlated with co-firing was detected. However, the fuel grindability during the co-firing test was 0.5% lower at the 1-mm sieve and 1.75% lower at the 200 µm sieve compared to the tests without co-firing. Furthermore, after the test with baled cardoon, significant biomass accumulation was found in the mills, even in the ones not used for cardoon. In fact, fibrous material like cardoon is difficult to be crushed with beater mills; the portion of coarse grain is high and, consequently, the combustion performance is reduced. Anyhow, the mill performance regarding the lignite appears unaffected by the presence of small quantities of herbaceous biomass. As for the temperature in the mills, no increase was detected. The temperature values were within the usual range of mill operation (90 – 135 °C) and well within the safe operation limits.
No impact on mill operation was detected for the co-milling of a lignite / pellet mixture at Kardia PP.
Summarising, the handling of baled cardoon has been proved to be difficult and to require dedicated solutions. Delivering cardoon as chopped material made possible the production of a homogenized fuel mixture in the yard that was used during measurements. Moreover, owing to the low weight of the material, even the presence of wind can be an issue. Nevertheless, an investment in a permanent milling and feeding system for biomass might be useful even for olive kernels.

### 6.2.2 Boiler modification

CFD simulations were realised with commercial software. The scope of the activities was to identify the optimum size of the biomass particles for the co-firing ratio to be used. One of the most important properties of the biomass particles is the non-roundness. Therefore, updated models for biomass combustion and equation of motion were implemented in the CFD model. The investigations were mostly focused on the effect of the biomass particle size on the fuel burnout. Different options of biomass feeding were investigated to identify the optimum positions for biomass injection. Based on the reference case (lignite feeding at nominal load), differences were estimated in the combustion performance when adding biomass. The results include calculations on velocity and temperature fields. Other parameters, such as NOx emissions, were also considered and heat and mass balance calculations result for the various co-firing scenarios.

![Boiler geometry of Kardia PP and schematic representation of simulated burner geometry.](image)

**Figure 7:** Boiler geometry of Kardia PP and schematic representation of simulated burner geometry.
Operating Scenarios

CFD simulations were performed based on current full-load operating conditions for lignite combustion and heat and mass balance calculations results for the various co-firing scenarios.

The biomass particle size is a key parameter in the evaluation of CFD results. Thereby, a number of cases were considered.

Two biomass diameters are examined (1 mm and 5 mm). The smaller particle size corresponds to typical biomass size for co-firing applications and can be achieved through a separate size-reduction step. The larger particle size, which is somewhat higher than the typical size ranges for co-firing, is achieved directly at the field when the collection of cardoon is performed with forage harvesters.

Results of the CFD modeling

- Overall, several important operational parameters are unaffected by co-firing biomass at low thermal loading: the furnace exit temperature is only slightly increased, so there is no expectancy of intensifying slagging/fouling phenomena related to the lignite particles in comparison with the reference operational scenario. The total heat transfer to the furnace wall is likewise unaffected. CFD analysis suggests that a potential benefit of co-firing conditions is a decrease of NOx emissions up to 10%, mostly due to the lower nitrogen content of the biomass fuel and the respective mechanism for fuel NOx formation. This trend is well attested by literature and pilot scale testing, but not by short term testing in the examined large scale boiler.

- The main impact of co-firing concerns the char burnout for lignite and biomass. UBC losses from the hopper are increased for lignite particles under co-firing, while the burnout of the particles exiting through the main outlet is largely unaffected. For biomass particles, the size is of outmost importance; particles with an equivalent diameter of 5 mm do not fall through the hopper unless they enter through the lower main burner, but exhibit very low char burnouts despite increased residence times. Smaller particles, with an equivalent diameter of 1 mm, exhibit very high char burnouts for all burner levels, despite being at least one size category larger than lignite particles. The increased hopper losses during co-firing of large biomass particle have been verified by experimental results of a co-firing campaign at Kardia.

- Particles entering the furnace through the lower main burner differ significantly in their trajectories compared to all other burner levels. The recirculation zone of the flow field in the upper hopper region tends to increase the trajectories and residence time of several particles, which fall initially into the hopper region and then find their way in the upward current as they gradually loss weight. On the other hand, depending on flow field intensity and particle density, a number of particles leave the furnace from the hopper with relatively high UBC content.

- Biomass particles that have undergone significant size reduction before entering the furnace pose no significant problems in the boiler operation. Larger biomass particles, which are not subjected to separate size reduction or for which current size reduction techniques are ineffective, increase the UBC content in the hopper and fly ash. Although the overall boiler combustion efficiency is not greatly decreased due to the low fixed carbon content of the biomass particles, other issues may occur, such as sintering of unburned fly ash particles at heat exchange surfaces or problems in the fly and bottom ash disposal routes due to higher UBC content. The intensity of these problems will increase with higher co-firing ratios.

- In conclusion, for the investigated boiler there appear to be two potential co-firing schemes, which should be further evaluated according to techno-economic criteria.
The first concept ensures adequate biomass size reduction, which can then be mixed with the lignite stream. Combustion is ensured regardless of the burner level of biomass entry. The second concept does not rely so much on milling, although some size criteria must be fulfilled before biomass particles are injected in the boiler. Instead, a separate feeding system is used to inject the biomass at an optimum position for maximum burnout. Based on the above findings, such an injection point should be located between the lower and upper main burner. The retrofitting of one or more oil burner for biomass injection is such a possibility.

6.2.3 Combustion and boiler performance

The boiler efficiency resulted not influenced by a biomass thermal share as low as 10%.

Mean values of the flue gas temperatures at various heights along the boiler, as well as after the ESPs, were measured. No significant changes were observed during co-firing.

The flue gas volume showed only one small decrease of 2% during co-firing. With regard to the composition, it resulted that:

- The oxygen content was almost constant and within the range 5-7% during the high-demand hours, rising to more than 11% during the night. This increase can be correlated to the corresponding decrease in load and to changes in the lignite quality.
- The CO emissions, which are an indication of the combustion efficiency, showed no significant changes during for co-firing.
- The SO2 emissions fluctuated greatly for co-firing, while coal firing presented a more clear figure, with sporadic peaks upwards. In all cases, however, SO2 emissions remained much lower than the limit of 400 mg/Nm3. The fluctuations can be attributed to changes of the CaO content in the ash, which can capture SO2 and form CaSO4. Furthermore, decreases in dust emissions concurring with SO2 increases and vice versa can be observed. In fact, SO2 influences the electrical conductivity of the flue gas, so that higher contents improve the ESP performances.
- The influence of the co-firing on the NOx-emission was (490±10) mg/m³ without co-firing and (458±32) mg/m³ with co-firing. In this context the origin of the biofuel may be important: agricultural waste produced under application of fertilisers may influence the production of NOx during the thermal utilisation. Furthermore, NOx is a function of the excess air, which increases in low-load operation caused by the cooling air for the burners not in operation.
- Dust emissions exhibited large variations during co-firing, as a result of lignite quality changes and ESP operation. A large decrease of dust emissions was observed upon firing of lignite with lower calcium content; this was accompanied by an increase of SO2 emissions, as discussed above.

Concluding, no negative effects of biomass co-firing on load, emissions or other operational parameters were observed. Unburned material content in the fly ash depending on the grindability also appears to remain the same, although a more intensive sampling should clarify the issue.

The only noticeable difference was an increase of UBC (and LOI) in the bottom ash during cardoon co-firing. The UBC resulted nearly doubled compared to pure lignite combustion.

From a technical point of view, olive kernel biomass is a promising candidate for co-firing, especially at the Kardia PP. For a permanent application, a more intensive investigation, focusing on slagging/fouling, should be undertaken. Some technical modifications should also be implemented, e.g. construction of suitable storage area and fuel weighting for the exact determination of CO2 savings.
Slagging and fouling

Fuel samples were collected and analysed in both cases of pure lignite and lignite with 10% cardoon. The representative ash components of the lignite/biomass mixture resulted in the range of the pure lignite, as well as the slagging behaviour and the ash melting temperature. Therefore, no influence of cardoon co-firing at 10% thermal share can be observed on the slagging behaviour in the boiler.

6.2.4 Air pollution control devices

ESP performance

The ESP performance of the unit under co-firing operation was measured using a cascade impactor; fly ash samples were taken directly before and after the ESP at a flue gas temperature of about 180 °C. The dust content before the ESP was very high owing to the high ash content of lignite. Generally, the ESP efficiency was very high, around 95.5%; however, the dust concentration after the ESP as measured was also high. In addition, the particle sizes of the collected samples revealed the emission of fine particles (PM 2.5) and aerosols into the atmosphere.

Fly ash particles consist of coarse particulates, which represent the largest fraction by weight in the cascade impactor samples before and after the ESP. Generally, the size of the fly ash particles does not exceed 20 µm. Further, the UBC has been identified and the submicron fraction, which exhibit 30% by weight of the total of the cascade impactor dust sample.

As can be expected from the fuel ash composition, calcium is the dominant specie of the dust particles, regardless of their size. Coarser particles, collected in the first stages of the impactor, represent the larger weight fraction and are mainly composed of lime and silicates. In the fine fraction (< 1 µm) the higher sulphur concentration reveals the presence of CaSO₄, as a result of the natural desulphurisation of the flue gas. Iron and potassium in the form of K₂SO₄ were also more prevalent in the fine fraction.

The high alkali and chlorine content of cardoon in particular did not appear to have a significant effect on the operation. Based on the findings of the measurement campaign, it appears that the relatively high sulfur content of lignite facilitated the sulphurisation of alkalis, which are characterised by higher melting points compared to alkali chlorides. Chlorine was present in very low concentrations in the deposits and as HCl in the gas phase; a possible mechanism for the fate of chloride is the reaction of gas phase HCl with lime in the fly ash and its retention in the fly ash particles.

Finally, no major impact of 10% cardoon biomass co-firing could be observed during the measurement campaign.

Evaluation of gas emissions

It should be noted that, apart from SO₂, the NOx and dust emission values are beyond the limits of Directive 2010/75/EU (IED) (12), which will come into force in 2016. Thus, for continued operation of the power plant, extensive retrofitting and the installation of more APCDs are required.
6.2.5 Utilisation of residues

At Kardia PP, co-firing was tested up to 10% cardoon thermal share. The main fuel of the plant is lignite from nearby lignite mines. A number of different lignite types are fired and a relatively wide range for the ash chemical parameters have to be considered. The cardoon biomass used for the tests is characterised by an ash content ranging from 9.5 to 14.5% by mass. The impact of co-firing on the ash quality was modest and, in general terms, the co-firing of the biomass resulted in a more consistent ash chemical composition than for the normal lignite fuel diet.

As the investigated ashes from lignite are not covered in the fly ash standard for concrete and as the chemical composition of these ashes is varying widely for a use as construction material, as e.g. filling material, the physical properties have to be considered more intensively as well as the trace element concentration, especially for the leaching limit values. If the co-firing is combined with lignite from a specific seam, also ash qualities for the use in cement and concrete may be obtained.
6.3 Fusina Power Plant (RDF co-firing)

Fusina Power Plant is located in North-Eastern Italy, in the neighbourhood of the Venice area.

The power plant consists of four pulverised coal (PC) fired units: two 160-MW_{el} boilers (Units 1 and 2), and two 320-MW_{el} boilers (Units 3 and 4).

Units 3 and 4 are tangentially fired dry-bottom boilers, equipped with a Low NOx Concentric Firing System (LNCFS) designed by Alstom Combustion Engineering (formerly ABB), a Selective Catalytic Reactor (SCR) for final NOx reduction, an electrostatic precipitator (ESP) and a flue gas desulphurization (FGD) system. The SCR consists of three layers of vanadium pentoxide catalyst (V_{2}O_{5} at 0.6 %). The ESP is equipped with 7 electric fields with five fields in operation at maximum voltage. The FGD consists of a pre-scrubber with two levels of sprinklers and a main scrubber with six levels of sprinklers fed by six suspension circulating pumps, five of which operate continuously.

In February 2009, it was authorised to co-fire 70,000 tonnes/year of RDF (Refuse Derived Fuel) up to 5% thermal input in two units. The RDF consists of separated municipal solid waste submitted to a bio-stabilisation process and delivered at the power plant as cylindrical pellets. The separately milled RDF is pneumatically injected into the pulverized coal pipelines before the primary air fans at the 2\textsuperscript{nd} and the 3\textsuperscript{rd} level. This has been evaluated by ENEL (on the basis of CFD simulations) as the best compromise to assure RDF complete burn-out and, in the meantime, avoid a huge increase of bottom ash production due to the fall of coarse RDF particles into the bottom hopper. The nozzles used for the PC/RDF mixture are the same previously used for PC.

6.3.1 Handling, storage and milling

The RDF has been successfully co-fired at Fusina PP since 2004. In February 2009 the permitting procedure to double RDF annual amount up to 70,000 tons was completed and, as a consequence, RDF has been increased up to 9t/h on each unit at full load on both units 3 and 4. This is one of the first examples of an integrated management and thermal treatment of Municipal Solid Waste (MSW) in Italy. The MSW management system includes a plant for the RDF production, a RDF power plant and a section for compost production, in order to provide suitable treatment for every type of waste. The processes and the main products of the MSW management scheme are shown in Figure 8.
At Fusina, the RDF is received at the station (Figure 9), and sent to two large storage silos. The RDF is then fed out of the silos and conveyed through ferrous and non-ferrous metal separation units to four high speed hammer mills. The size grading of the milled RDF varied with time between hammer and screen changes, due to erosion, but the following ranges of values were reported:

- 100% < 5 mm
- 50-70% < 2 mm
- 25-40% < 1 mm
- 15-30% < 0.5 mm

The milled material is then conveyed pneumatically to Units 3 and 4, and in each case the RDF is injected directly into the pulverised coal pipes, at a location just upstream of the primary air fans.

The RDF is co-fired through the burners in levels 2 and 3 only, i.e. two of the central burner levels. In this way, there are normally coal flames both above and below the burners co-firing the RDF to support the combustion process. This type of co-firing pattern is commonly employed and helps to maximise the combustion efficiency of the RDF. This helps to minimise the unburned fuel levels in both the furnace bottom ashes in the boiler hoppers and the fly ashes collected in the electrostatic precipitator hoppers.
**Separate injection system**

A number of potential RDF injection configurations were investigated by CFD modelling. In a first phase of the work, after the validation of a model for the calculation of pressure drops on the existing feeding system, four different RDF separate injection configurations were identified and the pressure drops as well as the auxiliary consumption for each configuration were estimated. This study was carried out by means of the 3D-CFD (3-Dimension Computational Fluid Dynamics) code IPSE (Industrial Process Simulation Environment, a code for three-dimensional simulation of combustion chambers, developed by ENEL). This code has been extensively used for the analysis, the design and the process optimisation of combustion systems for industrial steam generators. The code has been validated with experimental measurements (velocity, temperature and chemical species concentrations). IPSE code allows the simulation of both homogenous and heterogeneous combustion processes.

In order to evaluate the four different separate injection configurations, the boiler performance was calculated in terms of temperatures, thermal fluxes, residence time in the combustion chamber and fly and bottom ash.

The CFD simulations show no significant differences as for the average gas temperatures in the boiler and the thermal fluxes at the walls.

Regarding the RDF residence time in the boiler, all configurations guarantee the flue gas permanence at 850 °C for at least 2 seconds. Based on the experience, this value can be considered appropriate for achieving a good burnout.

No significant improvement in the boiler performance has been highlighted by this study to justify the cost of the investment and, therefore, dedicated RDF injection will not be implemented for now.

**6.3.2 Combustion and boiler performance**

As part of the activities planned within the DEBCO project, a series of 11 tests was carried out at RDF co-firing shares of 0-5% on a thermal basis (8.2% on a mass basis) and at the average unit load in the range 301-307 MWel. It clearly resulted that the impact of the RDF co-firing on the boiler performance was negligible at the tested ratios.

There are no clear trends of the oxygen concentration in the flue gas nor of the flue gas flow rate with the RDF co-firing level.

The measured flue gas temperatures at the ECO inlet, at the SCR inlet and outlet, at the air heater inlet and outlet as well as at the chimney were within very close bands and there are no clear trends in the flue gas temperatures with the RDF co-firing levels. This indicates that, with regards to the boiler convective section, there were no major differences in the fouling factors nor in the heat absorption resulting at the tested RDF co-firing ratios.
The most reliable indicator of the heat absorption performance of the furnace is provided by the measured superheater spray flow rates, and it is clear from the measured data that there is no significant trend. This indicates that there is no evidence to suggest that the co-firing of the RDF material had any significant impact on the furnace performance.

No clear variation of the total losses either appeared. They were estimated including the dry gas loss, the moisture loss, the humidity loss and the R&U losses, and depend principally on the moisture content of the fuel, the flue gas oxygen concentration and the flue gas temperature at the air heater outlet. On the contrary, the UBC loss could not be included since no relevant data is available for the trial periods.

The NOx, O2 and CO concentrations in the flue gas were measured downstream the ECO with a 5-point grid, both on the left and the right duct during a dedicated measurement campaign. The UBC was determined in the chemistry laboratory in the fly ash samples collected in both ducts downstream the ECO.

From a general point of view, the performed analyses indicate no significant differences between the emission values in the only coal and in the RDF/coal co-firing configurations with the same setting of the burner corner ports:

- The NOx emission is within the normal range of fluctuation experienced without co-firing.
- The difference of the steam consumption for the soot blower is negligible.
- The CO values resulted always under the lawful limit.
- The UBC in the ESP ash is within the range of the fluctuation experienced without co-firing.

The boiler temperature was measured in the super-heating area at the 6th floor (32 m) by means of temperature controlled probes. The measurements were performed at different distances from the left wall and for different combustion settings. The temperature in the RDF/coal assets resulted always lower than in the pure coal ones (from 10 to 80 °C in the tested configurations). These differences are due to the blowing cycle frequency being usually higher in the co-firing assets and, thus, increasing the thermal dispersion through the boiler walls.

**Slagging and fouling**

The slagging and fouling tendency was evaluated with appropriate short-term measurements campaigns.

Deposit samples were collected in two points of the boiler: the first one in the combustion chamber, at 28 m elevation (5th floor), on the front wall close to the left corner, the second one in the convective zone at 32 m elevation (6th floor), on the left wall.

The ash deposit was collected with proper probes and the Total Deposition Rate (TDR), which is as indication of the fouling and slagging tendency, has been calculated.

The TDR at the 5th floor, where chiefly slagging occurs, resulted higher the one at the 6th floor, where chiefly fouling occurs. Furthermore, the RDF/coal configuration is characterised by TDRs higher than in the pure coal configuration, both at the 5th and at the 6th floor.

Moreover, the fly ash was sampled downstream of the ECO and the main element concentration was determined. Higher values of potassium and sodium were obtained in the PC/RDF co-firing configurations. This result is related to the higher content of sodium, potassium, magnesium and calcium in the RDF than in the coal. Since these elements play also an important role in the ash melting temperature decrease, this evidence can be correlated to the slagging increase during the operation in the PC/RDF co-firing setting.

Some deposit was also dry-stone removed and analysed with the SEM/EDS technique. As for the 6th floor, no remarkable differences in the main element concentrations resulted...
between PC firing and PC/RDF co-firing. On the contrary, the analyses of the 5th-floor samples highlighted an increase in Na₂O, CaO and K₂O percentages during co-firing.

**Corrosion**

Four long-term (up to 5700 hours of fire) corrosion monitoring campaigns were carried out exposing samples of different materials (16Mo3 and A105 for the membrane wall of the combustion chamber, AISI 347 and AISI Super 304H for the convective pass) at different temperatures (current operating conditions and Ultra Super Critical steam cycle simulation). The results are summarised in Table 15.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature [°C]</th>
<th>Position</th>
<th>Corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>A105</td>
<td>440</td>
<td>combustion chamber</td>
<td>depending on probe position</td>
</tr>
<tr>
<td>AISI 347H</td>
<td>570</td>
<td>convective pass</td>
<td>negligible</td>
</tr>
<tr>
<td>16Mo3</td>
<td>450 (USC simulation)</td>
<td>combustion chamber</td>
<td>depending on probe position</td>
</tr>
<tr>
<td>AISI 304H</td>
<td>630 (USC simulation)</td>
<td>convective pass</td>
<td>negligible</td>
</tr>
</tbody>
</table>

The materials exposed in the convective pass present a negligible corrosion attack. Post-exposure metallographic analyses confirmed this result.

On the contrary, with regard to the combustion chamber, co-firing operation results to increase the corrosion grade compared with coal operation. In fact, the probe consumption resulted higher near the PC/RDF nozzles, and lower near the PC nozzles. The corrosion grade increase can be ascribed to the higher chlorine content in the proximity of RDF injection. The corrosion grade results generally higher for 16Mo3 than for A105.

### 6.3.3 Air pollution control devices

**SCR performance**

At the time of the measurements, the SCR catalyst (V₂O₅ 0.6%) had been in operation for 44,000, 16,000 and 80,000 hours.

The DeNOx efficiency ranged from 42 to 67% with no significant correlation with the RDF thermal input. As for Hg, the speciation varied across the SCR reactor, with an increase of ionic phase (Hg²⁺). The oxidizing reaction was promoted by the presence of the catalyst and the oxidation efficiency varied between 40% and 83% according to the RDF thermal input. In particular, Hg⁰ oxidation efficiency increased with the RDF percentage. The reason is the higher HCl concentration in the co-firing flue gas, which has an activating effect on Hg⁰ oxidation.

**ESP performance**

Particulate and micro-pollutants (Hg and heavy metals) are removed in the ESP, consisting of 7 electric fields. Heavy metals, due to the low volatility, are present in the bottom ash (removed in the boiler hopper) and in the fly ash (removed in the ESP). The highly volatile selenium is an exception and is mainly present in the gas phase and in the sub-micron particles.

The fly ash resulted quantitatively removed in the ESP with outlet concentration values two orders of magnitude lower than at the inlet and widely below the lawful limit with a 99.9% of reduction efficiency.
As for mercury, about 60% of the amount leaving the boiler was removed with fly ash in the ESP; as for the trace metals, except selenium, they were removed with an efficiency between 70 and 90%.

**Evaluation of gas emissions**

PC/RDF co-firing up to 5% RDF thermal input resulted not to affect the macro-pollutant and micro-pollutant emissions of the PC power plant. The measurement highlighted values fairly below the maximum lawful limits.

As for the micro-pollutants, the removal efficiency resulted about 90% for Hg, 99% for total trace metals, nearly 100% for particulate with diameter d > 2.5 µm. The mercury emission showed no problem in meeting the limit value requested by the IED for co-firing with waste. The efficiency in dust removal of ESP/FGD is comparable to the best available technologies.

**6.3.4 Utilisation of residues**

The fly ashes of Fusina PP were characterised in the long term in order to evaluate the impact of RDF on their composition and quality.

The RDF ash composition is dominated by silica, alumina and lime, largely associated with the mineral fillers in paper, and there are significant levels of potash and soda.

Compared with pure bituminous coal combustion, the analyses of the ashes sampled during 5% RDF co-firing showed a slight increase in the concentrations of same trace elements (Cu, Fe, Zn), alkalis and chlorides. The trace elements need to be taken into account in light of the future requirements for the product standards as well as in light of the existing national application rules.

The main conclusion of the fly ash characterisation is that RDF co-firing up to 5% thermal input has slightly increased the trace element contents but not affected the main oxide composition and, therefore, the use as concrete addition could be possible provided an ETA (European Technical Approval) for co-firing of RDF is granted.
6.4 Dorog and Mátra Power Plants (agricultural biomass co-firing)

The Dorog Power Plant, located in Hungary, is a co-generation plant producing hot water for district, process steam and electric energy. There are 3 operating boiler (Units 3, 5 and 6) and 1 boiler (Unit 4) is on reserve.

Units 3 and 4 are tangential fired lignite boilers with a nominal steam capacity of 50 t/h, 430 °C and 35 bar$_{abs}$. The design coal was of low heating value (12 MJ/kg) and of high ash content (25-30%). The boiler produces steam by having natural circulation in the water tube system. Units 5 and 6 originally were designed identically to Unit 4, but later redesigned to fire natural gas.

To increase combustion efficiency of Unit 3, in 2006 the low grade coal was changed for a lignite type with heating value of 17-20 MJ/kg and ash content of 10-15%. Boiler modifications had been necessary to meet the new operating conditions. Some more fan power was needed, however for a given boiler load, less fuel is necessary due to its higher heating value, which reduces the energy demand of grinding. Experiments showed that eventually less motor power was necessary by about 10%. In order to reduce UBC losses, a recirculation system was installed at the bottom of the furnace by which the fall-out material can be recycled (external fuel recirculation (EFR) system). The concept of EFR was successfully proven and after modification and using higher heating value coal, the boiler efficiency increased from 81% to 87%.

The 836-MW Mátra power station is the largest lignite fired plant in Hungary. Lignite of 7-8 MJ/kg heating value from a local open mine is supplied to five units through a sophisticated belt conveying system in a yearly quantity of 7 million tonnes. The steam capacity (165 bar, 540 °C) is 640 t/h for three units and 320 t/h for the other two. Prior to 2005, only short-term co-firing tests and trials had been carried out with residues of food industry, municipal wastes (sludge) and agricultural wastes. By the year of 2007 already 7% of the total boiler heat input was supplied by biomass. In 2008, a biomass feeding station of 1 million tonnes/year capacity was built near the coal yard to mix biomass of 12-13 MJ/kg heating value to the lignite. The biomass consists of wood-chips, saw-dust, agricultural by-products such as cut straw.

6.4.1 Handling, storage and milling

Firing of biomass started in 2007, when two fuel lines (fuel bunker, mills and burners) were retrofitted to allow the biomass transportation – mainly wood-chips and saw-dust. Basically, new and larger electric motors were installed to the mills and new burner configuration was applied. In addition, an External Fuel Recirculation (EFR) system was built to recycle solid material from the furnace bottom upstream of the mills. In this way, the heat loss due to the UBC in the bottom ash could be reduced.

Two ways are possible to overcome the feeding problems of agricultural by-products to PC plants. One is building a new feeding facility for biomass handling and feeding, which is a very expensive solution and power utilities are reluctant to invest, while the other is pelletising the material near the source of production. In the latter case, also used for the testing activities at Dorog PP, the technology is capable of feeding pellets without major investment at the plant. However, extra costs are due to the pellet production plant, and the price of the pellets, as of now, is higher than that of wood-chips and saw-dust.

Biomass/coal co-firing was tested at Dorog PP at 50% biomass thermal input. The biomass fuel consisted in a mixture of barley straw pellets an wood-chips, sunflower hull and wheat bran.

The tests were performed at 85% boiler load. Two separate fuel lines were used for coal and for the pellets, so they did not mix before the flame. One bunker fed two biomass mills and
one bunker one coal mill. The biomass feeding was not always continuous due to the inhomogeneous mixture. Wood-chips tended to form craters in the bunker and for avoiding plugging, mechanical agitation of the material was necessary.

![Figure 10: Dorog PP fuel handling and feeding system.](image)

### 6.4.2 Combustion and boiler performance

During the testing activities, the risk of ash deposition and corrosion was simply minimised by producing fresh steam at relatively low super-heating temperature. No problem in reaching the nominal steam temperatures was observed. The flue gas temperature at the boiler exit was in the design range (150 °C).

The NOx concentration resulted higher than with only coal and some combustion optimisation is needed. Slagging and fouling was not noticed thanks to the low furnace flue gas temperatures and to the careful selection of biomass with high ash initial deformation temperature. By now, the biomass co-firing has become a common technique at this plant.

Co-firing tests resulted successful also at Mátra PP, where a mixture of wood-chips and sawdust was burned with lignite in a heat ratio of 10% in boilers designed for PC with the combination of tangential and grate combustion.
6.5 Rokita (biomass co-firing)

PCC Rokita SA is a combined heat and power plant with 36% biomass thermal input. Particular focus was put on limitations and requirements to upgrade the biomass milling and feeding system up to 50% and to identify major limitations and risks on the combustion technology, boiler slagging/fouling and operation. Beside wood, agriculture by-products as rape seed and liquid biomass-crude glycerol and SRF were used.

Boiler characteristics:
- Steam capacity: 130 t/h
- Steam parameters: 540 °C; 9.6 MPa
- Firing mode: Tangential with zonal combustion
- Fuel preparation: 3 Fan-mills
- Boiler operation: Co-generation of steam and electricity (100 MWth, 8 MWel)
- Main fuel: Hard coal of 19-25 MJ/kg LHV
- Biomass fuel: rape waste (36% thermal input)
- Boiler efficiency: 83-85%

![Diagram of boiler and burners](image)

**Figure 11:** The location and arrangement of burners in PC OP-130 boiler and temperature measurements level by suction pyrometry probe.

The most remarkable results are:
- Decrease of UBC in the ash
- NOx emission drop from 500 mg/m³ to 300 mg/m³ in spite of the high content of nitrogen in the biomass
- Small increase of SO2 emission (sulphur content in rape waste and crude glycerol)
- The operational parameters were kept stable
- Grinding blend does not cause big problems with separation of biomass in fan mill
- No problem occurred with regard to fouling and slagging.
Appendix B - New findings

In the present Appendix B the key findings of the research and development activities performed by the DEBCO Partners are summarised.

7.1 Erosion and corrosion laboratory tests

RSE performed erosion and corrosion laboratory tests on some selected materials, simulating operation both in co-firing arrangement and in Ultra Super Critical (USC) steam cycle. Six different materials were selected: the steel 347H and steel Super 304H, Ni-base alloy Inconel 740 and R156 (materials candidate for USC operation as indicated by some EU projects), Ni-base alloy Inconel 625 and Sanicro 28 (currently used for corrosion protection in harsh environments). The samples temperature was set to 630°C, which is a typical value of the convective bundle tubes in USC power plants; the gas composition on the tests was that of the convective pass of a power plant, as indicated by calculations. Two erosion tests and two 1000 h corrosion tests were carried out in 2009-2011.

The main results of this research are the following:

- RSE developed an innovative erosion test rig (see Figure 12) able to characterise the samples of material at high temperature (up to 750°C).

- Erosion tests were performed at different Angles Of Impact (AOI) of the erosive powder (90° and 30°) and at different erosive velocity. The ranking of erosion resistance of the tested materials is reported in Figure 13 in the case of AOI = 30°, which is more critical angle for erosion attack, at three erosive velocities (42 m/s, 77 m/s and 93 m/s). The steel AISI 410 was also included in the tests as reference material, because is normally considered to have a good erosion resistance. At the lower erosive velocity, the highest erosive rate is showed by alloy IN625, intermediate erosion rate values were found for steels S304, 347H and Ni-base alloy Inconel 740, while the steel R156 shows the highest erosion resistance, which is close to that one of AISI 410.
By these test results it was possible to estimate the material consumptions at the USC temperature of 630 °C after 8000 hours of fire considering the real operational conditions of the convective pass of a PP (fly ash velocity = 10 m/s, AOI = 30°, ash density = 6 g/m³, ash granulometry d₅₀ = 90 µm). Table 16 reports the results of this estimation.

**Table 16: Erosion rate estimation in co-firing + USC steam cycle conditions.**

<table>
<thead>
<tr>
<th>Material</th>
<th>mm / 8000 hours of fire (±10% acc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 410</td>
<td>0.22 (reference material)</td>
</tr>
<tr>
<td>R156</td>
<td>0.24</td>
</tr>
<tr>
<td>IN740, SAN28, AISI 347H</td>
<td>0.26</td>
</tr>
<tr>
<td>AISI S304H</td>
<td>0.29</td>
</tr>
<tr>
<td>IN625</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Comparing these estimations with the classification of the seriousness of the erosion/corrosion in energy plants, reported in Table 17, we can conclude that all of the tested materials present a “significant” grade of consumption: the steel R156 is very close to the acceptance limit of 0.2 mm / 8000 h of fire, the steel AISI 347H, IN740 and SAN 28 have a moderate but higher consumption, while the worst performance is for IN625 and the steel S304H.

### Table 17: Ranking of the erosion/corrosion seriousness in PPs.

<table>
<thead>
<tr>
<th>Corrosion/erosion rate</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>nm/h</td>
<td>mm/y @ 8000 h/y (fc=91%)</td>
</tr>
<tr>
<td>&lt;25*</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>25-50</td>
<td>0.2-0.4</td>
</tr>
<tr>
<td>50-100</td>
<td>0.4-0.8</td>
</tr>
<tr>
<td>100-200</td>
<td>0.8-1.6</td>
</tr>
<tr>
<td>&gt;200</td>
<td>&gt;1.6</td>
</tr>
</tbody>
</table>

*25 nm/h is the conventional limit of acceptance

#### 7.2 Large-scale corrosion monitoring of pure wood-dust firing

Corrosion measurements were performed by USTUTT (IFK) at the super-heater area of Rodenhuize PP, Unit 4, located at 43 m. A temperature controlled probe was used to check the corrosion mechanisms of tested materials. After an exposure time of 90 hours, the corrosion samples with the deposit ash layer were removed. The surface area of the samples was embedded with epoxy for fixing the depositions for further preparation steps. To get an overview of the windward and lee sides of the materials, rings were cut into cross sections in a dry way and afterwards embedded one more time in a SEM adequate round form. To identify the existing corrosion mechanisms, SEM-EDX was the method of choice. To complete the preparation, all corrosion samples for each material were grinded and polished with appropriate abrasive papers and polishing cloths.

The gas temperature at the measurement point was on average between 1100-1200 °C. The biomass wood had a very low ash content, but relatively high contents of potassium and calcium. Calcium is able to build hard deposits on the super-heater pipes, which are difficult to clean. The chlorine content was very low in the wood.

The composition of the materials that were exposed is listed in Table 18. The ferrite is a standard material designed for super heaters up to 500-550°C. The Ni-based material was designed for temperatures up to 650-800°C and is characterised by high-temperature strength and oxidation resistance, along with an excellent resistance to a wide range of corrosive environments.
Table 18: Alloving composition of the exposed materials.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Cr [%]</th>
<th>Ni [%]</th>
<th>Fe [%]</th>
<th>Others [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite</td>
<td>low</td>
<td>low</td>
<td>&gt;90</td>
<td>C, Mn, Cu</td>
</tr>
<tr>
<td>Alloy 617 (Ni-based)</td>
<td>&gt; 20</td>
<td>&gt;50</td>
<td>low</td>
<td>Mo, Si, Mn, Co, Al, Ti</td>
</tr>
</tbody>
</table>

The Figure 14 shows the results of the SEM-EDX analyses. The ferritic material formed a nice oxide scale of about 30 µm thickness at a temperature of 535 °C. The oxide layer was formed before the K and Cl hit the material surface. No indication of Cl-induced corrosion was detected. Above the KCl border, loose particles build the deposit. The particles show a loose structure, which means an advantage for cleaning the super heater bundles.

Figure 14: SEM-BSE pictures of the ferritic sample after 90 hours’ exposure at 535 °C, windward (left) and lee side (right).

The Ni-based alloy shows a typical two-layer oxide scale with Ni-oxide below and Cr-oxide above (Figure 15). Differently to the ferrite at lower temperature, the deposit shows a molten structure where K and Cl are spread homogeneously. This adverse deposition behaviour is problematic for the cleaning system.

Figure 15: SEM-EDX element mappings of the Alloy 617 after 90 hours’ exposure at 660 °C, windward side.
Both the Ni-based and the ferritic materials show Cl in the deposits at different temperatures despite of the very low Cl content in the fuel, but in different forms. Ongoing damaging of material or decrease of material thickness should be detected with longer term tests (some hundred hours in the wood fired boiler).

Increasing the steam temperatures while firing biomass or fuels with high biomass content requires to use new materials or base materials with a coating properly designed for higher resistance against corrosion. In order to protect the super-heater materials, it is important to have a constant firing system, to avoid stable temperatures and to get a primary protecting oxide layer before (co-)firing biomass with high S and Cl contents. Additives (solid/liquid) could either catch alkalis to prevent KCl or NaCl from forming and depositing or support the sulphation of the alkalis. However, at steam temperatures above 600 °C an alkali adsorber without sulphur (e.g. Al-Si rich minerals) is preferred, since S-induced corrosion would be otherwise likely to occur.

### 7.3 Lab-scale and pilot-scale deposition tests

ECN and USTUTT (IFK) performed lab-scale and pilot-scale tests, respectively. From tests carried out on a lab-scale drop-tube furnace simulator, it was concluded that high cardoon percentages may create large amounts of fine ash due to an increased salt concentration in the ash. It is therefore beneficial to focus on co-firing cardoon with coals, as opposed to pure cardoon combustion.

In a pulverised-fuel pilot-scale 0.5-MW facility, experiments led to plugging of a heat-exchanger during pure cardoon (100% thermal share) combustion, while this did not occur for the high thermal share of 50% cardoon co-firing with Greek lignite. Also, visual inspection and testing of the deposits from pure cardoon combustion showed a very bright deposit, which was analysed and found to be rich with potassium compounds, i.e. alkali salts.

This potentially problematic deposit not being observed at 50% cardoon thermal share may be attributed to the high sulphur content of the lignite, which still has the potential to create sulphation of alkalis despite the calcium content. Thus, with a parent fuel of a lower sulphur content, sulphur lean fuel, there may be more risks regarding deposit phenomena in a boiler when firing high thermal shares of cardoon.

Hence, co-firing of herbaceous and agricultural biomass fuels may be challenging with certain coal types that are not a sulphur rich fuel. Further studies would be needed to determine those biofuels that may or may not be considered for high co-firing thermal shares with sulphur lean coals or for pure combustion.

### 7.4 Lab-scale combustion behaviour

WUT performed a co-firing test in an IFR (Isothermal Flow Reactor) fed with a fuel mix at 50% straw thermal share. The CO concentration resulted to increase by 80 ppm. In that case the higher emission of CO was due to the unstable co-firing, and a high LOI value was also noticed. Thereby, 50% and higher co-fired thermal shares of herbaceous and agricultural biomass fuels would need further studies to assess the combustion behaviour, since milling the fuels to a proper particle size to ensure good combustion and burnout in pulverised fuel boilers may result being challenging.

### 7.5 Modelling activities

USTUTT (IFK) performed modelling activities. The capability of the 3D combustion simulation code AIIOLOS was demonstrated to predict the combustion behaviour of co-firing a lignite coal with a herbaceous biomass. It was found that the calculated temperature and major species concentrations match most of the experimental data from the 0.5-MW pilot-scale test facility. Furthermore, the results which are classified as the basic simulation were utilised as
boundary conditions to predict the fouling tendency in a post processing step. It is believed that the study carried out resulted in a highly practical model able to predict the combustion behaviour, the formation of emissions, and the deposit build-up (mainly concerning the condensates in the first layer of a deposit due to a certain fuel quality, such as those with a high potassium content) on a cooled super-heater surface; thereby, this model provides a tool for the investigation of co-firing alternative fuels in a pulverised fuel combustion facility. Moreover, the use of soluble alkali species from chemical fractionation analyses of fuels in conjunction with the model will produce enhanced results.

7.6 Lab-scale pyrolysis tests

WUT carried out testing activities focused on the fuel devolatilisation and consisting in the pyrolysis of selected fuels in an IFR in nitrogen atmosphere. The global nitrogen flow rate was set at $3 \times 10^{-4}$ $\text{Nm}^3/\text{s}$ and $6 \times 10^{-4}$ $\text{Nm}^3/\text{s}$, while the fuel mass rate was 0.4 $\text{g/s}$. The solid residue produced in the IFR during the pyrolysis as well as the parent materials were characterised in accordance with the procedure schematically illustrated in Figure 16.

![Diagram](image)

**Figure 16:** Scheme of the analytical procedure.

The gas composition obtained from the biomass pyrolysis tests is shown in the Tables 19 through 22, indicating the concentration of $\text{CH}_4$, $\text{CO}$, $\text{CO}_2$ and $\text{H}_2$ in the gas probe obtained at 1000 $\degree$C with 1-second residence time. For rape waste, the data is also reported for the tests at 600 $\degree$C and 800 $\degree$C with 1-second residence time and for the test at 1000 $\degree$C with 2-second residence time. The gas concentration is referred to the gas mixture without nitrogen.
### Table 19: Composition of pyrolytic gases from wood biomasses.

<table>
<thead>
<tr>
<th>Biomass material</th>
<th>% CH₄</th>
<th>% CO</th>
<th>% CO₂</th>
<th>% H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood pellet A</td>
<td>11.71</td>
<td>50.58</td>
<td>6.32</td>
<td>31.39</td>
</tr>
<tr>
<td>Wood pellet B.</td>
<td>12.34</td>
<td>47.18</td>
<td>7.21</td>
<td>33.28</td>
</tr>
<tr>
<td>Wood pellet C</td>
<td>10.20</td>
<td>48.43</td>
<td>9.00</td>
<td>32.37</td>
</tr>
</tbody>
</table>

### Table 20: Composition of pyrolytic gases from agro-biomasses.

<table>
<thead>
<tr>
<th>Biomass material</th>
<th>% CH₄</th>
<th>% CO</th>
<th>% CO₂</th>
<th>% H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunflower</td>
<td>13.69</td>
<td>42.89</td>
<td>11.95</td>
<td>31.47</td>
</tr>
<tr>
<td>Wheat pasture</td>
<td>11.12</td>
<td>42.41</td>
<td>9.77</td>
<td>36.70</td>
</tr>
<tr>
<td>Wheat rye</td>
<td>11.98</td>
<td>48.99</td>
<td>8.93</td>
<td>30.10</td>
</tr>
<tr>
<td>Rape waste 1000 °C</td>
<td>14.79</td>
<td>38.47</td>
<td>10.01</td>
<td>36.73</td>
</tr>
<tr>
<td>Rape waste 1000 °C t_res= 2 sec</td>
<td>12.09</td>
<td>40.50</td>
<td>10.93</td>
<td>36.49</td>
</tr>
<tr>
<td>Rape waste at 800 °C t_res= 1 sec</td>
<td>31.11</td>
<td>40.91</td>
<td>12.63</td>
<td>15.36</td>
</tr>
<tr>
<td>Rape waste at 600 °C t_res= 1 sec</td>
<td>43.45</td>
<td>39.65</td>
<td>14.17</td>
<td>2.74</td>
</tr>
</tbody>
</table>

### Table 21: Composition of pyrolytic gases from RDF.

<table>
<thead>
<tr>
<th>RDF material</th>
<th>% CH₄</th>
<th>% CO</th>
<th>% CO₂</th>
<th>% H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDF A</td>
<td>16.1</td>
<td>36.9</td>
<td>10.9</td>
<td>36.1</td>
</tr>
<tr>
<td>RDF B</td>
<td>23.7</td>
<td>24.8</td>
<td>28.1</td>
<td>23.4</td>
</tr>
</tbody>
</table>
Table 22: Composition of pyrolytic gases from fuel blends.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>% CH₄</th>
<th>% CO</th>
<th>% CO₂</th>
<th>% H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard coal 1</td>
<td>16.98</td>
<td>18.10</td>
<td>5.21</td>
<td>59.71</td>
</tr>
<tr>
<td>10% Wood pellet B + 90% Hard coal 1</td>
<td>16.89</td>
<td>20.01</td>
<td>4.01</td>
<td>59.08</td>
</tr>
<tr>
<td>30% Wood pellet B + 70% Hard coal 1</td>
<td>12.14</td>
<td>32.92</td>
<td>5.22</td>
<td>49.71</td>
</tr>
<tr>
<td>10% Rape waste + 90% Hard coal 1</td>
<td>15.44</td>
<td>17.78</td>
<td>5.18</td>
<td>61.61</td>
</tr>
<tr>
<td>30% Rape waste + 70% Hard coal 1</td>
<td>15.19</td>
<td>24.87</td>
<td>5.77</td>
<td>54.17</td>
</tr>
<tr>
<td>Greek lignite</td>
<td>4.76</td>
<td>53.60</td>
<td>4.23</td>
<td>37.41</td>
</tr>
<tr>
<td>Hard coal 2</td>
<td>15.53</td>
<td>22.11</td>
<td>6.16</td>
<td>56.20</td>
</tr>
<tr>
<td>10% Cardoon + 90% Greek lignite</td>
<td>3.30</td>
<td>57.31</td>
<td>2.50</td>
<td>36.90</td>
</tr>
<tr>
<td>50% RDF + 50% Hard coal 1</td>
<td>10.7</td>
<td>31.6</td>
<td>12.6</td>
<td>45.0</td>
</tr>
</tbody>
</table>

The lowest H₂ content was observed in the pyrolytic gas obtained from the 1-second rape waste devolatilisation at 600 °C and 800 °C. Consequently, the hydrogen content in the relevant char was the highest.

The highest values of the H₂ content were noticed in the gases from pyrolysis of hard-coal/biomass blends, regardless of the H₂ content in the raw blend. The higher the coal amount in the blend, the higher the hydrogen content in the pyrolytic gas, with the exception of the 10% rape-waste/hard-coal blend showing a higher H₂ content than coal.

7.7 Lab-scale additive testing

The problem of the high fouling and slagging tendency while co-firing agricultural biomass limits the biomass share in the fuel blend. WUT carried out testing activities with the addition of halloysite (Al₆(OH)₂(Si₄O₁₀)(OH)₂). Halloysite is a mineral raw material from the group of the Kaolinites. It naturally occurs as nanotubes and platelets loosely linked together and is characterised by a high surface area (~70–85 m²/g) as well as high melting point and reactivity. Halloysite mainly contains compounds of Si, Al and Ti. Impurities of chromium, iron, magnesium, nickel and copper are also very often present.

The addition of halloysite is expected to raise the sintering and softening temperature of the ash and the test results confirmed this additive being effective in reducing slagging and deposit formation. Besides, further positive effects were observed, i.e. a burnout enhancement as well as lower NOx emissions.