EOS-LT Consortium
Biomass Co-firing
Final report 2006-2010

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Preface

ECN, KEMA and TU Delft have formed a consortium, with ECN as co-ordinator, to conduct R&D on biomass co-firing in large-scale power plants in the framework of the Energie Onderzoek Subsidie Lange Termijn (EOS-LT) subsidy programme, executed by AgentschapNL on behalf of the Dutch Ministry of Economic Affairs, Agriculture and Innovation. The staff of EPZ and E.On Benelux are greatly acknowledged for hosting and facilitating full-scale measurements as well as the Industrial Advisory Group for their cooperation and input. This report summarizes the consortium activities during the period 1 April 2006 until 31 March 2011.

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Project title: Mee-en bijstoken van biomassa in elektriciteitscentrales
Coordinator: ECN
Partners: KEMA B.V. and TU Delft
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Abstract

In the Netherlands, biomass is envisaged to play a major role in fulfilling national ambitions concerning the reduction of CO₂-emissions and the introduction of Renewable Energy Sources (RES). Co-firing of biomass is one of the most important options to realize these ambitions. Ambitious targets have been set in the Long-Term Energy Research Strategy (EOS-LT) programme of the Dutch Ministry of Economic Affairs, including targets of 25% and 40% biomass co-firing in 2020 and 2040 respectively. To meet these targets, not only existing fossil-fuel-fired power plants will have to be considered, but also new plants involving new conversion technologies aiming at higher overall efficiencies and a lower environmental impact.

Furthermore, the targets cannot be met with state-of-the-art technology. Technology developments are thought to be required in the following areas: biomass upgrading, pre-treatment and feeding technology, assessment and solution of technical bottlenecks in direct co-firing, indirect co-firing technology, process monitoring and control, and residues management.

ECN, KEMA and TU Delft, have formed an R&D consortium to address these biomass co-firing R&D requirements. Furthermore, there is a close involvement of the Dutch power generation sector, ensuring that the R&D activities are well targeted to market needs and facilitating the implementation and exploitation of the results. Within the areas mentioned above, the consortium has made a careful selection of specific R&D topics, which are of particular relevance to the Dutch power generation sector and where the consortium has clear added value based on available expertise and R&D facilities. Of these topics, the following eight are covered within the EOS-LT biomass co-firing consortium projects: fate of trace elements in biomass co-firing, development of indirect co-firing technology, sustainable ash management and development of new utilisation options, biomass co-firing in oxy-fuel combustion, fouling monitoring/boiler diagnostics and wet biomass processing and heat utilisation, pneumatic transport of biomass and biomass/coal blends and optimisation of numerical models for slagging and fouling.

In this report, the results on these eight R&D topics throughout the five consortium years are presented. Also a brief summary is given of the undertaken efforts to come to a joint valorisation of the obtained results and the dissemination of the generated knowledge.

Keywords

Biomass, co-firing, trace elements, gasification, ash recycling, ash utilisation, slagging, fouling, oxy-fuel combustion, Ultra Super Critical (USC) boilers, residues, wet biomass, heat utilisation, pneumatic transport
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Samenvatting

De verwachting is dat biomassa in Nederland een onmisbare rol speelt in het halen van nationale ambities op het gebied van het verminderen van CO₂ emissies en de introductie van hernieuwbare energie. In dit kader zijn ambitieuze doelstellingen geformuleerd in het Energie Onderzoek Strategie Lange Termijn (EOS-LT) programma van het Ministerie van Economische zaken. Dit betreft doelstellingen van 25% en 40% biomassa mee- en bijstoken in respectievelijk 2020 en 2040. Biomassa mee- en bijstoken omvat zowel a) meestoken (Eng. direct co-firing) waarbij de biomassa thermisch wordt omgezet samen met de fossiele brandstof en b) bijstoken (Eng. indirect co-firing) waar de biomassa een aparte thermische omzetting ondergaat en de verwerking van het resulterend product (bijv. stookgas) is geïntegreerd met een fossiele brandstof gestookte installatie.

Om deze biomassa mee- en bijstookdoelstellingen te halen, zullen ook nieuwe type processen gericht op hogere overall efficiency en verminderde impact op het milieu moeten worden overwogen. De Nederlandse elektriciteitssector verwacht dat in 2040 de op steenkool/biomassa gestookte capaciteit zal bestaan uit een mix van ‘near-zero’ en ‘zero emission’ installaties met een hoge efficiency (groter dan 50%) en CO₂ emissies die vergelijkbaar zijn met state-of-the-art gasgestookte combined cycle installaties. Biomassa mee- en bijstook is voorzien een belangrijke, kosteneffectieve rol te spelen, ook in combinatie met nieuwe technologieën, als kolenvergassing en oxyfuelverbranding.

In overeenstemming met de lange termijn visie van de Nederlandse elektriciteitssector, en gebaseerd op een gedetailleerde beoordeling van de verwachte gevolgen van biomassa mee- en bijstook op de prestaties van een elektriciteitscentrale en de huidige stand van de technologie, zijn volgende (technologische) ontwikkelingen op de volgende gebieden vereist:

- Biomassa-upgrading, -voorbewerking en -brandstoftoevoer,
- Beoordeling en oplossen van technische bottlenecks bij biomassa mee- en bijstoken,
- Ontwikkeling van bijstooktechnologie,
- Procesmonitoring en -beheersing,
- Residumanagement,
- Modellering van specifieke onderwerpen als vervuiling in de ketel en toevoer van brandstof aan de ketel.

ECN en de KEMA hebben een R&D consortium gevormd om een aantal van deze biomassa mee- en bijstook R&D onderwerpen te adresseren. De TU Delft ook betrokken bij dit consortium, initieel als subcontractant, maar in een later stadium als volwaardig partner. Verder is er een nauwe betrokkenheid van de Nederlandse elektriciteitssector, om er voor te zorgen dat de R&D activiteiten gericht zijn op marktrelevante en de implementatie en gebruik van de resultaten. Uit de hierboven aangegeven gebieden heeft het consortium een zorgvuldige keuze gemaakt. Gekozen is voor onderwerpen welke bijzonder relevant zijn voor de Nederlandse sector en waar het consortium een duidelijke toegevoegde waarde heeft op basis van aanwezige expertise en R&D faciliteiten. De volgende acht onderwerpen zijn beschouwd door dit consortium en worden beschreven in deze rapportage:

- Het lot van sporen elementen bij biomassa meestoken,
- Ontwikkeling van bijstooktechnologie,
- Duurzaam asmanagement en ontwikkeling van nieuwe toepassingen,
- Biomassa-meestoken onder oxy-fuel omstandigheden,
- Foulingmonitoring en boilerdiagnostiek,
- Gebruik van natte biomassa en warmtebenutting ten behoeve van droging van natte biomassa,
Gedurende de eerste twee consortium jaren (projectjaren 2006-2007), zijn nauwe relaties opgebouwd tussen ECN en de KEMA en door de post-doc studies bij de TU Delft. In het derde en vierde jaar (projectjaren 2008-2009) is de samenwerking voortgezet en uitgebreid, terwijl in het vijfde jaar (projectjaar 2010) de TU Delft als volwaardig partner is opgenomen. De samenwerking leidde tot een groot aantal resultaten. De interactie met de Industriële Advies Groep (IAG), bestaande uit vertegenwoordigers van de Nederlandse elektriciteitssector en de Vliegasunie, is in de loop van de jaren geïntensificeerd en hun rol in het sturen, begeleiden en monitoren van het werk is versterkt. De onderwerpen zijn afgedekt in de onderstaande acht werkpakketten:

Werkpakket 1: Gedrag spoorelementen bij biomassa-meestoken
Het gedrag van spoorelementen bij het meestoken van biomassa in hoge percentages is nog grotendeels onbekend maar kennis ervan is noodzakelijk in verband met het formuleren van ontwerp- en bedrijfsschijten en beheersing van emissies van kritieke elementen. De relevante elementen zijn stikstof en zwavel, macro-elementen1 en spoorelementen2. In dit werkpakket zijn verschillende onderzoekslijnen in gang gezet: thermodynamische modellering, meetcampagnes en experimenteel onderzoek op labschaal. Deze drie onderzoeksbenaderingen zijn complementair en hebben elk hun voordelen en beperkingen. De combinatie ervan levert een meer compleet beeld op van het volledige gedrag van (spoor)elementen in de ketel en het rookgas. Met name de modellering en het werk op labschaal bieden de mogelijkheid studie te doen aan nieuwe technologieën als USC en oxy-fuel verbranding. De onderzoekslijnen zijn de volgende:

- Thermodynamische berekeningen aan biomassa-meestoken in conventionele, USC en oxyfuel ketels,
- Twee grootschalige meetcampagnes zijn uitgevoerd, bij centrale Borssele (EPZ) in 2006 en bij centrale Maasvlakte (E.On) in 2008. In het kader van het EOS werd nadruk gelegd op onderzoek naar effecten op deactivering van de SCR (DeNOx) en de speciatie van spoorelementen in de assen. De speciatie van enkel specifieke elementen, waaronder chroom, werd gemeten met behulp van XAFS (X-ray absorption fine structure),
- Een serie labschaal experimenten werd uitgevoerd om het verbrandingsgedrag en de release van elementen te bestuderen in nieuw type boilers en om het gedrag van elementen in rookgas te bestuderen en
- Aanpassing en toepassing van een analytische methode in combinatie met computer modellering om speciatie/complexatie in complexe matrices te bepalen. De resultaten zijn vergeleken met metingen.

Verschillende conclusies zijn getrokken uit het onderzoek. Het vervluchtigingsgedrag van bepaalde elementen uit steenkool is anders dan van dezelfde elementen uit biomassa. De resultaten van de meetcampagnes laten een belangrijke rol van de SCR (DeNOx) zien, welke bijdraagt aan sterke omzetting (oxidatie) en afvangst van bijvoorbeeld kwik (Hg). Uit SEM onderzoek bleek dat deactivering van de SCR vooral is toe te schrijven aan de vorming van compacte afzettingen op het katalysatoroppervlak. Ook kan het diep binnendringen in het katalytische materiaal van bepaalde elementen hebben bijgedragen aan deactivering. Resultaten van het pH-statisch uitoogbaarheid onderzoek uitgevoerd op dezelfde (gedeactiveerde) SCR katalysatormonsters hebben laten zien dat meestoken van biomassa kan leiden tot een versnelde degradatie van de katalysatorelementen. Dit komt door de interactie van de biomassa gerelateerde elementen, zoals fosfor, met elementen afkomstig uit kolen (b.v. arseen), dat tot een verhoogde vergiftiging van de katalysator kan leiden. Verder kunnen elementen zoals K en Ca ook mobiele/vluchtige of reactieve fases vormen die op de katalysator oppervlakte kunnen

1 Macro-elementen: Na, K, Ca, Mg, Cl, and P
2 Spoorelementen: F, Br, As, B, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Te, Ti, V en Zn
neerslaan, waardoor de activiteit verder afneemt. De mate van deactivering bleek sterk afhankelijk te zijn van de precieze samenstelling van het brandstofpakket. Zo is het bekend dat de vervuiling bij het gebruik van (schoon) hout zeer beperkt is, terwijl agro- en voedselproductieresiduen hogere degradatie kunnen veroorzaken. Echter, zelfs onder de minst gunstige condities bleef de deactivering binnen de door de katalysatorproducent gegarandeerde grenzen, waardoor aan de NO\textsubscript{x} emissielimieten voldaan kon worden.

Verder werd de rol van de bedrijfscondities op de speciatie en het vervluchtigingsgedrag duidelijk, zoals de oxidatieomstandigheden in zowel de boiler als natte rookgasontzwavelingsinstallatie. Tot slot is een kennisdatabase opgezet om alle data en kennis van dit werkpakket, met betrekking tot speciatie onder meestookcondities overzichtelijk op te slaan en toegankelijk te maken.

**Werkpakket 2: Biomassa bijstooktechnologie**

Door middel van biomassa bijstoken met vergassing, kan het percentage biomassa dat in de centrale wordt gestookt verder worden verhoogd boven het directe meestookpercentage of moeilijkere brandstoffen, aangezien een aantal verontreinigingen buiten de ketel kunnen worden gehouden door middel van een voorgeschakelde vergassing/gasreiniging . In de eerste twee jaar van dit werkpakket is de aandacht gericht geweest op een technische economische evaluatie van de perspectieven van een relatief nieuw vergassingsproces, TORBED vergassing, vergeleken met de state-of-the-art technologie wervelbedvergassing. De resultaten van deze studie gaven aan dat er geen duidelijke voordelen zijn van de TORBED technologie boven de bestaande wervelbedtechnologie, terwijl de onzekerheden in technische prestaties en kosten veel groter zijn. Als een gevolg daarvan is in overleg met de IAG in 2008 besloten om dit werk pakket op wervelbedvergassing op lage temperatuur (<700°C) te richten. Deze studie betrof een literatuurstudie waarin de verschillende lage temperatuur concepten voor het gebruik van goedkope, moeilijke brandstoffen (met hoge gehalten aan alkalis en chloor) beoordeeld zijn. Eveneens is door middel van modellering bepaald wat de gevolgen zijn als een lage temperatuur vergasser wordt geïntegreerd met de kolenketel. De beoordeelde concepten waren directe wervelbedvergassing, alsmede de indirecte concepten FICFB, Silvagas en MILENA en de LT-CFB. Er is uit de literatuurstudie geconcludeerd dat er een groot gebrek is aan experimentele en operationele data in dit lage temperatuurgebied, bijvoorbeeld over de verdeling van alkalis over de as- en de gasfase. In een derde fase van het werkpakket is er door ECN kennis opgedaan op het gebied van lage temperatuur vergassing. Hieruit bleek dat de alkali belasting voor de kolen gestookte ketel aanzienlijk kan worden verminderd wanneer er via indirecte vergassing wordt bijgestookt. Dit leidt tot ongeveer 80-95% vermindering van alkalische en chloorbelasting voor de ketel. De resultaten zijn ook vertaald naar een massa- en energiebalans voor RDF en stro op een 300 MW\textsubscript{th} input basis. KEMA heeft met SPENCE berekeningen laten zien ingeval van 20 e/e % direct meestoken van A-hout gecombineerd met het bijstoken van 20 e/e% stro-pellets ten opzichte van 100% kolenstook er een elektrisch rendementsverlies van 2,7% wordt geschat. In het geval van het 20% e/e bijstoken van RDF is dit 1,6% t.o.v. 100% kolenstook. Wanneer dit vergeleken wordt met direct bijstoken van houtpellets op basis van 20% e/e is dit 0,3% minder elektrisch rendement voor RDF en 1,4% voor stro pellets.

**Werkpakket 3: Duurzaam asmanagement en -gebruik**

Na de verbranding van een vaste brandstof blijft er as over. Als biomassa in grote hoeveelheden wordt gestookt, zal de samenstelling van de as veranderen en daarmee ook mogelijke afzetmarkten. In dit werkpakket is een inventarisatie gemaakt van de beschikbare volumes en karakteristieken van toekomstige biomassa-assen. Op basis van deze inventarisatie zijn vijf specifieke cases bestudeerd, waarbij de assen niet meer in de bestaande routes naar cement en beton ingepast kunnen worden. Belangrijke punten in de beoordeling waren de noodzakelijkheid en de mogelijkheden van asrecycling als een middel om nutriënt- en mineralenkringlopen te sluiten. Dit heeft geleid tot heldere inzichten en een uitgebreidere beoordeling van een tweetal case: a) het terugbrengen van de hout-as naar de gronden waar deze bomen zijn geoogst en b) het recyclen van as van de verbranding van cacaodoppen naar de
plantage in Ivoorkust. De algemene conclusie is dat recycling in principe mogelijk is als de assen apart worden verzameld en dus niet worden gemengd met kolen-as. In het geval van bosbouw, kan het gehalte aan zware metalen de recycling belemmeren. Bij akkerbouw kunnen assen slechts in beperkte mate kunstmest vervangen. Het recyclen van as heeft minder milieueffecten dan storten. Een opmerkelijke conclusie was dat het gebruik van asse als grondstof voor de locale productie van kunstmest de beste optie is, omdat dit de milieucosts van het lange afstandtransport elimineert. Voor biomassas-assen die niet in bestaande toepassingen passen, is de productie van lichtgewicht kunstrond (Light Weight Aggregate, LWA) geïdentificeerd als de meest veelbelovende bulktoepassing. Er zijn testhoeveelheden geproduceerd en de materiaal eigenschappen bepaald. Er is geconcludeerd dat dit kunstrond geschikt is om grind te vervangen in beton. De markt is groot genoeg om de grote schaal productie van kunstrond van meestook-assen te accommoderen en de productiekosten (geschat rond de 35-45 Euro/ton) zijn het laagst van alle mogelijke alternatieve bulktoepassingen, maar wel duurder dan de huidige toepassingen van kolenvliegas in cement of beton.

**Werkpakket 4: Biomassa-meestoken onder oxyfuel omstandigheden**

Oxyfuel (onder verrijkte lucht condities) verbranding van kolen samen met biomassa is een van de opties om CO₂-afvangst mogelijk te maken. Over het vervuilingsgedrag in de boiler onder deze condities is weinig bekend. Het werk in dit werkpakket betrof een literatuurstudie naar de state-of-the-art kennis met betrekking tot oxyfuel verbrandingsconcepten, procesomstandigheden die verwacht kunnen worden (bijv. temperatuurprofielen, verblijftijd van deeltjes) en beschikbare gegevens over kolenvlak- en biomassaverbranding onder O₂- en CO₂-rijke omgeving. Dit literatuuronderzoek is gebruikt om een lab-schaal experimenteel programma op te stellen, waaronder een aantal foulingtesten. De resultaten van deze testen geven aan dat fouling toeneemt indien kolen, biomassas en mengsels daarvan onder oxyfuel condities worden gestookt. Met de nieuwe fysische en chemische data afkomstig van deze experimenten, is de Computational Fluid Dynamics (CFD) modelleringstool de Ash Deposition Predictor (ADP) is aangepast voor oxyfuel condities. Op termijn biedt dit de mogelijkheid het gedrag van as te voorspellen in gedetailleerde modellen voor nieuwe elektriciteitscentrales.

**Werkpakket 5: Foulingmonitoring/boilerdiagnostiek**

De verandering van het foulinggedrag en daarmee de veranderde warmteoverdracht van het rookgas naar de stoompijpen, is erg belangrijk als biomassa wordt meegestookt. Het is nuttig om dit gedrag on-line te kunnen meten. Dit werkpakket heeft zich gericht op de ontwikkeling van een sensor die het vervuilingsgedrag kan meten. Er is begonnen met experimentele werk om de gevoeligheid van de warmtefluxsensor in de bestaande ECN lab-schaal en industriële probes te verbeteren. Dit heeft geleid tot een algoritme dat het niet-lineaire gedrag beschrijft van de respons van de warmteflux signaal. De toepassing van dit algoritme maakt het mogelijk om nauwkeuriger metingen te doen aan fouling. In het bijzonder in het lage gevoeligheidsgebied, is de nauwkeurigheid twee ordes van grootte verbeterd. Daarnaast is een overzicht gemaakt van bestaande methoden voor boiler as depositiemetingen almede voor de beschikbaarheid van hoog temperatuur niet-invasieve stoommassastroommeters (Eng. non-invase steam mass flow meter) voor toepassing in boilers. Verder is de ontwikkeling van dit type meter succesvol geweest. Het prototype is ontworpen, gebouwd en uitgebreid getest op lab-schaal. Op basis hiervan is geconcludeerd dat de gevoeligheid onder hoge temperatuurcondities meer dan voldoend is. Om die reden is de lab-schaal versie aangepast om de toepassing in vol-schaal boilers mogelijk te maken. Aan het eind van het project is een plan gemaakt om deze te testen in de Borssele 12 boiler. Daarnaast is een conceptueel ontwerp van een geïntegreerd slagging/foulingmonitoring systeem voltooid, gebaseerd op de componenten ontworpen en getest in deze en andere EOS-LT projecten.

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3 Het testprogramma maakte geen deel uit van dit project.
**Werkpakket 6: Gebruik van natte biomassa en gecombineerd met warmtebenutting**

De combinatie van kolen/biomassa-gestookte installaties met de opwerking/conversie van natte biomassa door middel van warmte is een innovatieve mogelijkheid om de totale rendement van de centrale te verhogen. Het doel van dit werkpakket, dat is uitgevoerd in de tweede helft van 2009 en in 2010, is een eerste verkenning te doen naar en beoordeling van concepten die geschikt zijn voor de integratie van een centrale met een natte biomassaverwerking, alsmede een technisch-economische evaluatie van meest belovende technologieën. Dit is gedaan door middel van een deskstudie, site visits en contacten met leveranciers en technologieontwikkelaars. Als resultaat van deze verkenning zijn als potentiële interessante natte biomassa stromen geïdentificeerd: bermgras, de natte fractie van GFT afval, digestaat van anaerobe vergisting van agroresiduen en mest, mest en rioolslib. Deze selectie is gebaseerd op een aantal criteria, zoals beschikbaarheid in de nabijheid van de centrale, aanwezigheid in vergunningen en vochtgehalte. Op basis van een uitgebreid aantal criteria is een achtal processen beoordeeld. Van deze acht, zijn vier technologieën verder uitgewerkt in een technisch-economische studie. Deze zijn: 1) conventionele droging met een band droger, 2) anaerobe vergisting omdat het een commerciële en bewezen technologie betreft, 3) TORWASH (natte torrefactie) vanwege zijn eenvoud en was rendement, en 4) HTU (Hydro Thermal Upgrading) voor zijn potentieel om biobrandstoffen te maken uit lage kwaliteit biomassa en de relatief milde procescondities. In de technisch-economische analyse de beschikbare brandstoffen waarbij gras en GFT als grondstoffen zijn genomen, zijn ieder gekoppeld aan de voorbewerkingstechnologieën en vervolgens op basis van thermodynamische berekeningen die zijn uitgevoerd met de KEMA SPENCE® software, de daarop volgende conclusies getrokken:

- **Gras voorbewerken met een banddroger:** integratie van een banddroger volgens de lay-out zoals beschouwd binnen WP6 wordt verwacht technisch mogelijk te zijn, met enkele kleinere uitdagingen.

- **Gras voorbewerken met het TORWASH concept:** integratie van de TORWASH reactor volgens de lay-out zoals bestudeerd binnen WP6 zou technisch mogelijk moeten zijn maar is volgens de auteurs geen makkelijke oplossing. Het concept is in deze opstelling behoefte nog verdere optimalisatie.

- **GFT voorbewerken met HTU:** integratie van de HTU reactor volgens de lay-out zoals bestudeerd binnen WP6 wordt verwacht technisch mogelijk te zijn, met enkele uitdagingen.

Het onderzoek heeft hiermee aangetoond dat er mogelijkheden zijn natte biomassa voor te werken. De technologieën die hiervoor benoemd zijn, zijn divers, hebben ieder specifieke voor- en nadelen, zijn geschikt voor specifieke natte biomassa stromen, en hebben een verschillende mate van volwassenheid. Het integreren van deze concepten met een kolengestookte eenheid brengt echter kapitaalkosten en significante warmtekosten in de vorm van stoom met zich mee. Echter, gegeven de beschikbaarheid van natte biomassastromen zoals gras en GFT is de ontwikkeling van nieuwe technologieën relevant.

Daarnaast is een experimenteel programma uitgevoerd waarbij TORWASH materiaal is geproduceerd in een 20 liter autoclaaf. Hooi is voor dit programma gekozen als uitgangsmateriaal. De samenstelling en eigenschappen van dit materiaal komen overeen met materiaal dat al eerder geproduceerd is op kleine schaal. Het massa- en energierendement zijn wat lager dan in de eerder lab-schaal experimenten, maar dit kan verbeteren als er verder geoptimaliseerd wordt richting milder condities. De maalbaarheid van geTORWASH hooi is aanzienlijk verbeterd ten opzichte van het uitgangsmateriaal. De goed oplosbare zouten (K, Cl, etc.) zijn voor meer dan 90% verwijderd.
Werkpakket 7: Pneumatisch transport van biomassa en biomassa/kolen mengsels

Een typische centrale die biomassa meestookt zijn wijzigingen aangebracht aan de brandstofbehandelings- en opslagsystemen en soms de branders om biomass met kolen mee te stoken. Een belangrijk onderdeel is het maalysteem en haar componenten. Dit is waarom er in dit werkpakket aandacht is besteed aan een evaluatie van de luchtstroming en deeltjesverdeling in een brandstoftransportleiding van de EPZ centrale (Borssele) als een casestudie. Evaluatie van het maalysysteem heeft geleid tot de conclusie dat de capaciteit niet wordt bepaald door het malen of de thermische beperkingen opgelegd door de houtpelletbrandstof of de maalinstallatie zelf. De maalcapaciteit wordt meest waarschijnlijk bepaald door transportbeperkingen in de maalinstallatie en de brandstoftransportleiding.

De studie omvat de evaluatie van de brandstof deeltjesnelheden en de deeltjesverdeling tijdens transport, In dit kader werd een CFD (Computational Fluid Dynamics) model ontwikkeld.

De verkregen resultaten laten zien dat in het brandstoftransportledingsmodel de houtdeeltjes effectief worden getransporteerd door de primaire luchtstroom zonder significante circulatie en depositie. Echter, de hout- en kooldeeltjes lijken slecht te mengen in de lucht, waarbij er segregatie optreedt in de transportleiding, maar ‘roping’ werd in het model niet waargenomen. Met betrekking tot depositie is in het model waargenomen, dat deze meer optrad bij grote deeltjes met lage luchtsnelheden en minder bij hogere snelheden. De lichte deeltjes bleven meestal homogeen gedispergeerd in een homogene stroming. Door de grotere traagheid vertoonden grotere deeltjes duidelijk depositie nabij de onderkant van de wand en deze depositie werd significant bij hogere snelheid.

Werkpakket 8: Optimalisatie van numerieke modellen voor slagging en fouling

Bestaande poederkoolcentrales zijn oorspronkelijk ontworpen om kolen te verbranden met een tamelijk nauwe kwaliteitsmarge. Bij- en meestook van biomassa leidt dit tot een aantal operatieve uitdagingen, zowel in de branderzones als verder downstream. Een serieus probleem vormt de toename van verslakking (branderzone) en vervuiling van de warmteoverdragsoppervlakken in de ketel ten gevolge van veranderde as-chemie. De hogere gehalte aan vluchtige as-elementen, zoals alkali metalen, veroorzaakt een aantal ongewenste fenomenen die plaatsvinden in zowel de radiatieve als de convectieve zone van de ketel. Deze processen omvatten zowel chemische interacties tussen hoofdcomponenten van de kolen en biomassa-as (bijv. chemische reacties met alumino-silicaten) als fysische processen (condensatie van gasfase alkali zouten), die aerosolen vormen en coatings op asdeeltjes. Dergelijke processen worden als belangrijk gelden tijd onderkend een sleutelrol te spelen in ketelvervuiling en emissieproblematiek. Echter, de precieze details van deze fenomenen en de interactie van verscheidene processen worden nog steeds onvoldoende begrepen, laat staan dat ze alle zijn geïntegreerd in voorspellende numerieke modellen. Ontwikkeling van betrouwbare modellen wordt essentieel beschouwd voor succesvolle uitbreiding van de technologie met een wijde variëteit aan biomassabronnen.

Als resultaat van dit werkpakket zijn nieuwe correlaties voorgesteld, die de componenten omvatten gedurende geïdealiseerde en typische poederekoolverbrandingscondities uitgaande van de elementaire samenstelling van de brandstof. Enkelvoudige brandstoffen en blends zijn doorgerekend. Van specifieke belang zijn de componenten: SO2/SO3, HCl, KOH, NaOH, KCl, NaCl en K-AlSi. Hun moleaire concentraties in de gasfase (rookgas) zijn voorspeld. Deze informatie is gebruikt als input om op basis van balansberekeningen het lot van de componenten gedurende de rookgasafkoeltraject te bepalen. Een vereenvoudigd reacieschema, dat de ontwikkeling/combinatie van componenten tijdens dit afkoeltraject voorspelt, is eveneens voorgesteld. Verbeteringen in de voorgestelde componentvorming en -ontwikkeling zijn voorzien en correlaties dienen te worden gecomplementeerd met:
- een uittreiding van het aantal berekeningen voor relevante bij- en meestook brandstof blends;
- een gedetailleerde studie naar gasvormig calcium en magnesium die combineren tot carbonaten en oxalaten bij lagere rookgastemperaturen.
Verder dient voor het vereenvoudigde reactieschema het volgende te worden uitgevoerd:

- een volledige gevoeligheidsanalyse;
- de reactiesnelheden voor alle diverse reacties dienen te worden geïmplementeerd;
- de verkregen resultaten dienen te worden vergeleken en gevalideerd met boiler data met adequate experimentele tools (probe(s), conditionering en analyses).

Het werk is een stap verder op weg naar implementatie in een voorspellingen tool, bijvoorbeeld de Ash Deposition Predictor (ADP). Dit werk laat dan in het model niet alleen de fysische fenomenen modelleren die aanleiding geven tot depositie (impactie, turbulente diffusie en thermoforese), maar ook depositie ten gevolge van condensatie (heterogene condensatie op wanden en reeds bestaande deeltjes als ook homogene nucleatie). De ontwikkelde methodiek is aangehouden als een goed compromis tussen eenvoudigheid, realisme van voorspellingen en benodigde rekenkracht. Het werk zal de mogelijkheden van de ADP uitbreiden als een stap naar voorspelling van de invloed van condensatimechanismen op het overall depositiedrag. Deze realisatie van een dergelijk volledig condensatiemodel en de geassocieerde programmering in de ADP wordt geadviseerd als werk uit te voeren in het kader van een project van een (vier jaar durende) promotie.

**Valorisatie en disseminatie van de resultaten**

Tijdens de eindfase van het consortium zijn discussies tussen de partners gevoerd over de gezamenlijke valorisatie van de gemeneenschappelijk gegeeneerde resultaten en disseminatie hiervan. Hieruit is voortgekomen dat de gemeenschappelijk ontwikkelde *add-on* op het KEMA TRACE model perspectieven zou kunnen bieden.


Er kan worden geconcludeerd dat significante vooruitgang is geboekt en dat waardevolle kennis is opgedaan op het gebied van het mee- en bijstoken van biomassa om de lange termijn doelstellingen van het EOS-LT programma te bereiken en te faciliteren. De kennis en ervaring van de partners is in dit project door de betrokken industriële partijen in de IAG ervaren als waardevol en vruchtbaar. De beeldvorming over co-firing is realistischer en positiever geworden bij overheid en publiek, mede door dit onderzoek.
Summary

In the Netherlands, biomass is envisaged to play a major role in fulfilling national ambitions concerning the reduction of CO₂-emissions and the introduction of Renewable Energy Sources (RES). In this respect, ambitious targets have been set in the Long-Term Energy Research Strategy (EOS-LT) programme of the Dutch Ministry of Economic Affairs. This includes targets of 25% and 40% biomass co-firing in 2020 and 2040 respectively. Biomass co-firing comprises both direct co-firing, in which biomass is thermally converted together with the fossil fuel, and indirect co-firing, in which biomass undergoes separate thermal conversion and the processing of the resulting product (e.g., fuel gas) is integrated in the fossil-fuel-fired plant.

To meet the biomass co-firing targets, not only existing fossil-fuel-fired power plants will have to be considered, but also new plants involving new conversion technologies aiming at higher overall efficiencies and a lower environmental impact. The Dutch power generation sector expects that in 2040 coal-fired power generation capacity in the Netherlands will consist of a mix of near-zero and zero emission plants with a high efficiency (>50%) and CO₂-emissions comparable to state-of-the-art gas-fired combined-cycle units.

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

- Biomass upgrading, pre-treatment and feeding technology,
- Assessment and solution of technical bottlenecks in direct co-firing,
- Indirect co-firing technology,
- Process monitoring and control, and
- Residues management.

ECN and KEMA have formed an R&D consortium to address these biomass co-firing R&D requirements. TU Delft is involved as well, initially as a subcontractor, but in a later stage (2010) they will become a full partner. Furthermore, there is a close involvement of the Dutch power generation sector, ensuring that the R&D activities are well targeted to market needs and facilitating the implementation and exploitation of the results. Within the areas mentioned above, the consortium has made a careful selection of specific R&D topics, which are of particular relevance to the Dutch power generation sector and where the consortium has clear added value based on available expertise and R&D facilities. Of these topics, the following eight are covered within the EOS-LT biomass co-firing consortium projects and will be described in this final report:

- Fate of trace elements in biomass co-firing,
- Development of indirect co-firing technology,
- Sustainable ash management and development of new utilisation options,
- Biomass co-firing in oxy-fuel combustion,
- Fouling monitoring/boiler diagnostics,
- Wet biomass processing and heat utilisation,
- Pneumatic transport of biomass and coal/biomass blends,
- Optimisation of numerical models for slagging/fouling.

During the first two consortium years, close working relations have been established between ECN and KEMA, and through the post-doc studies with TU Delft. Within the third and fourth year, the co-operation was continued and extended further, leading to the generation of
numerous results. In the fifth year the TU Delft became a full partner of the consortium. Combining expertise and facilities of these organisations leads to clear added value. Moreover, the interaction with Industrial Advisory Group (IAG) members (representatives from the Dutch power generation sector) has been intensified and their role in guiding, monitoring and mentoring the work has been strengthened. The topics were covered in eight work packages.

**Work package 1: Fate of trace elements in biomass co-firing**
The behaviour of trace elements in conventional power plants at lower biomass co-firing percentages (up to 5-10% on energy basis) is rather well-known. However, this is not the case for higher co-firing percentages, with biomass containing different trace elements than coal. There is a need to improve the understanding of trace element behaviour in these processes to allow the formulation of design and operation guidelines for an adequate control of the emission of critical trace elements. This is relevant for regulations on emissions, waste and health. Relevant main and trace elements to be studied include the main elements nitrogen and sulphur, macro elements\(^4\) and trace elements\(^5\). With respect to the "Fate of trace elements in biomass co-firing", the R&D work comprised three complementary approaches, viz. thermodynamic equilibrium calculations (modelling), measuring campaigns at full-scale power plants (full-scale measuring campaigns) and lab-scale experiments. The three approaches are complementary and they each have their merits and their limitations. By combining them, a more complete picture of trace element speciation can be obtained. Moreover, modelling and lab-scale experiments allow the conditions to be extended to advanced clean coal technologies like USC and oxy-fuel combustion. Work along each of these lines has been carried out as follows:

- Finalising thermodynamic equilibrium calculations for biomass co-firing in conventional boilers, USC boilers and oxy-fuel combustion,
- Two full-scale measurement campaigns (Borssele 12 power plant of EPZ (2006) and Maasvlakte power plant of E.On (2008), focusing particularly on the influence of the SCR/deNOx installation, e.g. its deactivation and on the speciation of trace elements. Speciation of some specific elements, including chromium was measured using XAFS (X-ray absorption fine structure) techniques,
- A series of lab-scale tests to determine devolatilisation behaviour of trace elements in conventional and new boiler concepts and to study behaviour of elements in flue gas,
- Adaptation and application of an innovative analytical method combined with computer modelling to determine trace elements speciation/complexation in complex mineral matrices, including its validation against conventional speciation measurements.

Several conclusions were drawn from the work carried out. The devolatilisation behaviour of elements in coal was found to be different than the devolatilisation behaviour of the same elements from biomass. Results from full-scale measurements indicate that an SCR installation can play a significant role, e.g. by increasing the conversion (oxidation) and therefore the recovery of metallic mercury. SEM analyses of spent SCR catalyst have shown that two mechanisms play a role in deactivation: deposition on the surface layer and penetration of poisonous elements. Results of a detailed pH-static leachability study on these same spent SCR catalyst specimens have indicated that co-firing may indeed lead to increased deactivation rates, as the biomass-related elements as K, Ca and P may either interfere with and therefore enhance the poisonous action of coal-related elements as As, as well as form volatile/mobile or reactive phases (like Ca and K chlorides and sulphates). The extent of the deactivation turned out to be strongly depending on the exact composition of the fuel blend. It is well known that (clean) wood leads to a significantly less degradation than agricultural and food processing residues. However, even in the worst case the activity of the catalyst remained within the tolerance guaranteed by the producer, hence not compromising the NO\(_x\) emission limits.

\(^4\) Macro elements: Na, K, Ca, Mg, Cl, and P

\(^5\) Trace elements: F, Br, As, B, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Te, Ti, V and Zn
Results from the campaigns have also shown that SCR operating conditions do affect speciation and behaviour of elements, like the oxidising conditions in the boiler as well as in the FGD. Finally, in order to make all data and knowledge on speciation and co-firing conditions as found in the project available, a speciation knowledgebase has been built.

**Work package 2: Development of indirect co-firing technology**

The work on the "Development of indirect co-firing technology" has started in the first two years with a technical-economic evaluation of the prospects of a relative new gasification technology, TORBED gasification, compared to state-of-the-art fluidised-bed gasification. The results of the technical-economic evaluation did not reveal clear advantages of the TORBED gasification concept over circulating-fluidised-bed (CFB) gasification, whereas the uncertainties in technical performance and costs are much larger. Consequently, in consultation with the IAG it has been decided in 2008 to focus this work package on fluidized bed gasification. As strongly recommended by the IAG, this study has started with a desk study, in which different low temperature (< 700°C) fluidised-bed gasification concepts for indirect co-firing potentially suitable for using low cost, difficult fuels (rich in alkali and chlorine), and different ways of integrating gasification with the main coal-fired boiler were assessed. The compared concepts were CFB gasification, the indirect concepts FICFB, Silvagas and MILENA concepts, and LT-CFB. It was observed that there is a lack of experimental and operational data of low temperature gasification, e.g. on the distribution of alkalis. The third phase of this work package was dedicated to producing experimental data of low temperature gasification of difficult biomass fuels. This showed that the alkali load for a pulverized coal-fired boiler can be drastically reduced when the co-firing route is via indirect gasification. Roughly 80-95% of the alkali and chlorine will not enter the boiler. Based on the results, mass and energy balances have been made for indirect gasification (20 e/e%) of RDF and straw pellets on a 300 MW_in input basis, additional to 20 e/e% direct co-firing of A-wood. KEMA used these results for SPENCE calculations and showed that for straw pellets compared to 100% coal firing has an estimated efficiency loss of 2.7% compared to 100% coal. The RDF case shows better results with SPENCE and has 1.6% efficiency loss. When compared to 20% e/e direct co-firing the loss is 0.3% and 1.4% respectively the RDF and straw pellet case.

**Work package 3: Sustainable ash management and development of new utilisation options**

After combustion of a solid fuel, ash remains. When (co-)firing biomass, ashes with another composition remain and an alternative utilisation routes may be needed. In the work package "Sustainable ash management and development of new utilisation options", as a starting point an inventory was made of volumes and characteristics of future biomass ashes. Based on this inventory, five specific cases were studied where ashes could no longer be utilized in the existing routes to concrete and cement. Important points in the assessment were the necessity and possibilities of ash recycling as a means to close nutrient and mineral cycles. This has led to clear insights and a more elaborate assessment of two cases: a) returning wood ashes to the original soils where the trees were harvested, and b) recycling ashes from combustion of cocoa shells in the Netherlands to the plantation in Ivory Coast. The overall conclusion is that recycling is in principle possible when the ashes are separately collected (not mixed with coal ashes). In forestry, heavy metal contents of wood ash may prevent recycling. In agriculture, ashes can replace only part of the fertilizer used. Recycling has less environmental impact than land fill. A remarkable conclusion is that the best option is to use ashes as a raw material in local production of fertilizer. The reason is that it eliminates the environmental impact of long distance transportation. For fly ashes from biomass co-firing, production of light-weight aggregates (LWA) was identified as the most promising bulk utilization. LWA test batches were produced and material properties were determined. LWA from co-firing ashes were found to be suitable for replacing gravel in concrete applications. The market is large enough to accommodate bulk production of LWA from co-firing ashes and LWA have the lowest production cost (estimated in the range of 35-45 Euro/tonne) of all feasible bulk applications, but more expensive than established applications in cement or concrete for coal fly ash.
Work package 4: Biomass co-firing in oxy-fuel combustion
Oxyfuel with biomass firing is one of the options to make CO$_2$-capture possible, however not much is known about the fouling behaviour in the boiler under such conditions. The work on "Biomass co-firing in oxy-fuel combustion" has started with a literature study on the state-of-the-art concerning oxy-fuel combustion system concepts, process conditions to be expected (e.g., temperature profiles, particle residence times) and available data on coal/biomass combustion in O$_2$/CO$_2$-rich atmospheres. The results of this literature study have been used to define the lab-scale experimental programme, including amongst others a number of fouling tests. Results of the said runs indicate an increase in the fouling propensities of coals, biomasses as well as their blends under oxy-fuel firing conditions. With these and other new physical and chemical data gathered from the said tests, the Computational Fluid Dynamics (CFD) modelling tool the Ash Deposition Predictor has been adopted for oxy-fuel co-firing conditions. This will in the long run also help to predict the behaviour of the ash in detailed models of new power plant designs.

Work package 5: Fouling monitoring/boiler diagnostics
Change in fouling behaviour in the boiler is one of the important issues when co-firing biomass. It is therefore of interest to have on-line tools to monitor this phenomena. The work on "Fouling monitoring/boiler diagnostics" started with experimental work to improve the sensitivity of the heat flux sensor in the existing ECN lab- and industrial deposition probes. The said calibration work led to an algorithm describing the non-linear behaviour of the heat flux signal response. Application of this algorithm will allow for much more accurate measurements of the fouling propensity. In particular in the lower measuring range, the accuracy has improved by two orders of magnitude. Further, a review of the existing methods for the in-boiler ash deposition diagnostic techniques as well as non-invasive mass flow measurement has been completed. Next, the development of a high-temperature non-invasive steam mass flow meter, a component essential for further development of an online fouling monitoring system, has proven quite successful. The prototype of the said apparatus has been designed, built and extensively tested on the lab-scale, whereupon it was concluded that the sensitivity under the relevant high temperature conditions are more than satisfactory. Therefore the lab-scale prototype has been re-engineered to enable the application in the full-scale boiler. At the end of the project a plan was made to set up a full-scale test at the Borssele 12 boiler in the fall of 2010$^6$. Finally, a conceptual design of an integrated slagging/fouling monitoring system, based on the components developed and tested earlier on in this and other EOS-LT projects, has been completed.

Work package 6: Wet biomass processing and heat utilization
An interesting option to increase the overall efficiency is to combine coal/biomass-fired power stations with heat-demanding biomass upgrading or biomass conversion processes for wet biomass streams. The main objective of this work package is a first screening to identify and assess concepts for the integration of coal-fired power generation and wet biomass processing, aimed at increased overall efficiencies and cost reduction through optimal heat integration by performing a desk study, having site visits and from information of suppliers and technology developers. As a result of the first assessment according to the defined criteria, the following biomasses were identified as most promising biomass types: (roadside) grass, organic wet/compostable fraction (GFT), digestates from the anaerobic digestion of agricultural residues and manures, animal manures and sewage sludge. This selection is based on a number of criteria, like availability in the vicinity of the plant, permits and moisture content. Based on a number of criteria, eight processes have been assessed. From those, the four technologies have been evaluated techno-economically. These are: 1) thermal drying with a belt dryer as the reference technology, 2) anaerobic digestion because it represents a commercial and proven technology, 3) TORWASH (wet torrefaction) for its simplicity and efficiency in drying and washing, and 4) HTU (Hydrothermal upgrading) for its potential in extracting bio-fuels from low grade biomass

$^6$ Execution of the test plan is not a part of this project.
at relatively mild process conditions. In the techno-economic analysis the available biomass types (grass and GFT were considered) are both coupled to the pre-processing technologies and thermodynamic calculations have been performed with the KEMA SPENCE® software. For the feedstock technology combinations the following conclusions were drawn:

- **Grass pre-processing by belt drying:** integration of a belt dryer following the layout as studied is expected to be technically feasible with some minor challenges.
- **Grass pre-processing by TORWASH:** integration of the TORWASH reactor following the layout as presented in this report may be technically feasible but to the authors’ opinion it is not a convenient solution. The concept is far from optimized in the studied layout.
- **GFT pre-processing by hydrothermal upgrading:** integration of the HTU reactor following the layout as presented in this report may be technically feasible but in the authors’ opinion is not logical to do so.
- **GFT pre-processing by anaerobic digestion:** integration of an anaerobic digester following the layout as presented in this report is expected to be technically feasible with some challenges.

The study presented that wet biomass pre-processing technologies exist. The mentioned technologies are diverse, have each their own pro’s and con’s, are feasible for specific types of biomass, and have a different state of maturity. Integrating these technologies with a coal fired unit involves capital costs as well as significant cost of heat by means of steam. However, given the availability of wet biomass streams as grass and GFT, the development of new technologies is relevant.

As part of the experimental programme, a batch of TORWASH material was produced in a 20 litre autoclave. Hay was selected as the feedstock for this programme. The composition and characteristics compare well with those of the material produced previously on a small-scale. Mass and energy yield are somewhat lower than on the small scale, but this can improve with optimization towards milder conditions. The grindability of the material is significantly improved compared to the feedstock. The dissoluble salts (K, Cl, etc.) are removed for more than 90%.

**Work package 7: Pneumatic transport of biomass and coal/biomass blends**

A typical co-firing installation includes modifications to the fuel-handling and storage systems and possibly the burner to accommodate biomass. One important consideration is the milling system and its components. This is why the attention is put to evaluate the airflow and particle distributions in a pulverized fuel duct in the EPZ (Borssele) power plant, as a case study. Evaluation of the mill system in fact, led to the conclusion that mill capacity is not controlled by grinding or thermal limitations imposed by the wood pellet fuel or the mill itself. Mill capacity is most likely controlled by transport limitations within the mill and fuel pipe.

The study includes the evaluation of fuel pipe velocities and particle flow distribution because the evaluation of any pulverizer/mill system requires the determination of the transport limitations and a Computational Fluid Dynamics (CFD) model was developed. The results obtained show that in the fuel pipe transport model the wood particles are effectively transported by primary air without significant circulation and deposition observed. However wood and coal particles appear to mix poorly with air with particles segregation in the fuel pipe but “roping” phenomena does not occur. The deposition of heavier particles was found to be higher at lower velocities and lower at higher velocities. The lighter particles were found to remain mostly suspended with homogeneous distribution. Due to a larger inertia, the larger particles clearly showed deposition near the bottom of the wall and this deposition was found to be pronounced at higher velocity.

**Work package 8: Optimisation of numerical models for slagging/fouling**

Existing pulverized fuel (PF) boilers have originally been designed to combust coals of a fairly narrow quality range. Co-firing biomass results in a number of operational issues, both in the
Combustion zone, as well as further downstream. A serious issue forms the increase in the slagging (near-burner) and fouling of the boiler heat transfer surfaces, due to the altered fuel ash chemistry. Higher shares of volatile ash components, such as alkali metals, cause a number of undesired phenomena to occur both in the boiler’s radiant and in the convective part. These processes include both chemical interactions between main components of the coal and biomass ash (i.e. chemical reactions with aluminosilicates), as well as physical processes (condensation of the gas-phase alkali salts) forming fine aerosols and coatings on ash particles. Such processes have long been recognized as playing a key role in boiler fouling and emission issues. However, the exact details of these phenomena and the interaction of several processes are still insufficiently understood, let alone integrated into predictive numerical models. Development of reliable co-combustion models is considered to be essential to successfully expand the technology making use of a broad variety of green sources.

In this work package new correlations were proposed, defining the species formed during ideal and typical PF combustion from the elemental fuels composition. Pure fuels and blends were studied. The species of interest are: SO$_2$/SO$_3$, HCl, KOH, NaOH, KCl, NaCl and K-AlSi. Their molar concentrations were also predicted. This information will be used as input to determine from a balance the fate of species as temperature of the flue gas decreases in the boiler. A simplified reaction scheme simulating the evolution/combination of the components as temperature decreases was also proposed. Improvements of the proposed species formation and species evolution pattern are foreseen, a the species formation correlations would need to be complemented with:

- an extension of the number of calculations for relevant co-firing fuels combustion;
- a detailed study of the gaseous calcium and magnesium elements combining with carbonates and oxalates at lower flue gas temperature.

Moreover, for the reduced reaction scheme:

- a complete sensitivity analysis would need to be carried out;
- the reaction rates corresponding to the different reaction would need to be expressed;
- the results obtained would need to be compared and validated towards real boiler data, using an appropriate experimental set up.

This work is a first step towards implementation in a predictive tool, e.g. ADP. The work would allow to model not only the “physical” phenomena leading to deposition such as inertial impaction, turbulent diffusion and thermophoresis, but also, to consider deposition due to various condensation modes (heterogeneous onto walls and already existing particles as well as homogeneous nucleation). The methodology developed was retained as a good compromise between simplicity, realism of predictions and equivalent calculation burden. The work will re-inforces the capabilities of ADP as a step to predict the influence of condensation mechanisms on overall deposition behaviour. The realization of a full condensation model and its coding in the ADP is advised to be carried out within the scope of a future PhD project.

**Valorisation and dissemination of the results**

In the course of the third year of the consortium, discussion started on the joint valorisation of the commonly generated results and the dissemination of the gathered knowledge. A jointly developed add-on on the TRACE model has been identified as a possible candidate for joint valorisation.

The close involvement of the industry via the Industrial Advisory Group ensured that the knowledge generated in this project is well disseminated towards the end-users of this knowledge: the Dutch power producers. In May 2010 the consortium organized the Biomass Co-firing Symposium aimed at a broad public in Amsterdam, attended by 60 people. On this symposium the results of the consortium were presented and discussed. Furthermore, the project generated numerous reports, articles and contributions to conferences and results were used as a basis for two contributions in the form of two chapters for a book ("Solid Biofuels for Energy:

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ECN-E--11-037

Also, a consortium website domain ‘Biomasscofiring’ has been registered, which will be used both as advertising platform for the ECN/KEMA consortium itself, as well as for biomass cofiring as a sustainable energy generation concept.

Overall, it can be concluded that significant progress has been made and valuable insights have been obtained in the field of co-firing biomass in power plants to reach and facilitate the long-term targets of the EOS-LT programme. The combined knowledge and experience of the partners was experienced in this project as valuable and fruitful. The image of biomass co-firing has become more realistic and positive for government and public, partially by this research programme.
1. Introduction

In the Netherlands, biomass is envisaged to play a major role in fulfilling national ambitions concerning the reduction of CO₂-emissions and the introduction of Renewable Energy Sources (RES). In this respect, ambitious targets have been set in the Long-Term Energy Research Strategy (EOS-LT) programme of the Dutch Ministry of Economic Affairs (see Table 1.1).

<table>
<thead>
<tr>
<th>Time frame</th>
<th>Targets</th>
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| 2020       | • 20% electricity from biomass, first utilisation of residual heat in distributed biomass-based plants  
            • 25% biomass co-firing (on energy basis)  
            • 100% utilisation of conversion residues  
            • Technology available for indirect co-firing consisting of a 100 MWₘ biomass gasifier in combination with a gas-fired combined-cycle plant |
| 2040       | • 40% electricity from biomass  
            • 40% biomass co-firing (on energy basis)  
            • Conversion efficiency for coal + biomass to electricity > 50%, full utilisation of residual heat in distributed biomass-based plants (resulting in an overall efficiency of > 85%) and an electrical efficiency of 40% for waste incineration/processing  
            • Several indirect co-firing plants consisting of a 100 MWₘ biomass gasifier in combination with a gas-fired combined-cycle plant in operation |

As it appears clearly from Table 1, biomass co-firing is one of the main technology options, where biomass co-firing includes all forms of biomass conversion integrated with fossil-fuel-fired plants, i.e.:
- **Direct co-firing**, in which biomass is thermally converted together with the fossil fuel, and
- **Indirect co-firing**, in which biomass undergoes separate thermal conversion and the processing of the resulting product (e.g., fuel gas) is integrated in the fossil-fuel-fired plant.

Co-firing also includes co-gasification of biomass in coal-fired gasifiers.

For biomass co-firing, the focus in this project is on coal-fired plants. An earlier ECN-study has shown that in the Netherlands the possibilities for indirect biomass co-firing in gas-fired power plants are limited [Zwart, 2003].

**Long-term vision Clean Coal Technologies**

To meet the biomass co-firing targets, not only existing fossil-fuel-fired power plants will have to be considered. In the period up to 2040, the power generation infrastructure will undergo important changes, including the construction of new large-scale coal- and gas-fired plants. In fact, the design and construction of several new plants has been started already [Seebrecht, 2007]. In the case of coal, new clean coal technology will be introduced aiming at higher overall efficiencies and a lower environmental impact. In this respect, the Dutch power sector supports the vision described in the inventory study "State of the art studie techniekontwikkeling voor de elektriciteitsvoorziening", conducted by KEMA in the framework of the "Transitieplatform Duurzame Elektriciteit" [Bolt, 2006]. According to this vision, it is expected that in 2040 coal-fired power generation capacity in the Netherlands will consist of a mix of near-zero and zero emission plants with a high efficiency (>50%) and CO₂-emissions comparable to state-of-the-art gas-fired combined-cycle units. Coal gasification with CO₂ capture and oxy-fuel coal combustion with Ultra Super Critical (USC) steam conditions and CO₂ capture are envisaged to be the most cost-effective technologies. Based on this vision, the members of the Industrial
Advisory Group (IAG) supporting this consortium have formulated a set of notions concerning long-term research priorities [Jeurissen, 2008]. These form the basis of the consortium R&D programme.

1.1 R&D requirements to meet EOS-LT targets for biomass co-firing

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

1. **Biomass upgrading, pre-treatment and feeding technology.** Apart from their CO$_2$-neutral nature, most types of biomass have inferior properties compared to fossil fuels. This includes low energy density, hydrophylic nature (high water uptake when stored in open air), fibrous structure and tenacity (poor flowability and grindability), susceptibility to biodegradation and heating, and high contaminant levels (especially for biomass residues/waste and mixed streams). Dedicated upgrading/pre-treatment and feeding technology will be required to enable (and/or reduce the cost of) handling, transport and storage and to meet the narrow feedstock specifications related to thermal conversion processes. In this respect, it would be very attractive to develop technology for the upgrading of biomass into standard or "commodity" fuels with properties similar to existing fossil fuels like coal or oil.

2. **Assessment and solution of technical bottlenecks in direct co-firing.** Direct biomass co-firing in coal-fired plants, especially at higher co-firing percentages (>5-10% on energy basis), involves a range of potential technical bottlenecks (e.g., burn-out, flame stability, heat distribution, NO$_x$ formation, slagging/fouling, (fouling-induced) corrosion, impact on downstream gas cleaning, emissions, pneumatic transport). These bottlenecks will have to be assessed, and strategies, technology and predictive tools will have to be developed to avoid or overcome them. This holds not only for existing (conventional) pulverised-coal-fired plants, but also for new coal-fired capacity based on advanced coal conversion technologies such as USC combustion, oxy-fuel combustion and entrained-flow gasification.

3. **Indirect co-firing technology.** In coal-fired power plants, the targeted co-firing percentages will likely have to be met through a combination of direct and indirect co-firing. Direct co-firing is most cost-effective, which gives a strong incentive to maximise this option beyond the 2006 levels (typically 5-10% on energy basis). Indirect co-firing technology for both coal-fired and gas-fired plants is insufficiently proven and requires further R&D. This also holds for the smart, cost-effective combination of direct and indirect co-firing.

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

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

1.2 EOS-LT consortium on biomass co-firing

ECN and KEMA have formed an R&D consortium to address these biomass co-firing R&D requirements. TU Delft is involved as well, initially as a subcontractor, but in a later stage it is
foreseen that they will become a full partner. Furthermore, there is a close involvement of the Dutch power generation sector in three different ways, viz.:

- **Industrial Advisory Group (IAG)**. This IAG consists of representatives of the Dutch power generating companies ((Delta, Electrabel, E.On, EPZ, Essent, NUON) and Vliegasunie, and is chaired by dr W. Willeboer of Essent. It guides and directs the R&D programme. The composition of the IAG is the same as for the steering group of cluster 4 (New Technology) of the so-called Technical Service Agreement (TSA) between the Dutch power sector and KEMA. In the framework of this TSA, the power sector delegates specific R&D-issues to KEMA. By having the IAG and the TSA-cluster 4 steering group consisting of the same members, a congruent R&D portfolio is assured.

- **Mentorship**. The work in each work package is guided on a frequent basis by a designated member of the IAG.

- **Direct participation in specific R&D topics**. Several of the power generators and Vliegasunie participate directly in R&D topics, e.g. by making their boilers available for measurements and tests.

This close involvement of the Dutch power sector ensures that the R&D activities are well targeted to market needs and it facilitates the implementation and exploitation of the results.

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

The following specific topics have been selected to be relevant for further R&D:

1. **Torrefaction**. Torrefaction is regarded a key technology for the upgrading of biomass into standard (commodity) solid fuels, leading to substantial cost reductions in biomass handling, transport and storage, and improving the compatibility of biomass as a fuel for thermal conversion processes.

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

3. **On-line monitoring and control**. Focus is put on the development of two specific techniques, viz.:
   - EARS (Early Agglomeration Recognition System) for monitoring and control of bed agglomeration in fluidised-bed combustion and gasification systems, based on a unique measurement concept developed by TU Delft.
   - On-line fouling monitoring and control, based on a strong knowledge base on ash behaviour at ECN, specific sensor expertise at the Dutch firm Hukseflux and soot blowing expertise at Clyde Bergemann.

4. **Indirect co-firing**. The particular topics here are:
   - TORBED gasification potentially being superior to fluidised-bed gasification in terms of (fuel) flexibility, required plot space and investment cost, following earlier development work with KEMA involvement.
- Possibilities of low temperature gasification (<700º) to broaden the fuel portfolio of power plants with high ash/chlorine containing fuels.
- Optimising the gas-side integration of the gasifier with the main (pulverised-fuel) boiler, making use of state-of-the-art full-scale experience with indirect gasification by Electrabel (Ruien, Belgium) and Essent (Geertruidenberg, The Netherlands).

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

6. **Conversion-aspects of biomass co-firing in advanced clean coal combustion.** Focus lies in particular on USC combustion and oxy-fuel combustion. The knowledge base on the combustion characteristics, including ash formation, slagging/fouling and corrosion, in these new processes and with biomass co-firing is still in its infancy.

Only part of these topics were addressed in the EOS-LT biomass co-firing consortium projects. Other topics are being addressed in other projects. This includes other EOS-LT projects and earlier DEN/BSE-projects, such as:
- Torrefaction, for which there is a separate EOSLT project (EOSLT03017 - TORTECH).
- EARS, for which there is a DEN project (SenterNovem project number 2020-03-12-14-003 - EARS II).
- On-line fouling monitoring and control, for which there is a BSE project (SenterNovem project number 2020-04-11-14-003 - Boiler fouling). However, some of the work on this topic will be continued in the consortium projects.
- Fouling and corrosion during biomass co-firing in USC boilers, for which there is a separate EOS-LT project (EOSLT01009 - USC + biomass).
- Optimal co-combustion of biomass/waste in pulverised fuel firings (DEN project 2020-02-12-14-003).
- Operational problems with slagging and corrosion in biomass co-combustion (DEN project 2020-02-12-14-002).

In this report, only the results concerning the specific topics covered within the EOS-LT biomass co-firing consortium projects will be described. These topics are:
- Fate of trace elements in biomass co-firing,
- Development of indirect co-firing technology,
- Sustainable ash management and development of new utilisation options,
- Biomass co-firing in oxy-fuel combustion,
- Fouling monitoring/boiler diagnostics,
- Wet biomass processing and heat utilisation,
- Pneumatic transport of biomass and coal/biomass blends, and
- Optimisation of numerical models for slagging and fouling.
2. Results

For the selected eight topics to be covered within the EOS-LT biomass co-firing consortium projects, work packages were defined. These work packages are:

- **WP1**: Fate of trace elements in biomass co-firing (WP leader: KEMA)
- **WP2**: Development of indirect co-firing technology (WP leader: KEMA (2006-2009), ECN (2010))
- **WP3**: Sustainable ash management and development of new utilisation options (WP leader: ECN)
- **WP4**: Biomass co-firing in oxy-fuel combustion (WP leader: ECN), and
- **WP5**: Fouling monitoring/boiler diagnostics (WP leader: ECN)
- **WP6**: Wet biomass processing and heat utilisation (WP leader: KEMA)
- **WP7**: Pneumatic transport of biomass and coal/biomass blends (WP leader: TUD), and
- **WP8**: Optimisation of numerical models for slagging/fouling (WP leader: TUD).

The eight work packages are elucidated in the following sections. Each following section summarizes the problem definition, objectives, approach, results, conclusions and recommendations of each work package. More detailed information can be found in the separate extensive reports of each work package. These are listed in Section 4.

2.1 WP1: Fate of trace elements in biomass co-firing

2.1.1 Problem definition

The behaviour of trace elements in conventional power plants at lower biomass co-firing percentages (up to 5-10% on energy basis) is rather well-known. However, this is not the case for higher co-firing percentages, with biomass containing different trace elements than coal. Nor is it the case for advanced clean coal combustion plants, i.e. units working at extreme steam conditions (Ultra Super Critical (USC) boilers) or oxy-fuel combustion in combination with CO\(_2\) removal and storage. Furthermore, far less is known about the speciation of these elements (i.e. the chemical form in which they occur) and how this depends on the state of oxidation and the related complex building behaviour, especially in flue gas cleaners and scrubbers. Not much is known for instance on the influence of temperature, residence time, pH and redox potential.

There is a need to improve the understanding of trace element behaviour in these processes to allow the formulation of design and operation guidelines for an adequate control of the emission of critical trace elements. This is relevant for regulations on emissions, waste and health. Relevant main and trace elements to be studied include the main elements nitrogen and sulphur, macro elements\(^7\), and trace elements\(^8\).

2.1.2 Objectives

The overall objectives of this work package are:

- Setting up a knowledge database on the behaviour of trace elements at higher biomass co-firing percentages (>5-10% on energy basis) and for advanced (USC and oxy-fuel) coal-fired power plants. This database should include knowledge on the mechanisms of formation and speciation of trace elements under these conditions.

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\(^7\) Main elements: Na, K, Ca, Mg, Cl, and P

\(^8\) Trace elements: F, Br, As, B, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Te, Ti, V and Zn
Formulation of design and operation guidelines to control the emission of critical trace elements. Particular attention will be given to upgraded flue gas desulphurisation (FGD) units and to USC and oxy-fuel combustion in combination with flue gas cleaning and CO₂ removal.

2.1.3 Approach

As shown in Table 2.1, a combination of three different approaches is applied to obtain information about speciation of trace elements, viz. thermodynamic equilibrium calculations (modelling), measuring campaigns at full-scale power plants (full-scale measuring campaigns) and lab-scale experiments. The three approaches are complementary and they each have their merits and their limitations. By combining them, a more complete picture of speciation can be obtained. Moreover, modelling and lab-scale experiments allow the conditions to be extended to advanced clean coal technologies like USC and oxy-fuel combustion.

The full-scale measuring campaigns are conducted in conjunction with full-scale measuring campaigns in the framework of the TSA programme (TSA = Technical Services Agreement). In general, sampling and analysis to determine mass balances is conducted with TSA resources, while the complementary EOS-LT sampling and analysis is focused on trace elements and their speciation.

Table 2.1 Three complementary approaches to investigate trace element speciation

<table>
<thead>
<tr>
<th>Approach</th>
<th>Modelling</th>
<th>Full-scale measuring campaigns</th>
<th>Lab-scale experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditions</td>
<td>Theoretical Variable input</td>
<td>Real Fixed input</td>
<td>Semi real Variable input</td>
</tr>
<tr>
<td>Boiler</td>
<td>USC, oxy-fuel combustion</td>
<td>SC</td>
<td>USC, oxy-fuel combustion</td>
</tr>
<tr>
<td>Analysis/results</td>
<td>Calculated</td>
<td>Direct measurements (XAFS)</td>
<td>Direct/indirect measurements (LeachXS, CCSEM)</td>
</tr>
<tr>
<td>Elements</td>
<td>Ba, Cr, Mn, Co, Ni, As, Sb, Cd, Pb, Zn, Hg, Se, Te</td>
<td>Cr, V, Zn, As, Se</td>
<td>15 toxic metals</td>
</tr>
<tr>
<td>Partner involved</td>
<td>KEMA</td>
<td>KEMA</td>
<td>ECN</td>
</tr>
</tbody>
</table>

2006

- Make an inventory of future biomass streams for direct co-firing.
- Define operating conditions, to be used in the thermodynamic equilibrium calculations and in lab-scale experimentation.
- Set up a blueprint for full-scale measuring campaigns.
- Conduct a preliminary check of the blueprint in 1st measuring campaign
- Prepare the lab-scale test programme including development of appropriate lab-scale test and analysis facilities.
2007
- Conduct thermodynamic equilibrium calculations for biomass co-firing in conventional boilers, USC boilers and oxy-fuel combustion.
- Conduct lab-scale tests for simulation of 25-40% biomass co-firing in conventional and future USC boilers.
- Develop a first set-up of the knowledge database.

2008
- Carry out 2nd full-scale measuring campaign.
- Conduct lab-scale tests for simulation of up to 40% co-firing in oxy-fuel combustion including CO₂ removal.
- Fill the knowledge database with data obtained from lab-scale testing and full-scale measurement campaigns.

2009
- Formulate design and operation guidelines for the control of critical trace elements emissions.
- Develop a user-friendly version of the knowledge database.

2010
- Detailed study on SCR deactivation and the formation of SO₃ in the SCR installations

2.1.4 Results 2006-2010 and discussion
Below a summary of the main results in 2006-2009 is presented. The results are described in more detail in a series of topic-specific reports, to which reference is made [Beek, 2010; Cieplik, 2008; Eijk, 2010; Eijk, 2008; Kalivodova, 2008; Meij, 2007; Meij, 2008; Stam, 2008; Stam, 2007; Vredenbregt, 2010a; Vredenbregt, 2010b; Winkel, 2007].

Concentration of trace elements in biomass in the future
An inventory has been made of the concentrations of trace elements in biomasses, which are expected to be relevant for future use at high co-firing percentages in existing coal-fired boilers and in new USC or oxy-fuel combustion plants. Information about potential biomass types suitable for co-firing has been obtained from a study conducted in the framework of EOS-LT-project EOSLT01009 [Meijer, 2006].

Based on availability of biomass for energy use and suitability for co-firing, it was concluded that main biomass streams are woody biomass, oils and residues from the food industry. However, also other, new types of biomass may play a prominent role, depending on developments on the biomass and biofuel markets. These new types may include upgraded biomass (e.g. torrefied biomass), aquatic biomass and residues from bio-fuel production.

It appears that concentrations of trace elements in biomass are lower than in coal in all cases, but they can still be significant when ash content is taken into consideration. Mn and Zn content of most biomasses are comparable with coal. Torrefaction leads to an enrichment of trace elements due to the partial devolatilisation. Other elements that are present in relatively high amounts in one or more of the biomass samples are Na, K, Cl as well as N. More details on trace element compositions of major biomass types can be found in two separate reports [Winkel, 2007; Eijk, 2008].
Thermodynamic equilibrium calculations

The objective of this approach is to predict the speciation of trace elements in fly ash and to identify underlying mechanisms for biomass co-firing in conventional, USC and oxy-fuel boilers. The basic assumption is that thermodynamic equilibrium is reached. To determine trace element speciation, thermodynamic equilibrium calculations have been conducted with a software package (FactSage). This equilibrium approach is often used, although thermodynamic equilibrium is not likely to be reached in practice due to the short residence times (1-4 s). However, it gives an (expert) estimate and an insight in the processes of formation of compounds. As wood is expected to be the most important co-firing biomass of the future in the Netherlands, calculations on co-firing were performed with wood. Speciation was calculated for Ba, Cr, Mn, Co, Cu, Ni, Sb, Cd, Pb and Zn, Hg, Se, Te and sulphates. Detailed results are given in [Stam, 2008]. As an example, the calculated Cr speciation for different levels of co-firing in conventional boilers is given in .

![Figure 2.1](image.png)  
**Figure 2.1**  Typical result of thermodynamic equilibrium calculations: chromium speciation for 0-40% wood co-firing in conventional boilers

As can be seen in the above figure, the flux of all the selected phases containing chromium, formed in different temperature regimes, decreases when co-firing biomass. This is primarily due to the much lower chromium content of the biomass as compared with typical hard coals. However it can be observed that the temperature at which higher toxic hexavalent (6⁺), rather than trivalent (3⁺) chromium forms are predominating, is shifting towards the lower end of the scale.

In general, from the thermodynamic equilibrium calculations, the following can be concluded. Speciation depends mainly on:
- The furnace exit gas temperature in USC boilers,
- Fuel composition when co-firing biomass, and
- Recycling of flue gases in oxy-fuel combustion.

However, it appears that the fuel (blend) composition is the parameter with by far the most influence.

Full-scale measuring campaigns

For the full-scale measuring campaigns, a generic measuring programme (blue print) has been defined, based on previous experiences and on information from literature [Meij, 2007]. The blue print has been applied and validated during a first full-scale campaign carried out in October 2006 at unit 12 of the Borssele power station (BS-12). This is reported in detail in [Meij, 2008; Kalivodova, 2008]. During this campaign, almost 30% (m/m) of coal was replaced by a mixture of three types of secondary fuel, all residues of vegetable origin. This corresponds
with about 20% co-firing on energy basis (e:e). shows a schematic of the BS-12 power plant with the KEMA and ECN sampling points.

Samples of all inlet and outlet streams were taken by KEMA and ECN carried out fly ash and flue gas measurements at two intermediate points, viz. before and after the SCR/DeNOx installation. At these two locations, cascade impactors have been applied for fly ash collection. The samples obtained within two test days were then subjected to extensive analytical analysis at ECN. All input and output streams were analysed, namely (a) indirectly co-fired fuel, (b) coal, (c) biomass, (d) lime, (e) process water, (f) furnace bottom ash, (g) pulverised fly ash from 1st to 4th hopper, (g-C) pulverised fly ash (collected), (h) waste-water treatment sludge, (i) waste-water treatment effluent, (j) FGD sludge, (k) gypsum.

Figure 2.2 BS-12 power plant layout including sampling points during the first measuring campaign (SCR = Selective Catalytic Reduction (DeNOx), ESP = Electrostatic Precipitator, FGD = Flue Gas Desulphurisation)

All results are reported in detail in [Meij, 2008; Kalivodova, 2008]. As an illustration the distribution of the elements over the input and output streams on the first day is presented in...
Figure 2.3  Borssele 12 full-scale campaign: distribution of the elements over input and output streams on the first day. FBA = Furnace Bottom Ash, PFA = Pulverised Fuel Ash
Main (a) and trace element (b) concentrations in fuel, ashes and emitted dust throughout the Borssele 12 power plant of EPZ. (FBA = Furnace Bottom Ash, MARK III average = impactor sampling before SCR/DeNOx unit, MARK V average = impactor sampling after SCR/DeNOx unit, PFA = Pulverised Fuel Ash collected in the ESP)

shows a small but important increase in the concentration of some volatile metals in the ash downstream the DeNOx unit, Pb and V in particular. This is accompanied by a significant increase in chlorine load, while no such increase can be seen for common alkalis. Also sulphur shows a small but significant increase, which may likewise be an indication of the complexation of the condensing metals. In the absence of a proper reference measurement (without a DeNOx installation), it is somewhat speculative to claim that the observed increase in the levels of the said metals, coinciding with the increasing concentrations of Cl and S, may in fact have to do with the DeNOx unit itself. Nonetheless, it is known that the strong oxidation potentials existing in the DeNOx unit may lead to the formation of Cl₂ and SO₃ both being strong oxidative agents for the free, volatile metals. This is also in line with the clear correlation found between the mercury removal efficiency and the chlorine concentration in the flue gas.

The second full-scale measuring campaign took place in September 2008, at the E.On-Benelux Maasvlakte 2 power plant. During this campaign, almost 20% (m/m) of coal was replaced by a
A mixture of different types of secondary fuel. This corresponded with about 15% co-firing on energy basis (t/te). The location of the sampling points, as well as the sampling team involvement is very comparable with the previous measurement campaign at the BS-12 boiler. Detailed results are described in separate reports [Eijk, 2010; Kalivodova, 2010]. It was found that most elements leave the installation mainly via the ashes. The effluent is only an important output for Cl, Na, Br, I, Mg. The gypsum is an important output for Ca, S, F, I and Se, while the sludge of the waste water treatment plant is a significant output route for F, B, Hg and Se. Finally, flue gases are important only for C and to a much lesser extent for B, Hg, I, Se and S.

XAFS (X-ray absorption fine structure) results for the second and first campaign are described below. For the first campaign (2006) the speciation of chromium, vanadium and zinc was determined in the ashes, gypsum and sludge of the waste-water treatment plant by means of XAFS (X-ray absorption fine structure). For the gypsum, the levels were below the detection limits, so no results could be obtained. For the ashes, it appeared that 6% of the chromium was present as Cr(VI), comparable to previous findings with full coal firing. In the sludge 1% of the total chromium was present as Cr(VI). The predominant form of vanadium is a valence of five (V) both in the ashes and the sludge. Results for zinc were less clear.

For the second campaign (2008) the speciation of chromium, vanadium, zinc, arsenic and selenium was determined in the bottom ash, fly ash (collected from ESP) and fly dust (collected before SCR). Results obtained for arsenic in the two studied fly ash samples, indicate that all (>90%) of the arsenic is present as As(V) in arsenate complexes. Results obtained for selenium in three samples indicate that the only significant selenium species present is Se(IV) in selenite complexes. Results obtained for chromium in three samples from the same campaign indicate that most of the chromium is present as Cr^{3+} in aluminosilicate glass. Results obtained for zinc in three samples indicate that much of the zinc is present in four-fold coordination by oxygen. Spectra for vanadium in these materials remain to be collected. An example of a spectrum is given in .

Presented in the figure is a spectrum for arsenic, with the arsenate peak that is characteristic for As(V), clearly visible. Also noticeable in the same spectrum is a second peak, which has been recorded for iron arsenate - a reference material. By comparing its spectrum with that of the fly ashes (indicated as TOS/BEM/08-XX in the figure), it can be concluded that the iron arsenate is not a predominant complexation of arsenic in the studied samples.

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XAFS (X-ray absorption fine structure) is a unique analysis method capable not only of detecting the valency of an element but also its complexation, by bringing in chart atoms in close vicinity of the studied element. The experiments were performed at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory (USA).
Study on SO$_3$ and SCR deactivation

A literature survey on the role of SO$_3$ formation showed that this effect in relation to co-firing is not well documented. Several aspects play a role, such as presence of ammonia, alkali and alkaline earth metals as well as operational conditions, e.g. SCR temperature. General mechanisms that can contribute to SCR catalytic deactivation are poisoning (penetration of elements into the pore system and (irreversible) reaction with the catalytically active material, and plugging and fouling of the catalyst surface with deposits from fly ash particles that can result in the formation of a rigid deposition layer (masking).

In addition to the literature study information was obtained about catalyst deactivation from practice. Therefore, an SCR catalyst has been investigated from a power plant where the catalyst deactivation rate is relatively high because of co-firing. In a set of used SCR catalysts the amount and position of relevant elements is assessed with an electron microscope. From the comparison with fresh catalyst this revealed information about cause and mechanism of deactivation.

Within the part of the task, KEMA carried out microscopic analyses of the fresh and spent catalyst surfaces. It was found that a layer of deposits is formed on the catalyst surface. Several examples of the microscopic photographs of a fresh and the first (most exposed) layer of the SCR catalyst after a 22,000 hrs exposure, are shown in Figure 2.6.

Deposition of material on the surface of the catalyst is expected to be the most important cause of deactivation. The deposits consist mainly of silicon, sulphur, calcium, aluminium and oxygen and form a layer which has a thickness of 4 – 8 µm on the front catalyst layer (i.e. where flue gas enters first). Both sulphate and phosphate deposits are known for their capability to blind the catalyst surface effectively. As the amount of sulphur is six times higher than phosphorus (atomic base) it is expected that phosphorus does not play a dominant role in the deactivation.

Some elements that are poisonous or can contribute to deactivation indirectly, have penetrated the catalyst deeply such as sulphur, iron, arsenic, phosphorus, potassium, sodium and calcium. This will also have contributed partly to deactivation. Selenium was hardly detectable in all samples. Further details and SEM results are given in a separate report (Vredenbregt, 2010b).

Within this investigation ECN carried out an extensive pH-static analyses followed by modelling of the leaching behaviour of the fresh and the spent catalyst. The main objective was to verify whether the observed decrease in the activity of the catalyst was in any way connected with the co-firing and if so, what are the underlying mechanisms of the degradation.
The speciation of the elements was modelled by dedicated models derived in the earlier stage of the WP1 work, including interactions with adsorptive oxides (TiO$_2$, Fe$_x$O$_y$, V$_2$O$_5$). The primary focus of the investigation was put on the arsenic levels and speciation identification. Secondary goals included investigation of the depletion of catalytic metals/oxides (Mo, V, Ti) as well as levels and speciation of biomass-related species: Ca, P, K, Na.

An example of the obtained leaching curve is given in Figure 2.7.

![Figure 2.7 Arsenic pH-static leaching curves obtained by ECN for the fresh and the spent SCR specimens](image)

As can be seen above, there is a very dramatic increase in the concentrations of As when comparing the fresh SCR catalyst material with the spent one. Moreover it is also clear, that although the majority of arsenic deposition is taking place at the front catalyst layer, the inner catalyst layers are also seriously affected.

The speciation of the As was then modelled by means of the LeachXS geothermodynamic modelling. The resulting model fit allowed to verify that arsenic was indeed for the great majority deposited in the form of arsenates. Furthermore it was found that phosphorus might play an active role in the arsenate-induced poisoning, as molar levels of P correlate very well with those of As for all the most exposed materials (layer 1 and 2) investigated, as shown in Figure 2.8. This is likely due to the fact that As and P have by nature quite similar thermochemical characteristics, and therefore might interfere with one another. This can lead to the formation of a common phase which constitutes a higher overall mass fraction than arsenates alone, therefore enhancing the deactivation. This could also mean that the introduction of biomass, which is characterised by fairly high P levels compared with coals, might lead to an increase in the As-induced SCR.

Furthermore it was also verified that Ca and K, both associated with biomass co-firing, are also clearly represented in the deposits. Their association was found to be plane sulphates as both the elements show similar dissolution characteristics as sulphur. The two alkaline elements can be hold responsible for bonding up to 70% of the sulphur measured in the spent catalyst, as shown in Figure 2.9.
Overall, the results of the KEMA and ECN work on the SCR catalyst deactivation were very complimentary leading to improved insights into the deactivation phenomena and mechanism, especially in relation with biomass co-firing.

**Lab-scale experiments**

One of the ECN tasks within this work package has been to investigate the influence of various combustion conditions on the volatilisation behaviour, the release and the subsequent condensation of trace elements, which insights should help to estimate gaseous emissions. Further, the same data can be used in the ash management work package (WP3) to assess the behaviour of the resulting ashes in the environment (see Section 2.3). The main experimental facility for this investigation is the Lab-scale Combustion Simulator LCS). This apparatus is a flexible facility for the characterisation of solid fuel behaviour under typical pulverised-fuel-firing conditions. The facility comprises a drop-tube reactor together with a staged gas burner to simulate a flame/flue gas environment in which the conversion behaviour of fuel particles can be studied as a function of time. An adequate simulation of heating rate, gas temperatures and composition can thus be obtained independent of the test fuel.
For the trace element speciation tests, the LCS is operated using the same sampling and analytical schemes as used to determine SCR performance during the full-scale measurement campaigns, viz. ash sampling by means of a cascade impactor. Moreover, the tests are conducted with the same coal and biomass fuels, as applied in the full-scale campaigns. This will allow a good comparison of lab-scale and full-scale data. A schematic impression of the LCS is presented below.

To determine the operating conditions for the lab-scale tests, SPENCE software calculations have been conducted by KEMA to give indications of temperatures and residence times to be expected. A more detailed description of the experimental plan, including the foreseen additional analytical work employing for example ECN Leach XS-assisted evaluation of the leaching analyses, is given in a separate report [Cieplik, 2008]. The SPENCE calculations are described in more detail in [Stam, 2007].

Initially, the focus of the investigation is on the volatilisation of the trace elements (release tests) under the simulated pulverised-fuel combustion conditions, typical for various state-of-the-art and future PF-fired systems. This volatilisation process is crucial for further chemical reactivity as well as the physical condensation of the trace elements, which processes define the speciation and the distribution of the elements both in the flue gas, as well as in the solid combustion by-products, at the outlet of the furnace.

Results of the reference tests for coal blend and wood pellets under typical low NOx conditions are shown in Figure 7. As can be seen in this figure, the volatilization of elements expressed as mass fraction of the element contained in the fuel being transferred into the gas phase, varies greatly between coal and biomass. Nonetheless, it can be concluded that elements prone to be either converted into gaseous products (e.g. S) as well as those volatile (e.g. Pb and Zn) are indeed released at a very high rate in the case of both fuels.

For the latter two trace elements, the release after 1300 ms is almost complete, thus it can be assumed that the availability and subsequent chemical behaviour of the said elements will be similar in both cases. Naturally, as levels trace elements in biomass fuels are significantly lower the absolute concentrations of these elements throughout the whole system will be significantly lower.

However, it can also be observed that some other elements, such as Mn which is volatilised from biomass much more than from coal, reveal significant differences in volatilization behaviour, which may later translate into different complexation and hence emissions.

Figure 2.10  Schematics of the ECN Lab-scale Combustion Simulator (LCS)
The main series of the LCS test of tests within the work package, focused on the influence of the air-staging strategies on the release of (volatile) trace elements, as well as the main counter ion-forming elements, such as phosphorus, sulphur and chlorine. Furthermore the release of the alkaline metals, crucial for the formation of the aerosols on which surface the trace elements preferably condense in cool-down trajectory in the boiler, is closely monitored.

The said tests have been performed at one single residence time of 1300 ms, applying a fivefold of burner conditions, representing the following firing strategies:
- Unstaged combustion, characteristic for older-designs of PF boilers,
- Burner air staging, representative for power plants utilising air-staged burners, but without further in-furnace primary NO\textsubscript{x} control,
- Deep air staging, including both burner staging and over-fire-air (OFA) technology, representative for the state-of-the-art boiler designs,
- Oxyfuel combustion with 20% flue gas recirculation (FGR) simulation, representative for near-future, enriched-air boiler designs, and
- Oxyfuel combustion with 70% FGR, representative for future boiler designs operating at high CO\textsubscript{2} flue gas conditions.

Figure 2.11 Mass fractions released as a function of particle residence time in the LCS for (a) coal blend and (b) wood pellets for selected elements
Worth mentioning at this point is the fact, that despite the largely varying firing conditions, the actual temperature profiles were very comparable, hence making the interpretation of the results more facile. Furthermore, throughout this study, the same real-life fuel blend was utilised, namely the 35/65 %w/w wood pellets/coffee husks blend, from the 2008 EOS-LT Boiler Fouling/USC campaign at the Amer 9 power plant. The said blend was sampled as-fired directly from the pulversised fuel feeding lines, thus making the sample even more realistic.

The results of the said study are described in detail in a separate report [Cieplik, 2010]. A graphical summary of the most important results is given in Figure 2.12, next.

![Figure 2.12](image)

**Figure 2.12**  
*Mass fractions released as a function of firing conditions in the LCS for a blend of coal/wood and coffee husk pellets for selected elements*

As can be seen in the above figure, there are noticeable differences in the release of some of the elements, while others do not seem to be affected by the change in the firing conditions. For the trace elements the most differences are visible for Zn. Clearly, under air firing, the deeper the staging, the higher the fraction released, while under oxy-fuel conditions the release appears to drop significantly for the enriched air conditions, while remains comparable with the burner staged air firing for the full oxy-fuel combustion. The release of other trace elements, Pb, Cd, Zn, Se and Sn is complete under all firing conditions.

Other elements of relevance for the volatilisation, condensation and the emissions of trace elements, e.g. sulphur, chlorine and phosphorus as well as potassium, do show some dependence of the firing conditions. In all the cases the release is the lowest for the deep staged firing conditions, which is likely the result of the much extended devolatilisation trajectory under reducing atmosphere as compared with the other conditions tested. In consequence, the ash forming elements as well as the alkalis get the most chance to react, to form stable, or at least less volatile components. In doing so, the availability of sulphur, chlorine and phosphorus as well as the amount of the alkali-rich aerosol for the chemical and physical interactions becomes less, which may in turn delay capture and thus increase the release and emissions of trace elements.

**pH-static extraction**

Next to dynamic combustion tests in combination with standard analytical methods, also pH static extraction is applied to unravel the physicochemical composition of the ash and particularly in terms of the complexation and oxidation state of trace elements. In order to do so, data from the exhaustive pH-static extraction are fed into computer models LeachXS and Orchestra, which translate the composition of the leachate back into the composition of solid...
phase. The above-mentioned methodology has thus far been exclusively used to predict emissions of elements from combustion residues in the environment (water/soil, but no air). Furthermore, the analytical procedures applied are developed for kilogram-scale samples and not for the at best gram-scale specimens from the lab-scale combustion tests. The said methods need then to be adapted both in terms of the downscaling as well as software output.

A series of calibration tests needed to be performed in order to verify the analytical potential to identify various oxidation states and complexation of metals in the ash matrix. Results of the said calibration are depicted in Figure 2.13.

The said tests have been carried out with a threefold of ashes from three different installations using wood pellets, either as the only or co-firing fuel. The ashes were generated at different redox potentials as the conversion technologies span from gasification (strongly reducing) through grate-fired unit (mildly oxidizing) to PF boiler (strongly oxidizing). The results from the said extraction tests show the mass emission rate in the function of pH. As can be seen in , the course of the leaching curves varies greatly within the tested materials range. It can be concluded that the depth of the dip in the lines in the between pH 4 and pH 10 is getting shallower with the increase in the oxidative conditions of the conversion process. This particular region is very characteristic for the leaching behaviour of trivalent chrome (III) compounds, which at this acidity are highly insoluble. It can be also clearly seen that in most cases the extractable chrome in the pH range 4-10 range is far below the total chrome available in the samples, except for the PF co-firing fly ash, where it amounts to as much as 30-40%. It should be stressed however, that the actual concentration of the extractable hexavalent Cr in the PF sample from the high-share wood pellets co-firing is still very low and not exceeding the regulatory levels. The high share of Cr (VI) is in this case also related to the very low overall chromium concentration, which is likely due to the “dilution” of the coal ash, due to high co-firing share.

Finally, the pH static extraction was applied on the fly ash samples from both the projects full-scale campaign fly ash samples. Results of the said analyses are also depicted in . As can be seen in the figure, the extractable amount of chromium in the “fingerprint” pH range is in both the Borssele 12 as well as Maasvlakte 2 samples is fairly low, and amounts at best to ca. 1% of the total chromium load in the sample. This value compares well with the results of the traditional wet-chemical analyses or the aforementioned XAFS measurements, which indicates...
that this method could also be indeed used to characterise quantitatively the speciation of trace elements.

**Flue gas cleaning experiments**

An experimental setup has been installed and used to study flue gas cleaning under different conditions (NO$_x$, temperature and redox). Samples have been taken and analyzed for Cr, Tl, Mn, As, Se, Sb and Hg. The research shows that the behavior of elements that can be present in different speciations in the wet flue-gas desulphurization unit (FGD) can be influenced by changing specific process parameters such as redox potential and temperature. Details of this study can be found in a separate report [Vredenbregt, 2010a].

**Speciation Knowledgebase**

In order to make all data and knowledge on speciation and co-firing conditions as found in the project available, a speciation knowledgebase has been built. This knowledgebase enables a representation of experimental results, mechanisms and operator guidelines per chemical element. It also enables to search for detailed compositions of by-products as function of the fuels and conditions when they were formed. Overviews and summaries of specific experimental results or results from specific measurement campaigns can also be viewed (see figure below).

![Main screen of Speciation Knowledgebase](image)

**Figure 2.14** Main screen of Speciation Knowledgebase

### 2.1.5 Conclusions and recommendations

From the performed thermodynamic modelling, lab-scale measurements and direct measurements on ashes from real-scale trials, it was found that speciation of specific trace elements depend on type and composition of biomass, for example the high amount of calcium in woody biomasses. The redox conditions in the boiler as well as during flue gas cleaning also plays a role, particularly leading to the formation of higher valent species. Compared to conventional boilers oxy-fuel conditions may be expected to influence trace element speciation due to a different gas phase composition and the resulting redox conditions. The USC boiler conditions may also influence speciation due to changes in the furnace exit temperature, but to a lesser degree.

From the data at hand from the lab-scale co-firing tests it can be concluded that coal and biomass show some differences in the release and thus most likely later conversion and complexation of elements, including trace metals such as Mn and Cr. Furthermore, there is an influence of the oxidative conditions in the PF systems, for example as a result of oxy-fuel firing with or without flue gas recirculation or as a result of flue gas composition in the flue gas desulphurisation unit.
First ash leaching test results indicate that it might be indeed possible to study oxidation state and complexation of trace elements by means of computer-aided pH-static extraction techniques. The method shows clearly different behaviour for trace elements contained in the ashes from similar fuels but generated under different conversion conditions and technologies (gasification vs. grate firing vs. PF firing). Furthermore, it may be expected that the analyses can be made suitable not only for kilogram-scale samples from full-scale trials but also for lab-scale specimens.

Results from full-scale measurements indicate that an SCR installation can play a significant role, not only by increasing the conversion (oxidation) and therefore the recovery of metallic mercury, but also for other trace elements, to name Cu, V and Pb. More research is required in order to understand and prevent deactivation of SCR catalyst. This is important because increased deactivation rates may limit co-firing. Nonetheless it should be stressed that under current co-firing rates and with the current fuel blends, the observed deactivation rates are acceptable and do not lead to increased NOx emissions. Results from the campaigns also showed that operational conditions affect speciation and behaviour of elements, like the oxidising conditions in the boiler as well as in the FGD.

2.2 WP2: Development of indirect co-firing technology

2.2.1 Introduction

The expectations are that a combination of direct and indirect co-firing will be necessary to reach the ultimate EOS-LT target of 40% biomass co-firing, but the technology of indirect co-firing is still not very widely applied worldwide. Only a limited number of biomass gasification plants for co-firing purposes are in operation, all with a capacity of approx. 80 MWth and using fluidised-bed technology (e.g. the plants in Lahti – (Finland), Geertruidenberg/Amer (the Netherlands) and Ruien (Belgium)). This work packages consisted of two phases: first a project aimed at investigating the perspectives of the TORBED gasification technology was performed in the years 2006-2008. As a result of the decision not to continue the work on this technology, the work package obtained another direction by performing a study towards the perspectives of the development of indirect co-firing by gasification at low temperatures (<700ºC) of difficult fuels containing high ash/chlorine content in the years 2009 and 2010. These two studies are elucidated in the two separate sections below describing the TORBED study (Section 2.2.2) and the Low Temperature Gasification study (Section 2.2.3).

2.2.2 TORBED Study

2.2.2.1 Problem definition

Initially in this work package the TORBED gasification technology was recognised as a potentially attractive alternative to fluidised-bed gasification in terms of (fuel) flexibility, required plot space and investment costs. The TORBED concept is applied commercially for drying and combustion and the first small, stand-alone gasification plant is in operation in Zeeland. However, the application of TORBED as indirect co-firing technology has not been investigated yet.

2.2.2.2 Objectives

This work package aims at the development of optimised indirect co-firing concepts. Initially, attention was focused on elucidating the potential of TORBED gasification. If a technical-economic evaluation indicated that this technology can be far more attractive than fluidised-bed technology, and a proper development programme would be set up with the industrial partners involved, then further development of this option will be pursued. Otherwise, attention would be focused on optimising fluidised-bed gasification as an indirect co-firing option.
2.2.2.3 Approach
Initially, the approach as indicated below was defined in case of a continued focus on TORBED gasification. After the technical-economic evaluation of this technology compared to CFB gasification, it was decided to switch the focus to fluidised-bed gasification, in close consultation with the IAG. There for the indicated plans for 2008 and 2009 were not executed.

2006
- Technical-economic evaluation determining the prospects of TORBED gasification as an alternative to fluidised-bed gasification, based on ECN-KEMA expertise and results from earlier research.

2007
- Assessment of industrial support for the TORBED gasification option and of the possibilities to set up a proper development programme with relevant industrial partners (e.g. TORFTECH and Polow Energy Systems, owning the IP on the TORBED technology).
- Go/no-go decision concerning further development of indirect co-firing based on TORBED gasification.

2008 (not executed)
- Flow and reactor modelling.
- Design, realisation of a pilot-scale test facility.
- Performance of pilot-scale test programme.
- First mass and energy balance measurements and model validation.
- Long term testing.

2009 (not executed)
- Proceeding of performing pilot-scale test programme.
- Determination of design parameters and rules for scaling up.
- Development of a 15 MWth unit (approx. 2 m diameter) to be installed as a co-firing unit in an existing power plant.

2.2.2.4 Results 2006-2007 and discussion
To determine the technical and economic potential of TORBED gasification for indirect co-firing, a comparison with ‘state of the art’ circulating-fluidised-bed (CFB) gasification has been made for an integrated gasifier with a thermal input capacity of 75 MWth (5% on energy basis) and 300 MWth (20% on energy basis). Input on the TORBED technology has been covered by KEMA, with support of Polow Energy Systems, while data and information on indirect co-firing via CFB gasification have been provided by ECN. The details are reported in a separate report [Kleinschmidt, 2008]. Four cases were developed and compared, all of them based on indirect co-firing of B-wood at the Hemweg 8 coal-fired boiler of NUON in Amsterdam, assuming that 20% e/e A-wood is fired to the boiler directly already. The four cases are:
- **Case 1**: one 75 MWth CFB gasifier.
- **Case 2**: one 300 MWth CFB gasifier.
- **Case 3**: one 75 MWth TORBED gasifier.
- **Case 4**: four separate 75 MWth TORBED gasifiers (since scaling the current 3.5 MWth TORBED gasifier up to a 300 MWth size was considered as being not realistic within the EOS-LT time horizon (2020-2040)).

The technical-economic evaluation comprised process calculations and cost estimates (investment cost and operating cost) for these four cases, and a qualitative technical evaluation of the two technologies. The results of the process calculations showed that a TORBED gasifier can produce a good quality fuel gas (4.6 MJ/LHV/Nm³) for a broad range of fuel qualities and feed rates. By recycling 50% of the fuel gas, a TORBED gasifier achieves good thermal stability.
without the need for bed material. The fuel-gas recycle also functions as a low oxygen fluidisation medium. A negative effect of the fuel gas recycle is the production of fuel gas with a lower calorific value. The fuel gas is recycled at a temperature of 600°C, which is much lower than the operational temperature of the gasifier (850°C). To maintain thermal stability a TORBED gasifier must be operated with a higher air-to-fuel ratio, which consequently leads to a lower calorific value of the fuel gas. However, the electric efficiency of a TORBED gasifier is calculated to be somewhat higher (<1%-point), due to a claimed lower internal energy consumption of the gasifier. Contrary to what was expected from the start, the qualitative technical evaluation did not show clear advantages of the TORBED gasification technology, e.g. in terms of flexibility or required plot space above existing CFB technology.

The investment cost of the gasifier only are estimated to be 16% (300 MWth cases) to 43% (75 MWth cases) lower for a TORBED gasifier due to claimed smaller reactor dimensions. The aspect ratio (height/diameter) of a TORBED gasifier is claimed to be two, while the aspect ratio of a CFB gasifier with the same capacity is approx. five. However, the uncertainties in the investment cost estimate are much larger for the TORBED gasifier, since TORBED gasification has only been demonstrated at a scale of 3.5 MWth, while CFB gasification has been demonstrated at 75-80 MWth. The smaller dimensions of a TORBED gasifier lead to a smaller pressure drop over the reactor and a lower energy consumption than a CFB gasifier, resulting in lower operating cost.

But, although the investment and operating costs of TORBED gasification are envisaged to be lower than CFB gasification, this does not result in a significant economical advantage. The estimated break-even cost (€/MWh), which includes the total cost of integrating a gasifier to the Hemweg 8 boiler, is only 5-10% lower in case of TORBED gasification. For a 75 MWth TORBED gasifier, the calculated break-even cost is 53.0 €/MWh compared to 58.5 €/MWh for a CFB gasifier. For the 300 MWth cases, these numbers are 41.5 €/MWh and 43.8 €/MWh respectively.

The results of the technical-economic evaluation are reported in detail in a separate report [Kleinschmidt, 2008].

Figure 2.15  Process flow diagram of Hemweg 8 with an integrated biomass gasifier

2.2.2.5 Conclusions and recommendations

Based on the results of the technical-economic evaluation, the TORBED gasification concept does not show clear advantages over CFB gasification, while the uncertainties in technical performance and costs are much higher. Also, fuel flexibility and dimensions (footprint) of
TORBED gasification are not significantly different from CFB gasification. Consequently, it was decided in consultation with the IAG to terminate the further development of the TORBED concept within the EOS-LT programme and to redefine the work package focusing on fluidised-bed gasification. The results of this study are described in the next section.

2.2.3 Low temperature gasification of low quality biomasses

2.2.3.1 Problem definition

Based on recommendations by the IAG, the activities in the 2008/2009 project comprise a joint KEMA-ECN desk study, in which different fluidised-bed gasification concepts and different ways of integrating the gasification with the main coal-fired boiler are assessed. Focus is put mainly on low-cost biomass, which is not suitable for other applications, including direct co-firing, because of ash composition (alkalis, chlorine), moisture content, milling behaviour, etc. These difficult feedstocks are considered to gain importance in the long term by the industry, as easy fuels like wood pellets, are expected to be destined for processes with higher added value like e.g. liquid biofuel production or biochemicals.

Existing biomass CFB gasifiers for co-firing all operate within a relatively narrow temperature regime, around 850ºC. This means that some of the volatile inorganics (primarily alkali components) are vaporized into the product gas and hence transported into the pulverized fuel boiler. This is particularly troublesome in the case of low quality biomass fuels, which contain a higher share of volatile ash components. Low temperature gasification technology (lower than 700ºC) has been advertised as a potentially attractive alternative to conventional CFB gasification in terms of flexibility to use biomasses with high alkali chloride content. The low temperature concept is however still in laboratory/pilot-scale stage.

The fluidised-bed gasification concepts considered in this study include innovative low-temperature indirect gasification concepts. Figure 2.16 shows the basic principles of indirect or allothermal gasification. Biomass is gasified in the left reactor. The heat required for the gasification comes from a second reactor (right) where the char remaining from the first reactor is combusted. A circulating bed material (e.g. sand or olivine) is used to transport the heat from the combustor to the gasifier and the char from the gasifier to the combustor. The producer gas from the left reactor and the flue gas from the right reactor leave the installation separately. Air is used for the combustion of char; because the flue gas is not mixed with the producer gas the nitrogen in the flue gas does not dilute the producer gas. The producer gas from the gasifier contains the same components as gas from a CFB gasifier, but contains less CO₂ and N₂, because the gas is not diluted with flue gas, resulting in a higher cold gas efficiency (CGE).

![Schematic drawing of indirect gasification](image)

Indirect gasifiers seem especially suitable for biomass types rich in alkalis and chlorine, such as agricultural residues (e.g., straw, grass). The low temperature should prevent the evaporation of alkalis and chlorine, and thus prevent agglomeration in the gasifier itself and fouling and corrosion phenomena in the main boiler. The separate combustion step should ensure high
burnout, and thus a high fuel efficiency. The advantage of using an indirect gasifier at low temperatures is that the excess heat available from the combustor can be used for generating steam for the power plant, not resulting in a loss of efficiency. The so-called LT-CFB concept is under development in Denmark [Stoholm, 2008] but also the ECN MILENA concept is promising for this application as it appears from exploratory tests. There is a need for an accurate technical and economical assessment of the perspectives of indirect co-firing technologies at low temperatures for low quality biomasses.

2.2.3.2 Objectives
The objectives of this study were to make an overview and classify the possible attractive types of (difficult) biomass suitable for indirect co-firing in the Netherlands. Furthermore, to make an overview of possible (low-temperature) gasification systems (existing and under development) suitable for processing the identified difficult feedstocks and assess the integration of the gasification technologies with the boiler. Besides these activities, recommendations for further research are required.

2.2.3.3 Approach
In summary, this work package contained the following activities:

2008
- Desk study/literature search on suitable feedstocks and the technical prospects and limitations of different fluidised-bed gasification concepts and on different ways of integration with the main boiler.

2009
- R&D on most promising concept(s) through flow/combustion modelling and system calculations.

2010
- Experimental to obtain data on the behaviour of alkalis and minerals. The ECN indirect gasifier MILENA (5 kg/h, lab-scale) was used to test two fuels at different gasification temperatures. An extensive mass balance is needed to estimate the behaviour of alkalies and minerals under low temperature conditions (lower than 700ºC).
- The data generated by ECN on gas composition and conversion is used by KEMA to improve the assessment of the consequences of integrating a gasifier with a pulverized coal fired power plant using their SPENCE simulation model and identify the potential of this technology.

The following starting points were used in this study:
- Only indirect co-firing in dry bottom boilers will be assessed. The Hemweg 8 power plant was used as case study.
- A selection of the most promising biomasses for indirect co-firing is evaluated based on specific described criteria.
- A selection of the most promising gasification technology concepts is evaluated based on described criteria.
- Desk study on the above aspects based on in-house experience and contacts with experts/suppliers/developers.
- Limited system assessment, by taking a limited gas cleaning (limited dust removal) as a starting point.
2.2.3.4 Results 2008-2010 and discussion

Further details of this study can be found in separate reports [Van der Ven, 2010a; Vreugdenhil, 2010; Konings, 2011].

**Biomass selection**

A number of "difficult" biomass fuels were selected, that are less suitable to be co-fired directly. Furthermore, this selection more or less covers the whole spectrum available biomass streams and can be considered as representative for other relevant streams with comparable properties.

The selected biomass streams were:
- Poultry litter,
- Cocoa husks,
- Biomass fraction of refuse derived fuel (RDF),
- Meat and bone meal (MBM),
- Rapeseed press cake (residue from biofuel production), and
- Demolition wood.

**Technology selection**

As gasification technologies were selected:
- Direct gasification: CFB,
- Indirect gasification: the FICFB, Silvagas and MILENA concepts, and
- Low temperature CFB (LT-CFB).

Conventional CFB gasification is the most proven technology of the three technologies described here. In general CFB gasifiers are operated at 850°C. ECN and HoSt have some experience in operating CFB gasifiers at lower temperature using chicken manure as a fuel. The disadvantage of CFB gasifiers is the limited carbon conversion of the fuel. The conversion decreases when the gasification temperature is decreased. The typical fuels that require low temperature gasification (e.g. chicken manure) are more reactive than wood, so for some fuels CFB gasification can be an attractive option.

Indirect gasification is in potential a promising technology for indirect co-firing, but the experience in operating indirect gasifiers at low temperature is limited and the basic design needs adaptation to control the gasification and combustion temperature.

LT-CFB technology can be a serious option for some problematic biomass fuels like straw. The LT-CFB technology is the only known fluidized bed technology that is especially developed to keep the alkali compounds in the solid phase. The technology is going to be demonstrated at a commercial scale (6 MW by DONG Energy, planned 2010). The disadvantage of this technology is the incomplete fuel conversion, this has a negative effect on efficiency and will increase the amount of waste produced. Most of the alkali compounds will end up as fly ash in the gas. A bag house filter or other absolute filter is required to remove the fine ash particles. It is not clear yet if it is possible to use a bag-house filter in gas that contains tar.

**Technology assessment**

These technologies were evaluated on the following criteria:
- Fuel flexibility,
- Producer gas quality,
- Efficiency,
- Suitability for low temperature operation,
- Investment per kWth,
- Operational costs,
- Maturity, and
- Experience with operating at low temperature.
Table 2.2 to Table 2.4 summarize respectively the assessment of these criteria for respectively conventional CFB, the indirect gasification technologies and LT-CFB gasification.

**Table 2.2 Summary assessment CFB gasification**

<table>
<thead>
<tr>
<th>CFB</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel flexibility</td>
<td>++</td>
</tr>
<tr>
<td>Producer gas quality</td>
<td>□</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
</tr>
<tr>
<td>Suitability for low temperature operation</td>
<td>□</td>
</tr>
<tr>
<td>Investment</td>
<td>+</td>
</tr>
<tr>
<td>Operational costs</td>
<td>-</td>
</tr>
<tr>
<td>Maturity</td>
<td>++</td>
</tr>
<tr>
<td>Experience with low temperature gasification</td>
<td>+</td>
</tr>
</tbody>
</table>

**Table 2.3 Summary assessment indirect gasification technologies**

<table>
<thead>
<tr>
<th>FICFB</th>
<th>Silvagas</th>
<th>MILENA</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel flexibility</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Producer gas quality</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Efficiency</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Suitability for low temperature operation</td>
<td>-</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>Investment</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Operational costs</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>Maturity</td>
<td>++</td>
<td>+</td>
<td>□</td>
</tr>
<tr>
<td>Experience with low temperature gasification</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

**Table 2.4 Summary assessment LT-CFB gasification**

<table>
<thead>
<tr>
<th>LT-CFB</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel flexibility</td>
<td>++</td>
</tr>
<tr>
<td>Producer gas quality</td>
<td>+</td>
</tr>
<tr>
<td>Efficiency</td>
<td>++</td>
</tr>
<tr>
<td>Suitability for low temperature operation</td>
<td>++</td>
</tr>
<tr>
<td>Investments</td>
<td>+</td>
</tr>
<tr>
<td>Operational costs</td>
<td>+</td>
</tr>
<tr>
<td>Maturity</td>
<td>□</td>
</tr>
</tbody>
</table>
Experience with low temperature gasification
++ Solely developed for low temperature application

Uncertainties
This study made clear that in theory there is a lot of potential in using low temperature gasification for indirect co-firing. However, some key knowledge lacking was regarding the fate of the alkali compounds. These are not supposed to end up in the boiler and gasifying at low temperatures in principle can prevent this. Both the indirect technologies (SilvaGas and MILENA) and the LT-CFB gasification process look promising. However, many uncertainties were existing:
1. The behaviour of a CFB gasifier between 650°C to 700°C,
2. The behaviour of indirect gasifiers between 650°C to 700°C,
3. The fate/distribution/form of the alkali’s in any of the gasifiers in this temperature range,
4. The behaviour of the cooler at 600°C with a producer gas originating from low-temperature gasification is unknown, and
5. The behaviour of the boiler on the producer gas is unknown.

The work package of 2010 focussed on uncertainties number 2, 3 and 5. This has been achieved by experimental work and desktop modelling studies.

Based on a number of assumptions, modelling of the different gasification concepts in combination with the Hemweg power plant was performed in 2009. For the details of this study is referred to [Van der Ven, 2010a]. Due to the uncertainties described above, the program in 2010 was focussed on elucidating the gasification behaviour of alkalis by performing low-temperature gasification experiments and use the obtained data to update the said modelling.

Experimental work
The proposed exchange of knowledge between the DTU regarding their low temperature gasification results was not possible. The information they had was too limited to be of any value for the purposes of this work package.

For the experimental program performed in the lab-scale MILENA gasification set-up (25 kW_th inpu) of ECN, straw pellets and RDF were selected as fuels. Straw was chosen because it is known that straw typically contains large amounts of alkalis. Feeding feedstock in small-scale experimental installations is often a point of attention. The reason to select pellets was related to the feeding problems that occur during the feeding of normal straw due to is loose structure when it is untreated. To feed RDF to the reactor, the RDF was milled and mixed with the additional fuel (ground) beech wood to make it possible to feed the material to the gasifier. It was not possible to feed this feedstock on an individual basis due to the fact the fines cause bridging just before the feeding screw of the reactor, and thus preventing the material from entering into the reactor. The mixture of RDF and beech wood did not result in feeding problems.

Table 2.5 indicates that the concentration of alkalis in the RDF/beech mixture are high. These amounts are find their origin in the RDF. This means that when pure RDF is gasified there is a possibility that the results can be different towards the behaviour of the alkali components and thus the distribution over the gas and solid phases. The table below also indicates that the RDF/beech mixture contains more chlorine and sulphur than straw. It is the ratio of these components, the state of which there are present in the biomass fuel and the process conditions that will determine how these components will distribute over the gas and solid phase in the flue and producer gas and to what extent corrosion or agglomeration in an installation can be expected [Visser, 2004].
Table 2.5  Ultimate and proximate analysis of the tested fuels

<table>
<thead>
<tr>
<th></th>
<th>Straw pellets</th>
<th>RDF/Beech</th>
<th>RDF</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>6.7</td>
<td>9.5</td>
<td>15.1</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>Moisture</td>
<td>7.8</td>
<td>8.2</td>
<td>7.7</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>Volatiles</td>
<td>67.5</td>
<td>67.9</td>
<td>64.1</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>C</td>
<td>41.1</td>
<td>42.2</td>
<td>41.4</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>H</td>
<td>5.6</td>
<td>5.6</td>
<td>5.4</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>O</td>
<td>41.2</td>
<td>34.7</td>
<td>28.2</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>N</td>
<td>0.4</td>
<td>0.7</td>
<td>1.1</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>S</td>
<td>0.1</td>
<td>0.3</td>
<td>0.5</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>Cl</td>
<td>0.26</td>
<td>0.63</td>
<td>1.0</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>F</td>
<td>0.002</td>
<td>0.004</td>
<td>0.007</td>
<td>wt.% ar</td>
</tr>
<tr>
<td>Ca</td>
<td>3,300</td>
<td>16,700</td>
<td>25,900</td>
<td>mg/kg dry</td>
</tr>
<tr>
<td>K</td>
<td>10,700</td>
<td>1,350</td>
<td>1,400</td>
<td>mg/kg dry</td>
</tr>
<tr>
<td>Na</td>
<td>113</td>
<td>1,800</td>
<td>3,000</td>
<td>mg/kg dry</td>
</tr>
<tr>
<td>P</td>
<td>1,630</td>
<td>209</td>
<td>279</td>
<td>mg/kg dry</td>
</tr>
<tr>
<td>S</td>
<td>610</td>
<td>3200</td>
<td>5300</td>
<td>mg/kg dry</td>
</tr>
<tr>
<td>HHV</td>
<td>16,500</td>
<td>17,900</td>
<td>18,100</td>
<td>kJ/kg ar</td>
</tr>
<tr>
<td>LHV</td>
<td>15,100</td>
<td>16,400</td>
<td>16,700</td>
<td>kJ/kg ar</td>
</tr>
</tbody>
</table>

Table 2.6 contains the experimental conditions and results for gasification of straw pellets at 690°C and for a mixture of RDF and beech wood at 680°C. The composition is given as well. Based on this table, the mass and energy balance over the gasifier was made. This resulted in the conversion of the biomass to product gas (between 70 and 80 %) for the different tests. The duration of each gasification test was around 6 hrs.

Table 2.6  Product gas experimental composition for low temperature gasification

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Unit</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasification temperature</td>
<td>°C</td>
<td>690</td>
<td>680</td>
</tr>
<tr>
<td>Combustion temperature</td>
<td>°C</td>
<td>730</td>
<td>720</td>
</tr>
<tr>
<td>Fuel feed</td>
<td>gram/h</td>
<td>5.58</td>
<td>3.06 (RDF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.34 (Beech)</td>
</tr>
<tr>
<td>Steam</td>
<td>gram/h</td>
<td>1.08</td>
<td>1.19</td>
</tr>
<tr>
<td>Primary air</td>
<td>NI/min</td>
<td>119</td>
<td>100</td>
</tr>
<tr>
<td>Secondary air</td>
<td>NI/min</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>CO₂ purge</td>
<td>NI/min</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Product gas composition</td>
<td>vo% dry</td>
<td>39.2</td>
<td>26.8</td>
</tr>
<tr>
<td>CO</td>
<td>vo% dry</td>
<td>8.7</td>
<td>7.1</td>
</tr>
<tr>
<td>H₂</td>
<td>vo% dry</td>
<td>23.7</td>
<td>35.6</td>
</tr>
<tr>
<td>CO₂</td>
<td>vo% dry</td>
<td>15.1</td>
<td>10.5</td>
</tr>
<tr>
<td>CH₄</td>
<td>vo% dry</td>
<td>0.2</td>
<td>0.116</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>vo% dry</td>
<td>4.8</td>
<td>4.3</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>vo% dry</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Benzene</td>
<td>vo% dry</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Toluene</td>
<td>vo% dry</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>N₂</td>
<td>vo% dry</td>
<td>2.4</td>
<td>6.3</td>
</tr>
<tr>
<td>H₂S</td>
<td>ppmV dry</td>
<td>126</td>
<td>222</td>
</tr>
<tr>
<td>COS</td>
<td>ppmV dry</td>
<td>44</td>
<td>27</td>
</tr>
</tbody>
</table>
A difference from the assumptions used in the previous modelling [Van de Ven, 2010] is the amount of methane that is produced at lower temperatures and the ratio between methane and the other hydrocarbons in the fuel gas. This was a result from the lab-scale gasification experiments at low temperature. Furthermore, the lower observed overall fuel conversion results in less combustible product gas and an overall decrease in efficiency. The measured amount of tar is high in the product gas, due to the fact that at lower gasification temperatures significantly more primary tars are formed compared to gasification at higher more common temperatures in the range of 850°C.

Based on the obtained analysis results, the component balances were made of the experiments. The results are indicated in Table 2.7 and Table 2.8 and indicate the measured distribution of these components over the different outlet streams (see Figure 2.16). The first rows in these tables indicate the feed rate of each component that enters the system via the feedstock in stream 1. The streams 2 to 6 indicate the amount of each element in each outlet stream. The final row indicates the closure of the balance for each element.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Ca</th>
<th>K</th>
<th>Na</th>
<th>P</th>
<th>S</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDF and beech wood</td>
<td>18,500</td>
<td>59,700</td>
<td>630</td>
<td>9,100</td>
<td>3,400</td>
<td>16,000</td>
</tr>
<tr>
<td>Producer gas (Wash bottle)</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>5.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Producer dust (Dust filter)</td>
<td>17.6%</td>
<td>7.9%</td>
<td>9.1%</td>
<td>17.0%</td>
<td>4.3%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Producer char (Cyclone)</td>
<td>23.0%</td>
<td>28.3%</td>
<td>32.1%</td>
<td>25.3%</td>
<td>3.5%</td>
<td>ND</td>
</tr>
<tr>
<td>Flue gas (Wash bottle)</td>
<td>0.0%</td>
<td>0.0%</td>
<td>6.9%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Flue ash (Cyclone)</td>
<td>21.6%</td>
<td>29.4%</td>
<td>38.2%</td>
<td>25.8%</td>
<td>3.5%</td>
<td>ND</td>
</tr>
<tr>
<td>Bed material (Sand)</td>
<td>32.1%</td>
<td>29.9%</td>
<td>-</td>
<td>29.2%</td>
<td>1.6%</td>
<td>ND</td>
</tr>
<tr>
<td>Missing from the overall balance</td>
<td>5.8%</td>
<td>4.5%</td>
<td>65.0%</td>
<td>2.6%</td>
<td>81.2%</td>
<td>87.5%</td>
</tr>
</tbody>
</table>

ND = not determined
In case of indirect co-firing, stream 2 (de-dusted product gas) and possibly stream 4 (de-dusted flue gas) will end up in the boiler. This would result a reduction of chlorine to the boiler of about 88% and for difficult alkali components such as potassium it would mean a reduction of about 92% compared to direct firing. The analysed bed material showed an accumulation of calcium and potassium, which might lead on the long-term to bed agglomeration. Agglomeration has not been observed during these tests with limited duration of one working day and can easily be avoided by refreshing with new bed material, however at the expense of generating an additional solid waste and additional bed material and associated costs.

The results for the elemental distribution for the experiment with the RDF/beech mixture is given in Table 2.8 below.

Table 2.8  Elemental distribution for RDF/beech mixture gasification at 680°C  

<table>
<thead>
<tr>
<th>Stream</th>
<th>Ca</th>
<th>K</th>
<th>Na</th>
<th>P</th>
<th>S</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 RDF and beech wood</td>
<td>86.20</td>
<td>7.30</td>
<td>9.100</td>
<td>1.100</td>
<td>16.500</td>
<td>32.200 mg/h</td>
</tr>
<tr>
<td>2 Producer gas (Wash bottle)</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>10.3%</td>
</tr>
<tr>
<td>2 Producer dust (Dust filter)</td>
<td>2.3%</td>
<td>1.3%</td>
<td>0.5%</td>
<td>3.3%</td>
<td>2.9%</td>
<td>1.8%</td>
</tr>
<tr>
<td>3 Producer char (Cyclone)</td>
<td>34.3%</td>
<td>40.3%</td>
<td>21.3%</td>
<td>32.4%</td>
<td>27.8%</td>
<td>ND</td>
</tr>
<tr>
<td>4 Flue gas (Wash bottle)</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>5.5%</td>
</tr>
<tr>
<td>5 Flue ash (Cyclone)</td>
<td>23.2%</td>
<td>26.3%</td>
<td>11.5%</td>
<td>19.6%</td>
<td>15.6%</td>
<td>ND</td>
</tr>
<tr>
<td>6 Bed material (Sand)</td>
<td>26.9%</td>
<td>23.3%</td>
<td>63.0%</td>
<td>17.9%</td>
<td>11.7%</td>
<td>ND</td>
</tr>
<tr>
<td>Missing from the overall balance</td>
<td>13.3%</td>
<td>8.8%</td>
<td>3.6%</td>
<td>26.8%</td>
<td>42.0%</td>
<td>82.4%</td>
</tr>
</tbody>
</table>

ND = not determined

The obtained results differ from the experiment with straw pellets. The feed rate of alkalis is significantly higher if the values are compared with Table 2.7. The flue gas for this case does
not contain a lot of alkali components and is rich in chlorine. Based on the large amount of chlorine present in the fuel it is not surprising that there is an increase in both the gas phases. Also in the producer gas the amount is large, however in total only 12 wt% of the chlorine is accounted for. This is similar to the straw pellets gasification test at 690°C. The total load of chlorine to the boiler in case of indirect co-firing would be about 17.5 wt% of the chlorine present in the feedstock. The amount of potassium in this fuel mixture is low compared to straw pellets as this component finds its destination in the cyclone ashes for most part.

The feed rate of sulphur during this test is around five times larger than for straw pellets. Around 50 wt% ends up in the fly ash and char. The rest of the remaining sulphur is most likely to be present as H$_2$S and COS in the product gas. Based on the mass and energy balance for RDF and beech gasification the amount of sulphur going to H$_2$S and COS is roughly 1400 mg/h (8.5 wt% of the sulphur present). For the other elements, large amounts are captured in the solid phases (bed, ash and char).

With straw pellets the amount of sodium in the biomass is relatively low and it can be observed that the bed material releases sodium. In case of RDF/beech gasification, the amount of sodium in the feed is high and in this case this component accumulates in the bed. The exact interaction of this components and others (calcium and potassium) is unknown, however it can be assumed that agglomeration related issues might occur here as well, comparable as for straw pellets.

**System modelling**

The experimentally obtained results were used by ECN as input to model a 300 MW$_{in}$ input low temperature gasification plant. The results are indicated in The outcome (gas compositions, flows, temperatures) of this model were used by KEMA to perform calculations with the SPENCE model to determine the thermodynamic performance of low temperature gasification technology as a pre-processing step for indirect co-firing of difficult biomass fuels. The assessment is based on a case study in which the gasifier is integrated with a typical supercritical coal-fired power plant (Hemweg 8). The process data for the coal-fired power plant are reported in the previous modelling work which is reported in [Van de Ven, 2010]. The results of the modelling based on data obtained through experimental work is extensively described in [Konings, 2011].

Figure 2.15 gives a schematic representation of the configuration that was used in this study. The calculations have been performed with a gasifier temperature of 680-690°C. It is very advantageous to deduct the flue gas originating from non-white-list biomass types before it is injected into the coal-fired boiler to prevent alkalies entering the boiler. In the current study, ECN proposed to do the deducting with a fabric filter, which can only be operated at temperatures below 200°C. Therefore, the flue gas needs to be cooled to 200°C. The thermal effects are evaluated of co-firing and gasification in the Hemweg coal-fired boiler by means of 300 MW$_{in}$ of RDF or straw being gasified with the product gas and flue gas being injected in the coal fired boiler.
The thermodynamic feasibility of the indirect gasifier (MILENA) with cooling of the flue gas was evaluated assuming that the sensible heat from the flue gas is transferred to the high pressure feed water. Two feedstocks and corresponding process conditions were considered:

- **Case C**: indirect firing of straw pellets gasified at 690°C equivalent to 20% e/e and direct co-firing of 20% (e/e) of A-wood
- **Case D**: indirect firing of RDF gasified at 680°C equivalent to 20% e/e and direct co-firing of 20% (e/e) of A-wood

For these calculations ECN estimated a heat loss of 1.5 MW was estimated. In both the first study [Van de Ven, 2010] and the second study, two reference cases are considered for comparison. The reference cases exclude gasification. The reference cases are:

- **Case A**: coal in the 685 MWₑ (at generator terminals) Hemweg 8 plant
- **Case B**: coal and co-firing 20% (e/e) of A-wood

For all calculations it was assumed in both studies that there are no limitations in flue gas flow handling. This means that are no restrictions in flue gas velocity and capacity of the fans is assumed.

Biomass is fed to the gasifier at a constant rate of 300 MWₑ (LHV based) and converted in product gas and flue gas. The gasifier reactor temperature varies between 680 - 690°C. It is assumed by ECN that both product gas and flue gas leave the reactor at a temperature of 600°C. The heat that is released when cooling from 680-690°C to 600°C is assumed to be transferred to the high pressure feed water system of the power plant. This is taken into account in the modeling.

The flue gas leaving the reactor at 600°C is cooled to 300°C in a counter current flow high pressure feed water pre-heater. A pinch of about with a temperature approach 35°C is assumed as a reasonable value for a counter current gas-water heat exchanger that is not too large in size. Therefore, given the temperature of the feed water of 265°C at the inlet of the heat exchanger, the flue gas is cooled to about 300°C. The feed water is pre-heated in the heat exchanger to a temperature of approximately 300°C. The flue gas is subsequently cooled to 200°C without recovering the remaining heat. A temperature of 200°C is the highest flue gas temperature the fabric filter can handle. Both the product gas (at 600°C) and the flue gas (at 200°C) are fed to the burners of the lowest burner level of the coal boiler.
Table 2.9  **Results of the gasification calculations performed by ECN**

<table>
<thead>
<tr>
<th>Gasifier type</th>
<th>Indirect Straw pellets (690°C)</th>
<th>Indirect RDF (680°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (gasification temperature)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal input (LHV)</td>
<td>[MW]</td>
<td>300</td>
</tr>
<tr>
<td>Moisture content fuel</td>
<td>[wt% a.r.]</td>
<td>7.8</td>
</tr>
<tr>
<td>Product gas (incl. tar + remaining dust)</td>
<td>[MW]</td>
<td>225</td>
</tr>
<tr>
<td>Sensible heat producer gas to boiler</td>
<td>[MW]</td>
<td>23</td>
</tr>
<tr>
<td>Sensible heat flue gas to boiler</td>
<td>[MW]</td>
<td>9</td>
</tr>
<tr>
<td>Steam or pre-heated boiler feed water from product gas + flue gas cooler</td>
<td>[MW]</td>
<td>29</td>
</tr>
<tr>
<td>Heat loss</td>
<td>[MW]</td>
<td>1.5</td>
</tr>
<tr>
<td>Total boiler input (excl. steam)</td>
<td>[MW]</td>
<td>257</td>
</tr>
<tr>
<td><strong>Producer gas composition to boiler</strong> (wet basis)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>[vol%]</td>
<td>18.7</td>
</tr>
<tr>
<td>H₂</td>
<td>[vol%]</td>
<td>8.4</td>
</tr>
<tr>
<td>CO₂</td>
<td>[vol%]</td>
<td>11.9</td>
</tr>
<tr>
<td>H₂O</td>
<td>[vol%]</td>
<td>46.6</td>
</tr>
<tr>
<td>CH₄</td>
<td>[vol%]</td>
<td>8.1</td>
</tr>
<tr>
<td>N₂</td>
<td>[vol%]</td>
<td>1.2</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>[vol%]</td>
<td>0.1</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>[vol%]</td>
<td>2.6</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>[vol%]</td>
<td>0.6</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>[vol%]</td>
<td>0.2</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>[vol%]</td>
<td>0.1</td>
</tr>
<tr>
<td>H₂S</td>
<td>[vol%]</td>
<td>0.0</td>
</tr>
<tr>
<td>COS</td>
<td>[vol%]</td>
<td>0.0</td>
</tr>
<tr>
<td>NH₃</td>
<td>[vol%]</td>
<td>0.3</td>
</tr>
<tr>
<td>Tar</td>
<td>[vol%]</td>
<td>0.9</td>
</tr>
<tr>
<td>Producer gas flow to boiler</td>
<td>[Nm³/h]</td>
<td>71,694</td>
</tr>
<tr>
<td>Producer gas flow to boiler excl. dust</td>
<td>[kg/h]</td>
<td>76,763</td>
</tr>
<tr>
<td>Heating value product gas (excl. dust) (LHV)</td>
<td>[kJ/Nm³]</td>
<td>10,760</td>
</tr>
<tr>
<td>Temperature producer gas</td>
<td>[°C]</td>
<td>6.00</td>
</tr>
<tr>
<td>Dust concentration product gas to boiler</td>
<td>[mg/Nm³]</td>
<td>25673</td>
</tr>
<tr>
<td>Carbon content of dust to gasifier</td>
<td>[wt%]</td>
<td>72</td>
</tr>
<tr>
<td>Char/ash in gas to boiler</td>
<td>[kg/h]</td>
<td>1,841</td>
</tr>
<tr>
<td><strong>Flue gas composition</strong> (wet basis)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>[vol%]</td>
<td>4.6</td>
</tr>
<tr>
<td>CO₂</td>
<td>[vol%]</td>
<td>12.3</td>
</tr>
<tr>
<td>N₂</td>
<td>[vol%]</td>
<td>73.0</td>
</tr>
<tr>
<td>Ar</td>
<td>[vol%]</td>
<td>0.9</td>
</tr>
<tr>
<td>H₂O</td>
<td>[vol%]</td>
<td>9.1</td>
</tr>
<tr>
<td>Flue gas flow to boiler</td>
<td>[Nm³/h]</td>
<td>120,460</td>
</tr>
<tr>
<td>Flue gas flow to boiler excl. dust</td>
<td>[kg/h]</td>
<td>163,088</td>
</tr>
<tr>
<td>Temperature producer gas</td>
<td>[°C]</td>
<td>200</td>
</tr>
<tr>
<td>Dust concentration flue gas to boiler (after bag house filter)</td>
<td>[mg/Nm³]</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

When injecting the product gas and flue gas from the gasifier into the boiler, the coal input is reduced in such a way that the total gross generating output remains at a constant level of 685 MWₑ. The coal input is reduced on all burner levels equally. The calculations include the pre-
heating of the feed water by the hot gasifier flue gas. The set point for life steam temperature is 540 ± 0.5°C and for reheated steam temperature 568 ± 0.5°C.

Table 2.10  

<table>
<thead>
<tr>
<th>Code</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
<th>Case D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>coal only</td>
<td>direct co-firing</td>
<td>direct + indirect co-firing</td>
<td>direct + indirect co-firing</td>
</tr>
<tr>
<td>Primary fuel</td>
<td>coal</td>
<td>coal</td>
<td>coal</td>
<td>coal</td>
</tr>
<tr>
<td>Secondary fuel for direct co-firing</td>
<td>-</td>
<td>wood</td>
<td>wood</td>
<td>wood</td>
</tr>
<tr>
<td>Secondary fuel for gasifier (indirect co-firing)</td>
<td>-</td>
<td>straw pellets</td>
<td>RDF</td>
<td></td>
</tr>
<tr>
<td>Gasifier temperature</td>
<td>°C</td>
<td>n/a</td>
<td>n/a</td>
<td>690</td>
</tr>
<tr>
<td>Total fuel input (LHV)</td>
<td>MWth</td>
<td>1465</td>
<td>1507</td>
<td>1554</td>
</tr>
<tr>
<td>coal to boiler (LHV)</td>
<td>MWth</td>
<td>1465</td>
<td>1214</td>
<td>961</td>
</tr>
<tr>
<td>biomass directly to boiler</td>
<td>MWth</td>
<td>0</td>
<td>293</td>
<td>293</td>
</tr>
<tr>
<td>biomass to gasifier (LHV)</td>
<td>MWth</td>
<td>0</td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>Steam turbine gross power</td>
<td>MW</td>
<td>685</td>
<td>685</td>
<td>685</td>
</tr>
<tr>
<td>Loss of efficiency relative to CASE A</td>
<td>%</td>
<td>-</td>
<td>1.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Loss of efficiency relative to CASE B</td>
<td>%</td>
<td>-</td>
<td>-</td>
<td>1.4</td>
</tr>
<tr>
<td>HP steam production</td>
<td>kg/s</td>
<td>550</td>
<td>546</td>
<td>535</td>
</tr>
<tr>
<td>HP steam temperature</td>
<td>°C</td>
<td>540.1</td>
<td>540.6</td>
<td>540.3</td>
</tr>
<tr>
<td>IP steam to turbine</td>
<td>kg/s</td>
<td>460</td>
<td>463</td>
<td>469</td>
</tr>
<tr>
<td>IP steam temperature</td>
<td>°C</td>
<td>568.4</td>
<td>568.1</td>
<td>567.5</td>
</tr>
<tr>
<td>Furnace exit temperature</td>
<td>°C</td>
<td>1423</td>
<td>1405</td>
<td>1366</td>
</tr>
<tr>
<td>Flue gas flow</td>
<td>kg/s</td>
<td>653</td>
<td>687</td>
<td>715</td>
</tr>
<tr>
<td>O2 exit furnace</td>
<td>mol-%</td>
<td>3.1</td>
<td>3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>CO2 exit furnace</td>
<td>mol-%</td>
<td>14.7</td>
<td>14.7</td>
<td>14.6</td>
</tr>
<tr>
<td>H2O exit furnace</td>
<td>mol-%</td>
<td>7.2</td>
<td>9.0</td>
<td>11.5</td>
</tr>
<tr>
<td>LOI exit furnace</td>
<td>wt-%</td>
<td>3.9</td>
<td>4.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Sum H2O + CO2</td>
<td>%</td>
<td>21.9</td>
<td>23.7</td>
<td>26.0</td>
</tr>
<tr>
<td>pH2O/(H2O+CO2)</td>
<td></td>
<td>33</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>Secondary air temperature</td>
<td>°C</td>
<td>350</td>
<td>350</td>
<td>368</td>
</tr>
<tr>
<td>Flue gas temperature exit air heater</td>
<td>°C</td>
<td>123</td>
<td>136</td>
<td>154</td>
</tr>
<tr>
<td>Increasing FG temperature exit AH</td>
<td>%</td>
<td>-</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Fly ash production</td>
<td>kg/s</td>
<td>5.53</td>
<td>4.68</td>
<td>4.01</td>
</tr>
<tr>
<td>Carbon in fly ash</td>
<td>kg/s</td>
<td>0.21</td>
<td>0.23</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The indirect cases (Case C and Case D) include the use of 300 MWth biomass via gasification, 293 MWth (about 20% e/e) biomass via direct co-firing additional to 20% e/e direct co-firing of A-wood, and the matching coal amount such that a total generating output of 685 MWe at the generator terminals is achieved. These are compared against the two reference cases: Case A with coal firing only, and Case B with 293 MWth (20% e/e) direct co-firing.

Also temperature and heat release profiles inside the coal-fired boiler combustion chamber for the various cases are calculated. Figure 2.19 presents the flue gas temperature (cooling curve) in the furnace and Figure 2.20 presents the heat release in the furnace.
Table 2.11  *Corresponding levels for the boiler height values in Figure 2.22 and Figure 2.23*

<table>
<thead>
<tr>
<th>Height [m]</th>
<th>Boiler level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>hopper + 1st burner row</td>
</tr>
<tr>
<td>13</td>
<td>2nd burner row</td>
</tr>
<tr>
<td>17</td>
<td>3rd burner row</td>
</tr>
<tr>
<td>21</td>
<td>over fire air (OFA)</td>
</tr>
<tr>
<td>27</td>
<td>1st freeboard</td>
</tr>
<tr>
<td>33</td>
<td>2nd freeboard</td>
</tr>
<tr>
<td>41</td>
<td>exit furnace combustion chamber</td>
</tr>
</tbody>
</table>

Figure 2.19  *Flue gas temperature as function of the height in the furnace (Base = Case A, REF = Case B, Indirect 690 = Case C, Indirect 690 = Case D)*

Figure 2.20  *Heat release as a function of the height in the furnace (Base = Case A, REF = Case B, Indirect 690 = Case C, Indirect 690 = Case D)*

2.2.3.5 Conclusions and recommendations

In this study, the possibilities for increasing the co-firing percentage for a pulverized coal fired boiler through upstream fluidized bed gasification have been investigated. Different biomass streams exist that are difficult to co-fire directly, especially at higher percentages. Handling,
combustion properties, corrosion, slagging and fouling and ash quality are identified as the most important bottlenecks when it comes to direct co-firing high amounts of biomass. Most biomass streams are limited in direct co-firing percentage by at least one of these bottlenecks. The price and availability of biomass is another point of attention. The availability of several biomass streams is uncertain, or prices are rising because of increasing demand.

Slagging, fouling and corrosion in the boiler, by introducing high alkali loads has been identified as a potential bottleneck for high amounts of indirect co-firing through fluidized bed gasification. From an alkali point of view, the indirect co-firing approach is preferable over the direct co-firing approach because the load of undesired components on the boiler can significantly be reduced. If the flue gas is not send to the boiler but added just before the flue gas cleaning of the power plant this in effect can reduce the alkali and chlorine load to the boiler even further. By reducing the operating temperature of the gasifier, a higher amount of alkalis can be retained in the ashes. Standard CFB gasification, indirect gasification (MILENA concept) and LT-CFB have been assessed for low temperature operation (700 °C) and the integration with a pulverized coal fired boiler based on limited gas cleaning.

The results of ECN with respect to alkali/chloride distribution [Vreugdenhil, 2010] are indicative, but look promising. Verification on larger scale, longer experimental runs including recycling ash from the producer gas cyclone to the combustor is necessary. Lab-scale experiments with RDF/beech and straw indicate that over 90% of the ash can be removed from the product gas before feeding it to the boiler. The slip of alkali metals, chloride, phosphorous and heavy metal components to producer gas was observed to be in the order of 10-60% for a fluidized bed gasifier operating at 850 °C. It is concluded that this means a significant reduction with respect to direct co-firing.

Fluidized bed gasification offers the advantage of feeding coarser secondary fuels compared to direct co-firing. This advantage can be important for difficult to grind fuels with respect to capital investment and operating cost (maintenance as well as service load).

When the flue gas needs to be cooled for de-dusting and this sensible heat is transferred to the high pressure feed water, the effect on total plant efficiency loss can be limited. For firing a 20% e/e of RDF (Case D) additional to 20% e/e direct co-firing (Case B) the loss of efficiency is estimated at 0.3%, while the straw case (Case C) has an indicated loss of 1.4% respectively.

The ash produced by the gasification needs to be evaluated if it is considered a costly waste or a beneficial by product. This depends to a large extend on the fuel used.

A balanced evaluation of the overall economic viability of indirect gasification, as a means to achieve higher co-firing target, has not been done.

2.3 WP3: Sustainable ash management and development of new utilisation options

2.3.1 Problem definition

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

2.3.2 Objectives
The long-term objectives are:
- Development of a database\textsuperscript{10} and associated prediction model for biomass ash quality as a function of biomass fuel composition, conversion technology and process conditions.
- Assessment of the technical necessity and the possibilities for recycling (in order to close nutrient and mineral cycles) of the ash from the main volumes of imported biomass fuels (wood pellets and agro-residues).
- Development of specific alternative utilisation options for biomass ashes and ashes from very high co-combustion percentages.

2.3.3 Approach

2006
- Determination of the size, nature and characteristics of future biomass ashes.
- Simple modelling of ash characteristics from future biomass fuels using future conversion techniques.
- Start of the analysis towards the necessity and the potential for closing nutrient and mineral cycles by using biomass ashes and development of ash recycling products.

2007
- Continuation of the modelling of ash characteristics from future biomass fuels using future conversion techniques, the analysis towards the necessity and the potential for closing nutrient and mineral cycles by using biomass ashes and development of ash recycling products.
- Identification and proof of principle of future high-value niche applications and of large scale bulk applications.

2008
- Process development of ash recycling products in high-value and bulk applications. In bulk application (light-weight aggregates) and in niche application (recycling of ash from cocoa shells)

2009
- Finalizing research on bulk and niche applications and dissemination of results, in order to facilitate the (public) discussion on utilisation of biomass ashes and the necessity to close nutrient cycles.

2.3.4 Results 2006-2009 and discussion
The results are extensively described in a number of separate reports [Saraber, 2010; Cuperus, 2010; Saraber, 2009; Saraber, 2010a].

\textsuperscript{10}During the project it was decided to not create a separate ash database but to include the information in the BIODAT database (www.biodat.eu) on biomass fuels and ashes to have these data available in one joint database.
Volumes and characteristics of future biomass ashes

A scenario study has been conducted to determine volumes and characteristics of biomass ashes in the 2020-2040 timeframe. In this study, with the focus on ashes production, emphasis has been put on biomass co-firing and stand-alone biomass combustion/gasification. The results are used as a guideline for ash-related research in the EOS-LT Programme.

Future scenarios for electricity and heat generation have been worked out by Delft University of Technology. These scenarios have been extended for future analysis of ash volumes and origins. Two scenarios are environmental oriented and two are not. The two environmental oriented scenarios show that the ash volume from central power generation will be 1.0-1.5 Mtonne ash/year in 2020, which will increase to 1.1-1.9 Mtonne ash/year in 2030. The less environmental oriented scenarios show that in 2020 and 2030 these volumes will be both 1.7-3.0 Mtonne ash/year. These numbers include all ashes.

It is expected that the main feedstock will be imported wood from different countries; the role of domestic production and agricultural residues will be limited. The bulk of the imported biomass (clean wood) will be co-firing by the coal-fired power plants. Co-firing may be directly and indirectly (using gasification). Domestic biomass (wood trimmings, poultry litter etc.) will be mainly fired in dedicated Biomass Energy Plants (BEP). The biomass fuels which cause corrosion, slagging, fouling and/or contamination of the generated ashes may be co-fired indirectly to separate mineral matter of these fuels from the main boiler.

The scenarios all point towards an increase of co-combustion. However, since wood has a low ash content at average co-firing rates, the fraction of biomass ashes stays at a relatively low level (12-15 wt%). On the other hand, the variation in co-firing rates and hence in ash composition will increase, due to differences in fuel mix and to different capabilities of power plants. This can lead to fly ashes that no longer comply with existing utilization routes in concrete and cement, notably standard EN-450.

The ash compositions from co-firing have been calculated with an advanced KEMA TRACE model. The model is validated for dry bottom boilers. It is presumed, based on thermodynamic calculations, that the relative enrichment factors will not change, which means that the concentrations of macro and trace elements will not change significantly due to USC conditions in relation to current sub- and supercritical boiler conditions. Also the relative enrichment factors are presumed to apply to elements from biomass as well. The composition of fly ash from high co-firing rates in dry bottom boilers may have high concentrations of CaO and to a less extent K2O and P2O5, which makes these less suitable for use in concrete. Especially free lime may be a bottle-neck. The composition of ashes from fluidized bed boilers are basically different from dry bottom boilers due to the lower boiler temperature and to the different chemical composition (low Al2O3, high CaO, K2O, P2O5).

Irrespective of the details of the scenarios and the absolute amounts of ashes that are predicted, it became clear that the focus in WP3 needed to be put on one hand on co-firing fly ashes from dry bottom boiler that no longer comply with the specifications of existing applications, notably standard EN-450, and on the other hand fly ashes from fluidized bed combustion of selected fuels in BEPs. Ashes from IGCC, gasification and bio-refinery are not included because of the uncertain future. Following the scenarios, they may rise up to 15-20% of all ashes from energy production.
Figure 2.21 Predicted volumes of fly ashes from dry bottom boilers according to four scenarios

Figure 2.22 Predicted volumes of ashes from small-scale biomass combustion according to four scenarios

Identification of bulk and niche applications of co-firing and biomass ashes
Knowing what kinds of ashes can be expected to be produced in larger volumes in the coming decades, the next objective was to make an overview of potential applications of ashes from direct co-firing in coal-fired power stations and stand-alone processes and then to identify one or more bulk and niche application for these ashes, which are attractive from a technical, environmental and economical point of view. In Table 2.12 an overview is given of potential applications. It should be noted that well established applications for fly ashes are not included.
Table 2.12  Overview of potential applications for ashes (fly ashes and bottom ashes)

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

For each potential application the following items have been assessed: role of the ash in the application (positive and negative), status of technology, market and economy, regulations and sustainability. It is important that a new utilisation option has the potential to create a significant market (bulk application) or a smaller market with a high price (niche application). Bulk application is especially of interest for co-firing ashes. Niche markets appear most attractive for biomass ashes with special chemical compositions.

The following trends are expected to apply to the Netherlands:

- There will be no significant market (< 10 ktonne/year) for applications like: soil stabilisation, fuel, fillers in polymers and metals, phosphor production, metal recovery, soil improvement/fertilizer, neutralisation of waste acids, adsorption material.
- On the long term there may exist some market for utilisation as raw material for e.g. C-fix, zeolites and mineral fibres. Market will grow in sand-lime bricks, road construction material and alternative binders for standard cement.
- The only utilisation options with a significant market potential on the long term are synthetic aggregates and to a lesser extent utilisation as back-filling material in mining. Synthetic aggregates will replace natural aggregates/gravel and the product provides extra value to concrete. Back-filling is not seen as real sustainable ash management. Also, the market for back-filling will be limited in the Netherlands and export to Germany will be reduced.

As long as co-firing rates are relatively low, co-firing ashes have no specific (dis)advantage to coal ash without co-firing. Components that are present at elevated levels are not present in such quantities that they make these ashes in any way special. These ashes have no specific added value. The selling price for established applications of co-firing ashes will be negative to around 0 €/tonne.

The market for ashes from indirect co-firing and stand-alone combustion of biomass is limited, but the limitation will probably be determined by the annual production. The following ash-market combinations will be attractive:
• Ashes from combustion of meat and bone meal and some forms of manure or sewage sludge will be (very) suitable for phosphorus production.
• Ashes from combustion of uncontaminated virgin wood for soil improvement or recycling to forests.
• Ashes from combustion of virgin wood and agricultural residues for use as (raw material in) fertilizer.

These applications may have a positive selling price and can be seen as niche applications.

In general, biomass gasification and combustion ashes of various kinds may be used for the production of synthetic aggregates. Other biomass gasification and combustion ashes have to be treated as waste and have to be used for back-filling (mining) and other low-grade applications with a negative selling price.

**Assessment of nutrient and mineral recycling options**

In Figure 2.23, the chain from cultivating biomass, via energy production to ash utilisation is visualised. This chain has been used as a basis for the sustainability assessment study.

![Chain from cultivating biomass via energy production to ash utilisation](image)

Sustainability is regarded as a prerequisite for the large-scale use of biomass for energy production. One of the sustainability criteria will inevitably relate to the fertility of the soil, i.e. to prevent depletion of nutrients and minerals. In order to get a clear answer on the question which role ashes can play in sustainable biomass production, more precisely in closing nutrient and mineral balances, one should focus on a few representative cases.

The objective of recycling of ashes is to close nutrient or mineral balances and restore the soils after harvesting of biomass to its original or natural state. This recycling looks similar to utilisation as fertilizer, but they are fundamentally different. A fertilizer prepares the soil for the growth of crops. In practice, recycling is limited to forestry, so it applies to wood ash. Recycled wood ashes must be identical or similar to the ashes from the trees that grew on that particular piece of land. In agriculture ashes may be applied as fertilizer. When biomass ashes are used on a different kind of soil it should be regarded as utilisation as a fertilizer.

The number of ash types, resulting from the many biomass-conversion combinations, is too large for a comprehensive discussion. Five cases have been identified that represent the largest predicted volumes of biomass ashes and their most attractive application:
• **Case I**: clean wood pellets in fluidised-bed-combustion (FBC) or indirect co-firing and recycling the ashes to forests,
Case 2: residue from rape seed oil pressing in FBC and utilizing the ashes as fertilizer,
Case 3: cocoa shells in FBC and recycling the ashes to cocoa plantations,
Case 4: biomass blend in entrained-flow gasification (blend controlled by ash composition), and
Case 5: various biomass types in direct co-firing in coal-fired plants and utilizing the ash for the production of lightweight aggregates.

Case 1, 3 and 5 have been further investigated and further described in the sections below.

Case 1: Ash recycling in forestry
Wood ash recycling is becoming common practice in Sweden and is allowed in Finland and other countries. The Netherlands have no regulations for wood ash recycling. The question is whether the ashes from imported wood needs to be recycled.

The case study yielded the following conclusions:

a. Ash recycling may play a role in sustainable forestry and on sustainably managed energy plantations, depending on the forest management.
b. Biomass fuels from unknown sources may be suitable for recycling. When the ashes are similar to wood ashes from a certain area, they may be applied (practice in Sweden).

The most important aspect of sustainable forestry with production of biofuels is the management of forest residues\(^1\). Traditionally, forest residues are left on the site of the felling, so-called stem extraction, which means instant recycling of the bulk of the nutrients. Compensation from natural sources is sufficient to restore the nutrient balance. On the other hand, when forest residues are removed from the forest, so-called whole tree harvesting (WTH), too much nutrients are removed and artificial compensation is needed. Ideally, the combustion ashes from forest residues should be recycled, so that depletion is avoided.

As long as the wood fuels that are imported in the Netherlands have a very low ash content, which is the case for “white” wood pellets with an ash content of about 0.3 wt%, recycling of these ashes is not needed. Ashes from these pellets contain almost no nutrients, mainly Ca and Mg. These elements are in most cases not limiting elements for sustainable forestry. In nearly all cases, the loss of these elements through export of the wood pellets is smaller than the supply from natural processes (wear of rocks and deposition). The balance is sufficiently restored when the minerals in the forest residue are recycled. Nevertheless, wood pellet ashes may be used as a soil improver to stop acidification of forests, but other materials, like lime can be applied as well.

Clean wood ashes produced in the Netherlands may comply with foreign standards and be exported. For this recycling to forest soils, export will be permitted since recycling of ashes to forest soils can be regarded as a useful application.

Case 3: Nutrient recycling: ashes from cocoa shells combustion
The potential of recycling of ashes from combustion of cocoa residues to the original soil in terms of kg fertilizer/ha were assessed. The study dealt with the fertilization of 1 hectare of land in Ivory Coast, on which cocoa trees are grown together with shadow trees. The cocoa shells are available from the cocoa industry in the Netherlands and combusted in a circulating-fluidised-bed combustion installation in the Netherlands. Two scenarios have been compared:

- **Scenario 1**: Ashes are transported to a sea port in the Netherlands, from where the ashes are shipped to Ivory Coast. There, the ashes are transported by truck to a cocoa plantation. The ashes replace part of the artificial fertilizer, used to fertilize the soil of the plantation.

\(^1\) Forest residues include tops, branches, leaves and needles, which are removed on-site when trees are cut for harvesting. Forest residues contain the bulk of the nutrients. The bark contains also some nutrients, the stem almost nothing.
Scenario 2: Ashes are transported to a mine in Germany, where they are used as filling material. The fertilization of the soil of the cocoa plantation is taken care of by means of an artificial fertilizer.

System boundaries are shown schematically in Figure 2.24. The environmental effects have been assessed by determining the certain emissions of the process. CO$_2$ is one of the main causes of the greenhouse effect. NO$_x$ and SO$_2$ contribute to acidification.

Using the P and K in the ashes, it is possible to replace a maximum of 3.84 kg/hectare of artificial fertilizer. However to fertilize the soil properly another 3,000 kg artificial fertilizer per hectare is necessary (depending on the nutrient need). It is assumed that the availability/uptake of the nutrient for plant growth is the same as for artificial fertilizer (best case approach). This means that direct recycling of the ashes will only avoid about 1.5 wt% of the total needed amount of fertilizer in a best case approach. On the other hand, the avoided emissions of CO$_2$ and SO$_2$ make clear that the ashes have a potential to be used for fertilizing.

![Figure 2.24](image-url)  
Scenarios 1 (top) and 2 (bottom) with their system boundaries

The best solution turns out to be a combination of both scenarios. The P and K in the ashes should be used as fertilizer, but the best way – from an environmental point of view – is to do this close to the location where the ashes are used and not ship the ashes back to the plantations where they originate. From the point of logistics and organisation it is more attractive to compensate for the losses in the ashes with a bit of extra fertilizer. And to use the ashes as fertilizer near the combustion facility. In this way, the net reduction in fertilizer use is the same and you lower the total transport.

Case 5: bulk utilisation, light-weight aggregates from biomass ashes

The potential of producing light-weight aggregates (LWA) from ashes of co-combustion, gasification and bio-energy plants (BEP) was assessed. Firstly, an inventory has been made of the important aspects of cold bond/hydrothermal based and sintered LWA. Based on this a choice was made between these types of LWA. Further, the potential market for a new sintered LWA produced from fly ash is assessed. Melting and cold-bonding techniques have been dismissed in an early stage of the work.
There are two basic principles: sintering with a rotary kiln and with a sintering band. Rotary kilns are being used for LWA produced with clays (ARGEX) but also with secondary materials (Trefoil process). Sintering bands are used for the production of Lytag. The production process of Lytag is presented in Figure 2.25.

To substantiate the theoretical considerations, a batch LWA has been produced in a pilot scale rotary kiln. The raw material consisted of fly ash with high free lime content. An addition of 8% clay was added to get green pellets with sufficient strength. The processing time in the rotary kiln was half an hour, which is comparable to that of Lytag. The sintering temperature was at its maximum about 1200°C (measured in the free space of the rotary kiln using thermocouples). The basic properties of the LWAs were determined. The results are presented in Table 2.13.

<table>
<thead>
<tr>
<th>Measurement / test</th>
<th>Unit</th>
<th>Lytag</th>
<th>LWA-EOS-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose bulk density</td>
<td>kg/m³</td>
<td>760</td>
<td>945</td>
</tr>
<tr>
<td>Particle density</td>
<td>kg/m³</td>
<td>1400</td>
<td>1630</td>
</tr>
<tr>
<td>Aggregate size</td>
<td>mm</td>
<td>6-12</td>
<td>4-11.2</td>
</tr>
<tr>
<td>Water absorption 5 minutes</td>
<td>% m/m</td>
<td>n.d.</td>
<td>5.3</td>
</tr>
<tr>
<td>Water absorption 30 minutes</td>
<td>% m/m</td>
<td>15</td>
<td>6.0</td>
</tr>
<tr>
<td>Water absorption 24 hours</td>
<td>% m/m</td>
<td>18</td>
<td>8.4</td>
</tr>
<tr>
<td>Crushing resistance</td>
<td>N/mm²</td>
<td>n.d.</td>
<td>(3.7*)</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>% m/m</td>
<td>&lt;5</td>
<td>0.3</td>
</tr>
<tr>
<td>Grain shape</td>
<td></td>
<td>Spherical</td>
<td>Spherical</td>
</tr>
<tr>
<td>Colour</td>
<td></td>
<td>Light brown</td>
<td>Brown</td>
</tr>
</tbody>
</table>

* Average of ten tests with a pin crusher with a diameter of 15 mm

The particle density of the LWA-EOS-2 is somewhat higher and the water absorption is lower compared to regular Lytag LWAs, but it is still acceptable for replacing aggregate in concrete. There are no harmful components found in the LWA, which can influence the integrity of the concrete when made with this LWA, like free lime, which may cause expansion and thereby unsoundness of the concrete. The X-ray diffraction analysis showed that the free lime (CaO) had completely disappeared by formation of new amorphous phases.

The economical aspects are worked out for a production plant with a 200 ktonne/year capacity. Important starting points for this economical assessment are lifetime 10 years, interest 6%, minimum profit 7% and selling price LWA per tonne is equal to that of gravel.
The following conclusions are drawn:

- LWA production processes based on cold/hydrothermal bonding and sintering have specific advantages and disadvantages. The choice of the type of production process depends on the situation. The main differences concern investment and operational costs, carbon footprint and concrete properties in relation to applicability of the LWA and thereby potential market volume. In the Dutch situation, the balance is in favour of a production process based on sintering because of the better market perspective of the product.
- The main application in the Netherlands will be as substitute of coarse aggregate in concrete. Free (non-bound) applications are less appealing due the leaching behaviour. The market approach will be based on replacement of natural aggregate based on lower prices per m$^3$ concrete (concrete is sold per m$^3$ and not per tonne).
- Ashes other than dry bottom fly ashes, like biomass (gasification) ashes can be used to a limited extent, whereby the limitations will be based on content of organic matter and alkali and/or fineness.
- The cost price for the production of LWA using fly ash is about 35-45 €/tonne fly ash (gate fee). Some variation in selling price of the LWA does not change significantly the outcome of the cost price, and
- LWA can be produced by a sinter process using fly ash with high free lime content. This fly ash is typically from high percentages of co-combustion of wood. The LWA and the LWA concrete properties show that good performance of concrete can be obtained.
2.3.5 Conclusions and recommendations

At the closing of WP3 on sustainable ash management the following conclusions can be drawn:

- The volume of biomass ashes that will be generated will increase strongly up to 2020. However there is a high level of uncertainty due to macro-economical developments and national politics. Co-firing ashes will still play a dominant role. However, despite the high co-combustion percentages in the boiler (w/w or e/e bases), the share of biomass ash components will still remain minor in comparison with the siliceous coal ash, due to the low ash content of clean wood.
- Bottom ashes, both from co-firing and from BEPs, are expected to find an application as construction material, primarily in large infrastructural works.
- It is expected that most of the co-firing fly ashes will still fully fit in the current utilisation schemes. A minor share of the ashes, which does not comply with the standards (EN-450 etc.) need alternative forms of application. Recycling onto the land is the least attractive option, both from the economic as well as environmental points of view.
- The most attractive bulk application of biomass co-firing fly ash in the coming decades is the production of light-weight aggregates (LWA). Experiments to produce lightweight aggregates with fly ashes from co-firing make clear that a product can be obtained with comparable properties to that of Lytag. For LWA, also the market allows placement of several 100 ktonne per year. This application is also from an environmental point of view attractive. However, under current conditions the process is not economically attractive.
- For fly ashes from dedicated Biomass Energy Plants, there are several interesting niche applications for ashes. These ashes have a specific chemical composition, which provides an added value. The most attractive niche application is as raw material for production of fertilizer (ashes from combustion of agricultural residues in BEPs).
- Exporting BEP wood ashes for recycling to forests may be an option, but it is not strictly necessary for sustainable forest management.
- The use of ashes from the combustion of cocoa residues from a BEP in direct nutrient recycling on the plantation does not significant reduce the needed annual amount of fertilizer. The best solution, from an environmental point of view is to use is as raw material for fertilizer production in the region of the BEP is located.

2.4 WP4: Biomass co-firing in oxy-fuel combustion

2.4.1 Problem definition

Combustion in an O$_2$/CO$_2$ mixture (oxy-fuel) has been recognized as a promising technology for CO$_2$ emissions reduction as it produces a high CO$_2$ concentration flue gas ready for capture and storage. The combination of oxygen as oxidising agent and flue gas recirculation, excludes the presence of N$_2$ in the flue gas which becomes rich in CO$_2$ facilitating its capture. Furthermore, extreme steam conditions (Ultra Super Critical, 700°C, 350 bar) can be applied by using advanced materials for the heat exchanger sections (e.g., Ni-alloys) leading to high efficiencies (>50%). Finally, it is known that biomass and biofuels in general contribute to CO$_2$ reduction in comparison with fossil fuels as they are considered CO$_2$-neutral, therefore biomass co-firing could even make the oxyfuel power plant effectively into a net CO$_2$-sink.

Worldwide, several boiler manufacturers and power producers work on the development of the oxyfuel conversion technology for coal combustion. Some of the development work takes place in EU framework programmes and RFCS programmes, with ECN being involved in two co-operative projects [BOFCOM, 2006; ECOSCRUB, 2006].

A first inventory has revealed that development work on oxy-fuel combustion has consisted mainly of conceptual design and system assessments studies. Furthermore, some pilot-scale testing facilities are under construction (mainly comprising of modified existing rigs for pff-combustion testing). However, only limited attention has been given to the impact of process
conditions such as the high CO$_2$ concentrations in the boiler or the high O$_2$ concentration in the char combustion zone on combustion characteristics, including slagging/fouling and corrosion. This holds even more for the case of biomass co-firing. Ash formation and deposition (surface fouling) behavior of coal/biomass blends under O$_2$/CO$_2$ combustion conditions still needs to be studied.

Based on experience for biomass co-firing under conventional PF-combustion conditions, further development of the detailed mechanistic understanding of combustion phenomena is absolutely necessary to allow optimal and reliable operation. The EOS-LT consortium on biomass co-firing has unique facilities and know-how to help creating this understanding and support the technology development with the insight gained.

2.4.2 Objectives

This work package is aimed at advancing the knowledge base on the combustion characteristics of coal and secondary (biomass) fuels under oxy-fuel combustion conditions by means of (lab-scale) experimental investigations and subsequent modelling and chemical equilibrium calculations.

The focus of the present study is the ash formation and deposition mechanisms of solid fuel combustion under oxy-fuel conditions. The oxy-fuel gas environment experienced by fuel particles is thought to have an impact on the combustion processes including ignition, combustion characteristics, char reactions and burnout, and subsequently, ash and pollutants formation that differ from the conventional air combustion environment. Although significant work exists on the ash formation and deposition mechanisms, on the interactions of the most important ash elements (Si/K/Cl/S) and their significance in fine ash and aerosol formation, so far little work is reported on the possible effect of oxy-fuel combustion conditions on the elemental composition and the ash yield of ash in comparison to conventional firing for pure coal combustion and even less on coal/biomass blends combustion.

2.4.3 Approach

2006-2009

- Literature search on the state-of-the-art concerning oxy-fuel combustion system concepts, process conditions to be expected (e.g., temperature profiles, particle residence times) and available data on coal/biomass combustion in O$_2$/CO$_2$-rich atmospheres.
- Experiments in the Lab-scale Combustion Simulator (LCS) at ECN under simulated oxy-fuel combustion conditions focusing on proper particle heating rate, temperature, gas composition, particle residence time, defined as based on the literature search and information from involvement in international oxy-fuel development projects. Combustion characteristics to be investigated are: ignition behaviour, fuel burnout, ash formation, ash deposition and related slagging/fouling, fate of trace elements, fly ash quality. The experiments are exploratory, aimed at identifying the combustion characteristics. The fuels used were Russian and South African coal, and Greek lignite, either combusted separately or in blends (20 wt%) biomass with shea meal and olive kernel, as representatives of difficult fuels. The tests were carried out in several testing periods: (1) first carrying out tests with the Russian and South African coals and their blends with shea meal, then (2) the lignite with olive kernel tests followed and (3) a final testing period firing only lignite and Russian coal followed, in order to check and verify the observed results.
- Utilisation of the experimental data from the tests performed under air and oxy-fuel conditions for chemical equilibrium calculations and ash deposition modelling study using the Ash Deposition Predictor (ADP), developed and implemented by ECN, in order to obtain insight to the observed results and gain knowledge on the parameters that affect mainly the ash deposition under varying combustion conditions.
The work was conducted in cooperation with post-doc students from the Section Energy Technology (Department Process and Energy) of the TU Delft in close co-operation with ECN.

2.4.4 Results 2006-2009 and discussion

The detailed results can be found in two separate reports [Glazer, 2010; Fryda, 2010].

Within the reporting period, an extensive series of comparative experiments on ash deposition of coal and coal-biomass blends was carried out in the the Lab-scale Combustion Simulator (LCS) of ECN under air (O\(_2\)/N\(_2\)) and oxyfuel (O\(_2\)/CO\(_2\)) conditions. The experiments were carried out employing the LCS equipped with a horizontal deposition probe equipped with temperature and heat transfer sensors. The following phases can be identified:

a. The deposition ratio, deposition propensity and the fouling factor of the coals and blends were measured, and are all presented in the next paragraphs.

b. Deposited ash samples and also fine ash (fly) ash samples - the finer ash that did not fall on the deposition sample but was captured further downstream on the fine ash filter - were subjected to scanning electron microscopy/energy dispersed X-ray spectrometry (SEM/EDX) and inductively coupled plasma (ICP) analyses, which are standardised analytical procedures in order to define the elemental composition of the ash samples. Selected samples were also subjected to XRD analysis (crystallographic analysis) in order to search for possible phase variations between air and oxyfuel ashes. Finally, particle size distribution (PSD) measurements were carried out on the ash samples.

c. Thermochemical equilibrium calculations using FACTSage® were carried out to study the phase distribution of the ash and the behaviour of the most important inorganic elements for slag/gas phase formation (Si, K, Cl, S) under O\(_2\)/CO\(_2\) and air (O\(_2\)/N\(_2\)) conditions for the coals and their blends.

d. Finally, calculations using a model developed between ECN and TU Delft, the Ash Deposition Predictor (ADP), were carried out to facilitate the interpretation of the measured data, to obtain insight to the observed results and gain knowledge on the operating parameters or physical properties of the involved material streams that mainly affect the ash deposition behaviour under varying combustion conditions.

Ash deposition ratio and deposition propensity

First, all ash samples collected in the horizontal probe during the deposition experiments as well as the filter ash samples were weighed. In order to assess the deposition behaviour of the fuels, the ash deposition ratio \( DR \) is calculated, which is defined as the ratio of the ash collected in the probe \( m_{dep} \) for the duration of the experiment, divided by the fuel fed on the deposit probe for the same time frame, \( m_{fuel} \), both quantities measured directly:

\[
DR = \frac{m_{dep}}{m_{fuel}}
\]

In order to normalize the ash deposition in relation with the fuel ash content, the deposition propensity \( DP \) is introduced, defined as the percentage of the ash collected on the deposit probe \( m_{dep} \) to the ash fed through the fuel \( m_{ash} \):

\[
DP = \frac{m_{dep}}{m_{ash}} (\%)
\]

This ash quantity is calculated though the ash w/w % given by the proximate analysis. The deposition propensity, here expressed in %, provides more insight into the inherent deposition characteristics of the different fuels as it accounts for variations in fuel ash content. Both
experimentally derived parameters defined for the various test runs are presented in the figure below:

Figure 2.27  Deposition ratios and propensities for several coals and coal blends under air and oxy-fuel conditions

As observed in the figure above, the deposition ratio and propensity were systematically higher under oxyfuel conditions. Unburnt carbon in ash was observed in all the samples however this does not justify the systematic difference in the deposition behaviour. Another observation concerns the particle size distribution of the produced ash between air and oxyfuel conditions. In general, a larger PSD was observed under oxyfuel conditions, which could be linked to the increased deposition rates under oxyfuel conditions, because it is expected that larger particles are more prone to directly impact on the deposit surface. However, there were several cases where the particle size distribution was not clearly larger in the oxyfuel case, but the deposition ratio and propensity under oxyfuel was still larger.

Therefore, the particle size is definitely a parameter to consider, but does not seem to be the only factor influencing the deposition behaviour. Also the viscous elastic properties of the ash particles and the viscosity of flue gases are suspected to affect the deposition behaviour, and finally, the gaseous flow field itself (velocity vectors affecting the particle trajectories).

Finally, the blends have shown a lower deposition tendency than the unblended coals. This can be explained by the fact that biomass introduces elements that are more probable to enter the gas phase and at the same time combine with the ash elements of the coal ash, therefore the total available solids for deposition is becoming less. This is however a common observation in co-firing coals with biomass, independent of the oxyfuel process.

Fouling factor calculation
Based on the heat flux data measured on-line, the so called fouling factor $R_f$ of the obtained deposits can be estimated, which corresponds to the heat transfer resistance of the ash deposit. The determined fouling factors of selected fuel blends are depicted in Figure 2.28 as an almost linear function of the cumulative ash feed rate. All the fuels and blends showed the same trend.
The slopes of the curves plotted become independent of the fuels’ various ash contents. The point at which fuel feeding started was considered the beginning of the heat flux measurement. Steady state operation of the cooled deposition probe was established prior to that. In all cases the heat flux, surface temperatures, cooling air flow rate and furnace temperatures were established constant by the start of the deposition measurement.

It can be observed that the coal/shea meal blends show a lower fouling factor than the coals, which is also in accordance with the lower deposition propensity for the blends shown in Figure 2.28. However, it has to be noted that a higher deposition propensity does not always imply that the fuel has a higher specific fouling propensity (slope of the fouling factor against cumulative ash fed), since other parameters, as the thermal conductivity of the deposition layer or the scattering of the deposit on the probe, might also play a role in the heat transfer properties of the deposition layer.

**Chemical and crystallographic analyses**

The chemical analyses of the ash samples as well as the electronic microscopy analyses did not reveal significant changes in the ash chemistry in the oxyfuel case compared to the air case. The effect of combusting coal/biomass blends under air and oxyfuel conditions is reflected in the ash chemistry and can affect the subsequent sintering tendency; this seems to happen independent of the combustion conditions and is a well known phenomenon when blending fuels with different ash composition. A slight depletion of potassium (K) was shown in the deposited ash for the blends, probably due to the higher reactivity of the biomass bound potassium (K) and the addition of increased chlorine (Cl) input due to the shea meal. Almost complete absence of Cl and sulphur (S) was observed in the deposited ash.

A more detailed analysis of the fine ash using a cascade impactor implied some effect of the oxyfuel combustion compared to the air case, apart from the effect of the biomass addition. In some of the oxyfuel cases the values of the refractory elements (Ca, Mg, Si, Al) seem slightly higher than in the air case, while the volatile elements (K, Na, Cl, S, P) show the opposite trend. This could be explained by the effect of local char combustion temperatures, which can
be higher in the oxyfuel case, as well as the varying CO$_2$/CO ratio in the char combustion area, which affects the release of refractory vs. volatile elements, as suggested in the available literature. However this was not observed systematically. Therefore it can be concluded at this stage that no significant differences were detected in the ash composition between air and oxyfuel conditions, and the only variations in the ash composition is due to the fuels blending.

**Evaluation of the experimental results and conclusions**

It was observed that the deposition ratio is as expected increasing with the ash content of the blends, and that the deposition ratios are lower under air combustion, for the same fuels, the same fuel feed rates and the same gaseous volume flows. The fouling factors are also higher in the oxyfuel case. In order to evaluate these observations, first, slag (melt) formation has to be excluded, which would increase the weight and density of the ash deposited, leading to wrong conclusions. Indeed, there was no melt observed. Secondly, unburnt fuel particles falling on the deposit probe would also increase artificially the mass of the deposit sample. The carbon in ash was measured in the lab and the results do not show unburnt carbon contribution to the increased deposit formation, the combustion was satisfactory, not loading the deposited ash with high loads of carbon particles or slag. The particle size of the sampled ash from oxyfuel tests seems larger compared to the air combustion cases, which can be a factor contributing to increased deposition because large particles increase the impaction efficiency; however the size shift into larger particles was not always the case when firing under oxyfuel. Therefore more parameters seem to affect the deposition behaviour of ash such as the gas physical properties, e.g. the flue gas viscosities, the velocity vectors (in general the gas streamlines around the probe), or the viscous elastic properties of the ash formed under the various conditions. These parameters may contribute to varying deposition rates under air vs. oxy-fuel firing. The ADP (Ash Deposition Predictor) is a useful modelling tool to assess the effect of these parameters on the ash deposition process.

The coals studied present lower deposition propensities when they are blended with biomass, either shea meal or olive, but the trend between air and oxyfuel does not change. This implies interactions of the ash material of the fuels, but it does not seem to be linked with the oxy-fuel conditions in particular. There does not seem to be any additional effect of the oxyfuel conditions on biomass addition in the coal/biomass blend. This was verified by chemical equilibrium calculations using FACTSage® that took into account the ash composition of the tested fuel blends and the combustion conditions. The calculations showed similar phase distribution and behaviour for the most important inorganic elements for slag/gas phase formation (K, Cl, S) under O$_2$/CO$_2$ and air (O$_2$/N$_2$) conditions, for the coals and their blends. Therefore the next paragraphs focus on the results from the ADP tool.

**Ash deposition modelling of coal/biomass mixtures at air/oxygen combustion conditions**

*The Ash Deposition predictor code and Simulation settings*

In order to provide comparative data to the experimental deposition tests performed under the oxy-fuel conditions ash deposition modelling study has been done using the Ash Deposition Predictor (ADP) developed and implemented by ECN/Petten. The ADP is a tool which post-processes the data originating from the Computational Fluid Dynamics (CFD) based modelling of the boiler. The predictor is an independent particle tracking code which includes inertial impaction, thermophoretic attraction and dynamic reaction of particles on surfaces in order to predict the location of the deposited ash, and the growth of the deposit. The numerical calculations have been performed in order to simulate the deposit formation observed during experiments on a deposit probe inserted within the Laboratory Combustion Simulator (LCS) and to compare with the experimental combustion tests.

The CFD modelling tool called CINAR has been used in order to perform the CFD calculations. CINAR is a commercial code developed by the College University London and has been used to numerically model industrial combustion boilers. The CFD calculations have been performed for two different operational conditions namely air based combustion environment and the oxy-
fuel combustion environment. For each of these settings the process gases have been specified. The parameters like oxygen, nitrogen, water content etc. have been specified in order to reflect the conditions used during the LCS experiments.

As a result of the CFD simulations a flow field is calculated, for which a set of characteristic and describing parameters has been obtained: velocities, pressure, temperature distribution, etc. within the numerical domain. This flow field has been used as input for ADP to perform the numerical calculations.

**Input parameters for the CFD code (CINAR) and the Ash Deposition Predictor**

The CFD calculations with the CINAR code have been performed for the two different combustion regimes, namely, the oxyfuel combustion regime and the “standard” air combustion. The conditions mirror the LCS experiments in order to compare the results of the numerical simulations with the experimental findings and to assess and evaluate the differences in deposition phenomena for these two varying combustions conditions. In addition the experiments can help in the interpretation of the numerical findings.

The fuels used for the simulations were Russian coal, lignite, and blends with biomass (20 wt%): Russian coal with shea meal, lignite with olive stones. The simulation matrix is summarized in the Table 2.14.

**Table 2.14 Simulation matrix – ADP**

<table>
<thead>
<tr>
<th>Experiment number/ADP number</th>
<th>Environment</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air</td>
<td>Russian coal</td>
</tr>
<tr>
<td>2</td>
<td>Oxyfuel</td>
<td>Russian coal</td>
</tr>
<tr>
<td>3</td>
<td>Air</td>
<td>Russian coal with shea meal</td>
</tr>
<tr>
<td>4</td>
<td>Oxyfuel</td>
<td>Russian coal with shea meal</td>
</tr>
<tr>
<td>5</td>
<td>Air</td>
<td>Lignite</td>
</tr>
<tr>
<td>6</td>
<td>Oxyfuel</td>
<td>Lignite</td>
</tr>
<tr>
<td>7</td>
<td>Air</td>
<td>Lignite with olive stone</td>
</tr>
<tr>
<td>8</td>
<td>Oxyfuel</td>
<td>Lignite with olive stone</td>
</tr>
</tbody>
</table>

The particles are introduced to the ADP modeller. In total, the deposition behaviour of 10,000 particles was tracked. There are certain physical properties specified in the code, such as particle size distribution (PSD) with the mean diameter, particle density & composition based on Si molar fraction, viscous - elastic properties of ash, the ratio of non-bridging oxygen to tetrahedral oxygen (NBO/T). Particle viscous - elastic properties and NBO/T have been specified based on the formula proposed in literature. Some of the parameters have been assumed to be constant for all the calculations some others were particle specific (PSD, NBO/T).

The following Table 2.15 shows the results of the main sets of ADP calculations, one using Russian coal and blends, and the other using lignite and blends, for two particle size distribution values. The initial PSD values are called ‘old’ PSD values, and are directly obtained from the measurements. In the alternative calculation set, the PSD values were equalized (homogenized) for the two fuels (Russian coal and lignite), in order to eliminate the ash particle size influence. This PSD values are called ‘new’.
Table 2.15  “Old” and “new” deposit rates for the Russian coal and its blends (20wt% biomass). The PSD of the lignite coal and blends has been used as the input parameters for the second set of ADP calculations

<table>
<thead>
<tr>
<th>Test</th>
<th>Environment</th>
<th>Fuel</th>
<th>PSD &quot;old&quot; (set 1) [micron]</th>
<th>PSD &quot;new&quot; (set 2) [micron]</th>
<th>Ash propensity &quot;old&quot; [kg/kg]</th>
<th>Ash propensity &quot;new&quot; [kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air</td>
<td>Russian coal</td>
<td>46</td>
<td>39</td>
<td>0.35</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>Oxyfuel</td>
<td>Russian coal</td>
<td>28</td>
<td>86</td>
<td>0.28</td>
<td>0.60</td>
</tr>
<tr>
<td>3</td>
<td>Air</td>
<td>Russian coal with shea meal</td>
<td>44</td>
<td>40</td>
<td>0.34</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>Oxyfuel</td>
<td>Russian coal with shea meal</td>
<td>33</td>
<td>49</td>
<td>0.31</td>
<td>0.40</td>
</tr>
<tr>
<td>5</td>
<td>Air</td>
<td>Lignite</td>
<td>39</td>
<td>39</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>Oxyfuel</td>
<td>Lignite</td>
<td>86</td>
<td>86</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>7</td>
<td>Air</td>
<td>Lignite with olive</td>
<td>40</td>
<td>40</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>8</td>
<td>Oxyfuel</td>
<td>Lignite with olive</td>
<td>49</td>
<td>49</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>

With the PSD being replaced for the Russian coal the trend is different in the “new” case than in the ‘old’ case. In the case of the homogenised (uniform) particles sizes the oxyfuel gaseous environment, mainly CO₂ with some O₂, produces more deposited particles compared to the air combustion environment, which is mainly N₂ and some O₂. This trend is in agreement with the experiments where the oxyfuel tests results to more deposition. The next paragraph shows some further results on the deposition behaviour relative to the gaseous environment.

**Sensitivity of the code to the air/oxyfuel conditions**

In order to test the sensitivity of the code to the given oxyfuel or air combustion conditions, the following parameters were considered constant:

1. Particle size constant, but the viscous elastic properties (NBO/T) test specific
2. Particle size constant, as well as the NBO/T ratio

Especially the second case is expected to provide information on whether the oxyfuel conditions (temperature, pressure, gas streamlines, velocity vectors) influence the deposition process assuming ashes with a standard chemical composition (reflected in the NBO/T) and the same particle size.

The first case (Table 2.15) where the PSD values are equal but all the other parameters including the NBO/T are test specific reveals and confirms the relationship between the lower NBO/T (sticky ash) and the increased deposition rates. From the second case it is visible from table that the deposits rates are slightly higher for the oxyfuel conditions where all the other parameters are the same. This comes in agreement with the experimental findings.

Table 2.16  ADP results on deposition ratios for lignite calculated under oxyfuel and air conditions

<table>
<thead>
<tr>
<th>Test</th>
<th>Environment</th>
<th>Fuel</th>
<th>PSD (homogenised) [micron]</th>
<th>NBO/T [mole/mole]</th>
<th>Ash deposition ratio &quot;new&quot; [kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>air</td>
<td>lignite</td>
<td>86</td>
<td>-0.085</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>oxyfuel</td>
<td>lignite</td>
<td>86</td>
<td>-0.100</td>
<td>0.60</td>
</tr>
<tr>
<td>Case 2</td>
<td>air</td>
<td>lignite</td>
<td>86</td>
<td>-0.092</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>oxyfuel</td>
<td>lignite</td>
<td>86</td>
<td>-0.092</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Conclusions and recommendations on the ADP study
A set of numerical calculations was performed in order to evaluate the ash deposition during the combustion of two coals and their biomass blends under oxyfuel and standard air conditions. The code seems sensitive to the particle size (Particle Size Distribution) and the viscous elastic properties of the ash. The sensitivity analysis of the code to the ash particle size and the viscous elastic properties of ash revealed large particles are more easily separated from the gas flow and deposit more easily on surfaces, while stickier ash is also more prone to deposit than dry ash. If these two parameters are kept constant, in order to eliminate their influence, then the deposition ratios are again clearly higher under oxyfuel combustion, which is finally in line with the experimental observations. These observations indicate the effect of the flow field (gas streamlines) on the deposition behaviour.

The ADP is still missing the possibility to numerically model the condensation phenomena so at this moment the code represents a simplification of the reality. In addition to particle formation and the deposit formation process direct condensation of aerosols forming species on furnace walls and in this case on the deposition probe must be considered. The ADP code should be further developed and equipped with additional functionality and validated for different fuels and sets of conditions.

2.4.5 Conclusions and recommendations
Based on the work performed, the following conclusions can be drawn:

- Ash deposition experiments of coal and coal-biomass blends were carried out in the LCS facility under air (O₂/N₂) and oxy-fuel (O₂/CO₂) conditions. The deposition ratio and propensity are systematically higher under oxy-fuel conditions; the blends have shown a lower deposition tendency than the unblended coal. An attempt of results interpretation lead to the conclusion that the altered flow fields, the difference in the ash particle sizes and the different flue gas physical properties of the two combustion environments are the reasons for the increased deposits observed under oxy-fuel conditions, excluding ash melt formation and further change of chemistry in the oxy-fuel case.
- The blending of coals with biomass in both combustion conditions affects the ash chemistry and therefore the sintering tendency in a much greater way than the combustion environment. Depletion of potassium (K) was observed in the deposited ash for the blends, probably due to the increased chlorine input due to the shea meal. Cl and S were almost completely absent from the deposited ash.
- The ADP code estimated that the deposition rate follows the trend of the experimental results with an admissible error but has to be developed further in order to eliminate current difficulties in using it. Thus, a thorough sensitivity analysis has to be carried out, followed by further comparisons between test and model results in order to develop a useful design tool for oxy-fuel firing installations.
- The use of FACTSage® software gives a good estimation of the expected ash composition tendency and their phase (liquid, solid, gas). The FACTSage® software can be used complementary with the experiments in order to evaluate the ash chemical composition results. In that case, it can be used as a predictive tool in the design phase of an oxy-fuel application either in existing or new boilers.

2.5 WP5: Fouling monitoring/boiler diagnostics

2.5.1 Problem definition
High percentages biomass co-firing (>5-10% on energy basis) require a more detailed process monitoring and control to avoid excessive maintenance cost and unplanned outages. This holds for existing coal-fired power plants, but even more for new units based on advanced clean coal technologies such as Ultra Super Critical (USC) boilers and oxy-fuel combustion. Particular
points of attention are corrosion and boiler slagging and fouling, and related soot blowing. There is a need for measurement systems, both for periodic diagnostics and for continuous (on-line) monitoring and control.

At ECN, the development of methods for on-line boiler fouling is being addressed already. However, the coupling with soot blowing (so-called intelligent soot blowing) has not been established yet. KEMA has available a method for corrosion monitoring (KEMCOPs). Diagnosis en monitoring of other boiler characteristics are not being addressed by the consortium partners yet.

2.5.2 Objectives
The objectives of this work package are:
- Development of an advanced method for on-line fouling monitoring, which enables intelligent soot blowing, and
- Determination of the state-of-the-art with respect to boiler diagnostics and monitoring/control, and identification of necessity/possibilities for the development of advanced diagnostic and/or monitoring methods.

2.5.3 Approach
2007 -2009
- Development of a measurement system for local diagnosis and early detection of fouling in the convective part of boilers (fouling monitoring).
  - This development is linked directly to on-going work at ECN and concerns an extension to enable intelligent soot blowing. To achieve the final goal of a working prototype, the following activities are foreseen:
  - Calculations to determine the response of single and multiple steam pipes on locally reduced heat transfer,
  - Inventory of existing measurement principles to determine the optimal combination for this application,
  - Conceptual design of the measurement system,
  - Prototyping - engineering and construction.
- Inventory of existing methods for boiler diagnostics and monitoring/control aimed at determining the state-of-the-art and identifying the necessity/possibilities for the development of advanced diagnostic and/or monitoring methods.

The work was conducted by a post-doc from the Section Energy Technology (Department Process & Energy) of the TU Delft in close co-operation with ECN.

2.5.4 Results 2007-2009 and discussion
The detailed results are described in a separate report [Dyjakon, 2010].

According to the WP5 work plan (which started only in January 2008 due to late appointment of the post-docs), first the calculations have been performed to establish whether the additional heat resistance from ash deposits could be a good indicator of the extent of fouling on steam tubes in the convective part of the boiler. It was concluded that this additional heat resistance does form a good basis for a measurement system, however due to the rather local nature of the measurement, it should be accompanied by a reliable measurement of the steam flow in the tube bundle in the vicinity of a heat flux sensor. This should be done because of the fact that the decrease in heat flux may both be caused by a growing ash deposit, as well as a locally reduced steam flow. This finding was further confirmed by the outcome of the first full-scale application
trial of the heat flux sensor in the framework of the national BSE project “Boiler Fouling” [Boiler Fouling, 2006].

Secondly, it was concluded that the sensitivity of the heat flux sensor, forming the core of the future measurement system, needed thorough examination in order to understand all the physical phenomena that may influence the measurement. To this purpose, an experimental set-up for heat flux sensor calibration was constructed and extensive calibration tests were conducted as described in more detail below.

**Heat flux sensor calibration**

The horizontal deposition probes, developed by ECN for the application in lab and full-scale deposition tests can be used for on-line visual observation of the deposit growth process, estimation of the deposition rate, direct heat flux measurements and naturally for collecting the deposits for off-line analyses. Both lab- and industrial-scale instruments are equipped with a ring-shaped heat flux sensor consisting of four independent thermo resistance/temperature sensors (Figure 2.29).

However, the application of the deposition probe in the wide range of the operation conditions, typical for the lab-scale as well as full-scale investigations, requires thorough sensor calibration, since many physical parameters can influence the sensor sensitivity $k_i$ and, as a result, the quantitative and qualitative measurements of the heat flux. Thus the aim of the described work was the quantification of the parameters’ influence on the sensor sensitivity $k_i$ to enable for their subsequent application in the heat flux formula. To obtain the necessary data for the heat flux sensor calibration, measurements were performed by means of the purpose-built experimental test rig, shown schematically in Figure 2.29.

![Figure 2.29 Schematics of the experimental set-up for heat flux sensors calibration:](image)

The deposition probe (9) is externally heated by an electric heating wire (5). The power supply is provided by regulated, stabilised and electrically separated transformers (1) and (2). The temperature on the surface of the heating wire is measured by a K-type thermocouple (6) and controlled by a solid-state rely based regulator (3). The power supply parameters (voltage and intensity) of the heating wire are measured by a multi meter (4). In order to minimise heat losses the instrument has been thermally insulated (8). The deposition probe is cooled by cooling air,
which simulates steam in the described system. Cooling air parameters, such as the temperature and the mass flow, are controlled by a thermocouple (6) and a flow meter controller (10). The temperature of the air can be increased by an electric air pre-heater (7). Heat transferred from the heating wire to the deposition probe is measured by a fourfold of heat flux/temperature sensors (11) installed inside the wall of the deposition probe. Measured values of the heat flux and temperature are registered by a PC. The deposition probe surface temperature is measured by a thermocouple (12) integrated into the heat flux sensor. Cooling air temperatures inside the deposition probe (near the heat flux sensors location) are measured by thermocouples T1, T2, T3 that are located alongside the cross section axis of the deposition probe.

Depending on the simulated combustion conditions, the deposition probe can operate with a surface temperature of up to 750°C, which entails different settings of the probe operating parameters (air cooling temperature/stream). To cover this broad range of settings, the experiments were performed under the several sets of conditions, varying the deposition probe temperature (100-750°C), the cooling air temperature (25-400°C) and the cooling air flow (5-1000 l/min).

Exemplified detailed results for lab-scale probe

The experimental tests revealed that the main parameters influencing the sensor sensitivity \( k_i \) are deposition probe temperature and cooling air flow. The influence of other parameters is negligible. Taking into account the nearly logarithmic influence of the said parameters on the sensor sensitivity \( k_i \), an equation has been proposed that enable to recalculate and determine the current value of the sensor sensitivity for given operation conditions of the deposition probe (deposition probe temperature and cooling air flow).

The calculated values of the sensor sensitivity \( k_i \) for a given thermal sensor based on the regression equations from the above mentioned tests are shown in Figure 2.29. For comparison, the measured sensitivity for the probe temperature of 150°C is presented, a point which was originally used as a fixed reference for the whole measurement range. As can be seen the values range widely, which makes clear indeed how important proper calibration is for a reliable measurement at any temperature or flow conditions applied during sampling by means of both the lab- as well as industrial-scale deposition probes.

Finally, the equations have been incorporated into the slagging/fouling measurement subsystem/software, which is an integral part of the Lab-scale Combustion Simulator (LCS). Similarly the data obtained for the industrial deposition probe have incorporated in its data handling system.

Figure 2.30 Determination of the sensor sensitivity value in dependence on the cooling air flow and deposition probe temperature
High-temperature non-invasive steam flow meter

As the third part of the work, a review of the existing methods for the non-invasive mass flow measurement has been performed. After the completion of this survey, a few industrial parties developing such systems have been contacted to start discussions on the potential incorporation of their system into the on-line fouling monitoring system to be developed. However, upon contacting commercial/industrial parties, it was found out that the existing methods are not directly applicable for measurements in the harsh environment of the SC/USC power plant (where temperatures in the penthouse above the superheater tube headers can reach temperatures above 400°C). Also, the hard and thick materials used for the manufacture of high-pressure/high-temperature steam tubes are highly problematic for the available ultrasonic-based measurements techniques. Furthermore, none of the parties was prepared to share the exact details of the commercial systems and discuss possibilities for further development. Therefore, it was decided to design an all-new system, based on a measurement principle which was discovered during the earlier mentioned heat flux sensor calibration work.

Lab-scale high temperature steam flow meter prototype

The general design of the said tool is based on a direct measurement of the minute heat flux changes transferred from the steam flowing in the superheater pipe to a sensor installed on the steam pipe (Fout! Verwijzingsbron niet gevonden.). It should be noted here, that due to intellectual property issues parts of the design have been made confidential.

The sensor is enclosed in a small chamber, through which a small reference medium flow is passed. The reference medium flow through the chamber is controlled in such a way as to obtain sufficient signal-to-noise ratio and response time, while minimising the medium use. The output of the sensor, a microvoltage signal, is measured by an electronic device and can be directly transmitted and registered on-line by a computer.

To explore the operation characteristics (overall sensitivity, signal/noise ratio, response time) of the lab-scale flow meter, an exhaustive series of tests has been performed. To do so, the apparatus has been integrated with the ECN lab-scale Horizontal Deposition Probe which in this series of tests was used basically as a source of high temperature steam. A photograph of the apparatus mounted onto the probe is given in Figure 2.31.

![Photograph of the lab-scale high temperature steam flow meter integrated with the ECN Horizontal Deposition Probe](image)

Throughout this series of tests ambient temperature air was used as a cooling reference medium, while the hot environment of the “penthouse” – the space in the boiler where steam tube bun-
The headers are located and which is the target location for the developed flow meter – has been simulated by simply insulating the whole assembly and thus allowing it to heat up during the test to relevant temperatures.

From the results of the preliminary lab-scale tests of the flow meter, the following conclusions can be drawn:
- The response of the sensor is sensitive enough in all regimes (i.e. the combination of the lowest reference medium flow and steam temperature results in sufficient sensitivity).
- The higher the flow of steam the higher the sensor response.
- Increase of the steam temperature results in an increase of sensor sensitivity.
- Increase of the reference medium flow also increases the sensor sensitivity.
- Relatively small changes in the steam velocity are clearly detectable.
- The static response time (the time after which signal fully stabilises after small change of the steam flow) of the system is ca. 5 minutes, whereas the dynamic response time (after a major change in the steam velocity) adds up to approx. 15 min, yet the main part of the response is clearly measurable within 1-2 minutes.
- With regard to the application in the power plants the determined response time and sensitivity appear to be more than satisfactory for the application in the fouling monitoring of the super heater panels.

**Pilot-/full-scale high temperature steam flow meter prototype**

In-line with the project plan, based on the promising experimental results described above, it was decided to adapt the lab-scale prototype of the flow meter for further testing in a full-scale power plant. This was done by changing the design of the flow meter chamber from a closed tubular “weld in” type, which requires installation by slicing through and replacing a part of the steam pipe, to an open “clamp on” design, which allows for mounting of the apparatus on any existing steam tube.

**Conceptual design of an integrated fouling monitoring system**

After the completion of the fouling sensor calibration tests and the subsequent development of the high temperature flow meter, in the last part of the project a conceptual design of an integrated fouling monitoring system has been developed. Schematics of the said system are detailed in Figure 2.32.
The foreseen slagging/fouling monitoring system relies on the installation of the heat flux sensors in the evaporator walls and a combination of thermocouples and high temperature steam flow meters on the steam pipes (close to the headers) of the super heaters. The application of the slagging sensors on the evaporators’ walls yields data for the boiler operator on the following aspects of the combustion process:

- Uniformity of heat distribution and heat flux in combustion chamber,
- Location of the slagging areas on the evaporators’ walls,
- Temperature profile near the walls, and
- Flame dislocation during the combustion.

The fouling sensors clamped on the steam superheater pipe (at the inlet and outlet to the superheater) may bring the following information:

- Location of the fouling areas on the superheater panels,
- (Local and global) disturbances in steam temperature, and
- (Local and global) fluctuations in steam flow.

The number and the location of the sensors depends on many factors: both engineering, such as the furnace design (wall- or tangentially fired), or the desired system sensitivity (i.e. the number of bundles to be monitored or a possible extension of the system into the convective boiler part), as well as the investment capacity, of the boiler owner, related to the economics of the boiler operation but also its age.

Ultimately the proposed integrated slagging/fouling monitoring system should also include automated data analysis functionality, which should translate the observed boiler characteristics in directions/alerts for the boiler operator on the necessary actions needed for the optimization of the boiler operation. Furthermore the said data analyses system may further be integrated with the soot blowing system (water cannons, steam blowers, acoustic blowers etc.) installed in the boiler. Conclusions and recommendations

Based on the extensive experimental calibration of the heat flux sensor constituting the heart of the fouling diagnostic probe as well as of the foreseen integrated fouling monitoring system, an algorithm has been proposed describing the non-linear behaviour of the heat flux signal response as a function of cooling medium mass flow and temperature, and flue gas and surface temperatures. The algorithm developed thusly has been incorporated into the on-line lab- and industrial-scale deposition probe measurement system, allowing for very accurate measurements of the fouling propensity. In particular in the lower measuring range, the accuracy has improved by one order of magnitude.

The developed lab-scale prototype of the non-invasive high temperature steam flow meter has proven quite successful. It was verified that the instrument is indeed capable of measuring small changes in the flow of steam inside the steam tube under conditions relevant for the application in the full-scale power plant. After redesigning the instrument, allowing for clamp-on application on the existing steam tubes, the apparatus is ready for further testing in a power plant. At the end of the project, contacts have been made with the EPZ Borssele power plant to proceed with further testing.

A conceptual design of an integrated slagging/fouling monitoring system has been proposed, based on the sensors and instruments developed in this work package. The design includes both the suggestions of the location of the measurement equipment as well as the way the produced data can be interpreted and translated in action alerts for the boiler operator or further integrated with the existing soot blowing system.
Summarizing, the work within this work package has been fruitful. The gained experience forms a solid base for further (commercial) development and the application of both the fouling diagnostic probes as well as the conceptual integrated slagging/fouling monitoring system.

2.6 WP6: Wet biomass processing and heat utilisation

2.6.1 Problem definition

A large fraction of the biomass potential consists of wet biomass with a moisture content of typically more than 50 wt%. Because of the high moisture content and the often high concentrations of alkalis (mainly K) and halogens (Cl), these types of biomass are not suitable for direct co-firing. Generally, conventional washing and drying is not attractive because of high energy requirements. Therefore, these types of biomass are typically used in wet, biochemical conversion processes like digestion and enzymatic ethanol production. Not all types of biomass are suitable for these wet processes, since they yield large residue fractions and they often require considerable heat input as well.

Most coal-fired power stations currently produce only electricity. Although the electrical efficiency in itself is high, the overall efficiency could be raised substantially (up to >80%) by combining electricity supply with heat supply. This might become crucial, when EU-regulations will be adopted with minimum efficiency requirements for sustainable biomass use. One of the main challenges will be how to combine the (base load) heat supply of a coal-fired power station with activities that have a similar heat demand.

Potentially, interesting options lie in combining coal/biomass-fired power stations with upgrading of wet biomass feed stocks to biomass fuel. On one hand, heat from the power plant is then used for biomass conversion processes or drying. On the other hand, the biomass fuel can be directly co-fired in the main boiler. Interesting biomass conversion processes might include not only digestion and bio-chemical ethanol production, but also innovative bio-refinery concepts.

One of the interesting upgrading options for integration with a coal-fired plant is the TORWASH concept, currently under development at ECN. According to this concept, washing and torrefaction are conducted simultaneously at elevated temperature and pressure, followed by a drying step. The TORWASH principle leads to high washing efficiencies and relatively low energy requirements. In the EOS-LT consortium on co-firing, the potential for combining TORWASH with a coal-fired plant is investigated. The technical development for the stand-alone application of the TORWASH technology is the subject of a separate EOS-LT proposal (acronym ETAP) and is outside the scope of this project. Both initiatives are complimentary. ETAP aims at small-scale, stand-alone application, while in the co-firing consortium, a large-scale TORWASH application is investigated focusing on the opportunities for combining TORWASH with pulverized fuel combustion.

2.6.2 Objectives

The main objective of this work package is a screening to identify and assess concepts for the integration of coal-fired power generation and wet biomass upgrading/processing, aimed at increased overall efficiency of the plant and cost reduction through optimal heat integration. It appeared not easy to compare mature technology such as anaerobic digestion with innovative new technologies such as HTU (pilot plant scale) or Supercritical Water Gasification (bench scale). An additional objective is to assess the techno-economic feasibility of the most promising concepts. The objectives of the TORWASH experiments are a) to verify whether promising results previously found on a small lab-scale can be reproduced on a larger bench-scale (from 0.5 to 20 litre autoclave) and b) to determine the combustion reactivity of TORWASHed material and therefore its suitability for co-firing.
2.6.3 Approach

A desk study has been performed to identify attractive biomass streams and to do a screening to assess the most promising technologies suitable for integration with a power plant. For a number of configurations of technology and wet biomass types, it was necessary to prepare mass- and energy balances based on best available experimental data. Also investment cost (CapEx) and operational cost (OpEx) estimates were determined to assess the economic viability. Technology developers and hardware suppliers were contacted and experimental facilities were visited. Process simulation studies with the SPENCE power plant model have been performed in order to assess how these technologies can be integrated with existing and future coal-fired plants for optimal efficiency of electricity production from low calorific value, difficult to use wet biomass streams.

A TORWASH experiment was performed in 20 litre autoclave (bench scale). A feedstock was selected that emerged from the desk study and that was previously tested on small scale (0.5 litre autoclave). Mass and energy balances were determined, and also the degree to which problem elements (K, Cl, etc.) are removed. The potential for mechanical dewatering, the grindability and reactivity are determined as well.

2.6.4 Results 2008-2009 and discussion

A desk study has been performed in project year 2009 (Phase 1) to identify the most promising concepts and a techno-economic evaluation has been performed of the most promising concepts in 2010. A KEMA-ECN report has been written that presents the selection of applicable biomass types, and a first evaluation of wet biomass processing concepts. For details, especially of the different technologies, the reader is referred to this report [Magneschi, 2010]. Additionally, a second KEMA-ECN report has been written that presents the techno-economic evaluation of the most promising concepts, referring to [Magneschi, 2010a] while for the results of the TORWASH experiments is referred to [Pels, 2011].

Biomass selection

In the phase 1 study candidate biomass types were selected. The selection of candidate biomass types was based on the following criteria:

- Biomass must be considered as a wet biomass, i.e. a biomass type that consists of a high moisture content, such that it is not-likely to be feasible as a normal co-firing fuel (even with normal air drying) without significant dewatering,
- Biomass types must be mentioned in existing (environmental) permits of the Dutch co-firing plants (available to the WP6-group) or it must be easy to include them in permits. Obtaining a permit for co-firing biomass types can be a difficult and time-consuming task. Therefore, attention will go to biomass types that are currently considered as ‘clean’ biomass types, i.e. biomass types that are part of the so-called White List [Infomil, 2010], together with the ones that are currently permitted,
- Biomass must be available within 100 km of the power station (basically in the Netherlands). Transporting wet biomass over more than 100 km is in most cases considered to be economically unattractive, and
- The wet biomass types must be available for electricity and heat generation on the long-term.

Since this work package regards possible long-term innovative developments (> 5 years) from a techno-economic point of view, currently applicable subsidy schemes serve as indirect criteria for selection of certain biomass types.

In a first assessment according to the defined criteria, the following biomasses were identified as most promising biomass types:

- (Road shoulder) grass,
- Organic wet/compostable fraction (GFT),
Digestates from the anaerobic digestion of agricultural residues and manures,
Animal manures, and
Sewage sludge

It is concluded on the suitability of certain feedstocks for this application that:
- **Most** eligible biomass types are the wet biomass types that are on the White List, available in the Netherlands, and currently permitted as co-firing fuel in one or more of the coal fired units,
- **Less** eligible biomass types are the wet biomass types that are on the Yellow List, available in the Netherlands, and currently permitted as co-firing fuel in one or more of the coal fired units,
- **Less** eligible biomass types are the wet biomass types that are on the White List, available in the Netherlands, and currently not permitted as co-firing fuel in one or more of the coal fired units,
- **Least** eligible biomass types are the wet biomass types that are on the Yellow List, available in the Netherlands, and currently not permitted as co-firing fuel in one or more of the coal fired units, and
- **Not** eligible are all other biomass types.

**Heat availability**
In general, a combined heat and power plant can achieve a higher overall efficiency, if steam is extracted at a low pressure level and can be converted effectively for example for district heating. Extracting steam results in loss of electricity. Therefore, the often used power loss factor is known as the loss of power (net) divided by the resulting heat that is extracted from the system, and that can be used effectively. The lower the power loss factor, the more effective it is to extract heat from the plant for example for district heating. As a result, the overall efficiency of the power plant increases. Extracting heat at a low-pressure level results in a limited loss of electrical load, while the extracted steam has still the ability of condensing and consequently transfer heat to the cooling water system or district heating system. One of the aims of this project was to determine the penalty when this heat is used for biomass processing.

It was concluded that extraction of low-pressure steam from the power plant for external heating, as in district heating, increases the overall plant efficiency. Furthermore, from an exergy point of view, extracting steam at temperatures close to that of the hot water in the district heating system is optimal. However, district heating is costly, mainly due to the high investment costs of a distribution network. It needs to be investigated what the effect is of using (part of) this heat for wet biomass processing. Therefore, specific wet biomass processing technologies were evaluated and selected, which is done in the next section.

**Technology assessment**
Pre-processing of the selected biomass types is considered by using waste heat from power stations. If waste heat is not available or its application not economically viable as in modern “wet stack” power plants, then the extraction of low-pressure steam is considered. In general, extraction of low-pressure steam from the power plant for external heating, as in district heating, increases the overall plant efficiency. However, it is concluded from this study that using the low pressure steam in integrated concepts is exergitically less economic at temperatures in excess of 100 °C compared to exporting heat for district heating. On the other hand, compared to (stand-alone) drying techniques, integrated concepts are in general exergitically more economic. The effect on the overall plant efficiency of using this low-pressure steam for wet biomass pre-processing is dependent on the biomass pre-processing concept.

The following technologies have been surveyed:
- Anaerobic Digestion (biochemical process),
- MixAlco process (biochemical process),
- TORWASH (thermal pre-treatment process),
- SWG - Supercritical Gasification (hydrothermal process),
- HTU - Hydrothermal Upgrading (hydrothermal process),
- SCWO - Supercritical Wet Oxidation (hydrothermal process),
- IBUS - Integrated Biomass Utilization System (biochemical & hydrothermal process), and
- RWE WTA - Integrated drying concept for very wet lignite coal (integrated drying).

Figure 2.33  The largest anaerobic digestion plant in the world, built in Germany at Penkun, 15 hectare plant, producing 20 MW [Source: renewable energy focus]

The features of each process have been evaluated and the most suitable and promising technologies have been selected according to the objectives of this study:
- The concept is or can be aimed at using of wet biomass streams that are available in the Netherlands within a distance of 100 km from the utilization point, and
- The concept can be integrated with a coal fired power station such that:
  - heat of the power station could be used in the drying concept
  - the main dry product is primarily applicable as co-firing fuel, and not as a commodity for industrial use.

The major aspects considered in the selection are the convenience of the technology for operations with wet biomass, the scale, the maturity and the integration with fossil fired power plants. The results of this preliminary selection are summarized in
Table 2.17 together with relevant information. Most concepts considered have few large-scale applications. Furthermore, many concepts are still in the testing/demonstration phase.
Table 2.17 **Evaluation summary of concepts for wet biomass utilization in co-firing applications with heat integration (as presented in the Phase 2 report)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Selected</th>
<th>Maturity</th>
<th>Fit with available biomass streams</th>
<th>Fit with product as co-firing fuel type</th>
<th>Simplicity of the system</th>
<th>No heat demand or only waste heat</th>
<th>Expected low investment costs</th>
<th>Site/footprint</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic Digestion</td>
<td>Yes</td>
<td>+</td>
<td>+</td>
<td>+/-</td>
<td>+/-</td>
<td>+</td>
<td>+/-</td>
<td>-</td>
<td>Integration to a fossil fired plant seems to be feasible. Low productivity; the footprint is very large. Difficult process control. The concept in itself is commercially available.</td>
</tr>
<tr>
<td>MixAlco™</td>
<td>No</td>
<td>+/-</td>
<td>+</td>
<td>+/-</td>
<td>+/-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>The output of the process is a mix of alcohols, which so far has never been used for co-firing purposes. Difficult process control. Hydrogen is needed.</td>
</tr>
<tr>
<td>TORWASH</td>
<td>Yes</td>
<td>-</td>
<td>+</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+</td>
<td>Relatively simple pre-treatment process. Possibly flexible on feedstock type. Large-scale applications must be proven.</td>
</tr>
<tr>
<td>Super Critical Water Gasification</td>
<td>No</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+/-</td>
<td>+/-</td>
<td>-</td>
<td>-</td>
<td>Still at early stage of development. Big issues with salts dissolutions that limits feedstock types. High pressures/temperatures. Not expected economic for co-firing applications, more intended for niche applications.</td>
</tr>
<tr>
<td>Hydro Thermal Upgrading</td>
<td>Yes</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+/-</td>
<td>Heavy Fuel Oil like product is interesting for co-firing applications. HTU is suitable for wet biomass feedstock. Integration with power plants can be possible. Some issues (as fouling resistance) must be proven.</td>
</tr>
<tr>
<td>Super Critical Water Oxidation SCWO</td>
<td>No</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+/-</td>
<td>This process is used for waste water treatment. Energy released as steam is too insignificant to integrate with power plant. Concept is currently available in small sizes. Oxygen is required.</td>
</tr>
<tr>
<td>IBUS</td>
<td>No</td>
<td>+/-</td>
<td>+/-</td>
<td>-</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>-</td>
<td>Seems promising and medium scale is currently demonstrated. Has been developed for ethanol production integrated with power plants. Not aim here.</td>
</tr>
<tr>
<td>WTA</td>
<td>Yes</td>
<td>+</td>
<td>-</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+</td>
<td>Being developed on a large scale and in a number of lignite fired power stations. Well-integrated, using waste heat. The question is how to get it applicable for biomass.</td>
</tr>
</tbody>
</table>

The four technologies that can be marked as most promising are:
- Reference drying
- Anaerobic digestion because it represents a commercial and proven technology,
- TORWASH for its relative simplicity and efficiency in drying and washing,
- HTU® for its potential in extracting bio-fuels from low grade biomass at relatively mild process conditions.

The potential of these technologies has been reviewed techno-economically in the phase 2 (2010).
Combinations of biomass types and pre-processing technologies were chosen, and mentioned as configurations, based on the suitability of grass, GFT, manure and sewage sludge for with the abovementioned pre-processing technologies. Belt drying has been chosen as the reference technology.

Table 2.18  *Suitability of pre-processing technologies with pre-selected wet biomass types* *)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Grass</th>
<th>GFT</th>
<th>Manure</th>
<th>Sewage Sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt drying</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TORWASH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WTA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*)green = suitable, yellow = not known or limited suitability, red = not suitable

Initially, WTA was also considered as a promising technology. However, there is no experience with biomass fuel types, and although the concept seems a promising concept for certain granular types of wet biomass, the abovementioned biomass types are likely to be of limited applicability. Therefore, this concept was not taken into account in the remainder of the study.

The configurations presented in Table 2.19 assessed both technically and economically.

Table 2.19  *Configurations for techno-economic evaluation*

<table>
<thead>
<tr>
<th>Pre-processing concept</th>
<th>Biomass type</th>
<th>Feed (wet) [ktonne/y]</th>
<th>Feed LHV [PJ/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>Belt drying</td>
<td>Grass</td>
<td>80</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>TORWASH</td>
<td>Grass</td>
<td>80</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>Anaerobic digestion</td>
<td>GFT</td>
<td>80</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>Hydrothermal upgrading</td>
<td>GFT</td>
<td>80</td>
</tr>
</tbody>
</table>

It was not the aim to rank these configurations but more to discuss them individually, as the state of development of these technologies and their applicability to various wet biomass types are very different.

The assessment was based on literature, interviews and site visits. Thermodynamic calculations have been performed with the KEMA SPENCE® software. Cost calculations are due to lack of detailed data based on very rough estimates of capital costs, operations and maintenance costs as a fixed percentage of the capital costs, and loss of electricity generation due to the steam that is extracted from the steam cycle for the process.

Logistics and feedstock costs and their subsidies are not included in the cost analysis, and the feed is in all cases taken equal to 10 tonne/h (on a wet basis) with a yearly availability of the processes of 8,000 hours.

The cost of the entire process is the total of the several cost items within the battery limits as given in Table 2.20.
Table 2.20  Battery limits for economic calculations

<table>
<thead>
<tr>
<th></th>
<th>Included</th>
<th>Excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet biomass</td>
<td>- Feedstock</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Logistics of feedstock</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- On-site receipt</td>
<td></td>
</tr>
<tr>
<td>Capital costs</td>
<td>- Reactor</td>
<td>- Ground costs (footprint)</td>
</tr>
<tr>
<td></td>
<td>- Pre-treatment equipment</td>
<td>- Civil works (limited)</td>
</tr>
<tr>
<td></td>
<td>- Waste water treatment</td>
<td>- Modifications of the DCS</td>
</tr>
<tr>
<td></td>
<td>- Intermediate storage</td>
<td>- Fuel injection into the boiler</td>
</tr>
<tr>
<td></td>
<td>- Conveying</td>
<td>- Steam integration costs as steam piping, valves (limited)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reducing stations</td>
</tr>
<tr>
<td>Operational costs</td>
<td>- Operations and maintenance</td>
<td>- Waste water treatment</td>
</tr>
<tr>
<td></td>
<td>- Steam for the process (heat)</td>
<td></td>
</tr>
</tbody>
</table>

Steam extracted from the steam cycle for the pre-processing of the wet biomass results in a loss of net generation of the power plant, as is accounted against an electricity purchasing price of 51 €/MWh₂.

Integration of a belt dryer following the layout as presented in this report is expected to be technically feasible with some minor challenges. The belt dryer has with an estimated cost of 4.5 EUR/GJ of dried grass (LHV of the dried grass as co-firing fuel) the lowest specific costs, but this figure will be significantly higher when drying gas treatment would be required. Efficiency can be further improved by installing a closed-loop dryer, but contains higher capital costs.

The TORWASH concept is currently in a proof-of-principle phase, working in a batch mode. It has the advantage that it removes the salts out of the grass by washing. Integration of the TORWASH reactor following the layout as used in this report may be technically feasible but to the authors’ opinion convenient far from optimal solution for this application. In its lab-scale approach, the TORWASH concept has an estimated high specific cost of 25.7 EUR/GJ (on a LHV basis of the TORWASHed grass), which mainly results from the high steam demands. After optimization, applying energy recovery from the TORWASH process, it is expected that the specific costs will be reduced significantly.

Full scale commercial application of HTU does not exist yet. The main resulting product is a crude that would be applicable to several appliances including pulverized fuel fired power stations, but may have a have a higher value in other industries. Integration of the HTU reactor following the layout as presented in this report may be technically feasible but in the authors’ opinion is not logical to do so. The HTU concept has an estimated high specific cost of 16.1 EUR/GJ (i.e. per LHV of the crude that leaves the HTU process). There may be some room for further optimizing the thermodynamic cycle and thus reducing the specific cost.

Anaerobic digestion is a mature technology that does not require a significant heat source in terms of amount and temperature level. The biggest challenges are the large footprint of the complete digestion installation and the treatment of the digestate. Integration of an anaerobic digestor following the layout as presented in this report is expected to be technically feasible with some challenges. The specific cost of the anaerobic digestor is estimated at 12.1 EUR/GJ (per LHV of the biogas, digestate not taken into account). This mainly originates from the high capital costs, due to the large facility that is needed. Furthermore, about two-third of the calorific value is in the digestate and not in the bio-gas. As the digestate is not accounted as a fuel for co-firing here, a relatively high specific capital and overall costs for the bio-gas exists.
TORWASH experiments and analysis

Feedstocks selected in the project period 2009 were compared to the list of feedstocks that were tested previously at ECN for TORWASH on a small scale (0.5 l autoclave). Hay (dried grass) that cannot be used as cattle feed was on both lists. It is locally available in large quantities and attractive from an economic perspective. A quick scan of TORWASH conditions indicated that 190-200°C is the optimal condition. In a 20 litre autoclave a TORWASH experiment was carried out with 1.2 kg hay (dry basis, corresponding to 2.5 - 3 kg of freshly mowed grass). The mass yield after TORWASH was 54%, lower than the expected 70%, from earlier tests. As a result of the lower mass yield, the energy yield is also lower, 66% instead of 85%. This is attributed to suspension of small particles that were not collected in the solid fraction. Another reason can be the long heating and cooling time that effectively resulted in a more severe heat treatment in the large facility. This is an important observation for scale-up. The more realistic conditions in the larger autoclave suggest that at full-scale lower temperatures and/or shorter residence times at maximum temperature can lead to the desired product: easy to dewater biomass fuel.

The TORWASHed hay was subject to a grindability test and it behaves similar to dry torrefied wood. The powder made from TORWASHed fuel consists mainly of short brittle fibers. By means of simple mechanical dewatering it is possible to make TORWASHed fuel with 65% dry matter content, which means that three-quarters of the moisture originally present in the feed stock is removed and only a small amount of heat is needed to dry the fuel to the desired level of >85% dry matter content. The degree of salt removal was estimated to be 90-98 % for the easily dissolved ions like K, Na, and Cl, elements known to cause problems in co-firing. Simple washing will result in only 60-70% salt removal and a soaking wet fuel.

A combustion experiment in ECN’s Lab-scale Combustion Simulator showed that TORWASHed hay is highly reactive, better than high-volatile coal. It is expected that TORWASHed material will perform similarly to torrefied wood.

2.6.5 Conclusions and recommendations

Eight technologies that can be used to effectively process wet biomass have been evaluated for their potential integration with power plants. Most concepts considered have few large-scale applications. Most of the technologies are concepts that are still at the testing/demonstration phase.

The evaluation resulted in a preliminary selection of four potential technologies and one reference:
- Anaerobic digestion because it represents a commercial and proven technology,
- TORWASH for its simplicity and efficiency in drying and washing,
- HTU® for its potential in extracting bio-fuels from low grade biomass at relatively mild process conditions,
- Thermal drying as the reference technology (belt drying).

Combinations of technologies and biomass types were formed. These include two technologies associated with grass and two technologies associated with GFT. The configurations assessed are:
- Configuration 1: grass pre-processing by belt drying;
- Configuration 2: grass pre-processing by TORWASH;
- Configuration 3: GFT pre-processing by hydrothermal upgrading;
- Configuration 4: GFT pre-processing by anaerobic digestion.

The configurations have been subject to further techno-economic evaluation individually. It was not the aim to rank them, as they differ significantly in terms of e.g. maturity. Furthermore, it
shall be emphasized that the configurations are assessed when they are integrated with a coal-fired power plant.

Conventional drying techniques are calculated to be feasible at moderate cost by restricted steam consumption. The more innovative technologies as HTU and newest TORWASH technologies are more expensive in terms of steam consumption. However, especially the TORWASH technology may have significant process optimization, leading to a reduced specific cost.

TORWASH material was successfully produced in a 20 litre autoclave using hay as a feedstock. The yields of mass and energy are relatively low compared to earlier tests. The primary objectives of TORWASH: mechanical dewatering, salt removal and improved grindability have all been accomplished. The test in the 20 litre autoclave confirmed earlier results obtained in the smaller (0.5 litre) autoclave. The quality of TORWASH fuel related to co-firing looks promising based on the chemical composition. The LCS combustion test showed that TORWASHed hay is a highly reactive fuel, which exceeds high-volatile coal. Combined with the low ash content and near absence of problem elements makes TORWASHed hay an attractive fuel. As a result of this work, the TORWASH operation is one step closer commercialization, a process design and verification at pilot plant level are the next challenges.

2.7 WP7: Pneumatic transport of biomass and coal/biomass blends

2.7.1 Problem definition

A typical co-firing installation includes modifications to the fuel-handling and storage systems and possibly the burner to accommodate biomass. Costs can increase significantly if wood needs to be dried, size needs to be reduced, or the boiler requires a separate feeder. One important consideration is the milling system and its components.

Ground biomass particles are very different from coal particles, not only in density and size but also in shape. Coal particles have a shape that can be approximated by a spherical or even cubic shape. Biomass particles tend to have a fibrous structure. The difference in hydrodynamic behaviour is related to density and size, but especially the shape difference will have a large influence. In a co-fired power plant the biomass particles are often fed into the coal stream at a position downstream of the coal mill. Even in the hypothetical case that at a certain downstream position the biomass and coal streams are fully mixed it is possible that due to geometrical effects or due to hydrodynamic forces de-mixing of the biomass/coal stream occurs. For instance the biomass could accumulate in the near wall regions and the coal particles in the core regions. This is why in this WP a study of the hydrodynamic transport of biomass particles and biomass/coal mixtures in the transport system between the coal grinder and the burners is undertaken.

This section describes an approach to evaluate the airflow and particle distributions in a pulverized fuel transport duct in EPZ (Borssele) power plant, as a case study. The current design was evaluated with regard to air and particle flow dynamics, pressure drop and particle distribution. The modelling results are discussed in detail.

2.7.2 Objectives

In this WP the hydrodynamic transport of biomass particles and biomass/coal mixture in the transport system between the coal grinder and the burners is studied. A Computational Fluid Dynamic (CFD) model was developed. This model quantifies the behaviour of different particles in the transport system. An important goal of the sub project is to evaluate the flow dynam-
ics, the particle distribution of the mixture and the deposition phenomena in the pipe considering the size and the shape of the particles.

2.7.3 Approach
A CFD model for the transport system was developed, based on a given a rough estimation for the particle size. The application CFD in this process allows engineers to get a better understanding about the physical processes like fluid flow, heat transfer and solid-fluid interaction.

2.7.4 Results 2010 and discussion
The computational fluid dynamics (CFD) modelling was conducted on a fuel transport duct of the EPZ plant (see Figure 2.34). Details can be found in [Fantini, 2011; Fantini, 2011a]. The tube selected is the number 32 where the number “32” indicates that the duct comes from the mill “30”, goes to the 2nd corner of the boiler reaching the 3rd level.

Figure 2.34 Lay-out of the co-firing plant

Figure 2.35 shows the drawing of the pipe done with the code Gambit and setting and geometry data are summarized in the table. The figure also indicates the four locations (circles) put at the inlet of the pipe to simulate the injection of coal and biomass. Biomass and coal enter on four locations due to symmetry reasons. The properties of coal are taken from the ANSYS Fluent data base. The particles selected are inert. This means that they have associated models for describing the heating and cooling or heat transfer between the particle phase and the continuous phase.
Figure 2.35 Gambit drawing of the pipe 32 (left) and detail of the inlet of the fuel transport duct (right)

Table 2.21 Setting and geometry data of fuel transport duct 32

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td>-</td>
<td>38,844</td>
</tr>
<tr>
<td>Z</td>
<td>M</td>
<td>11.4</td>
</tr>
<tr>
<td>X</td>
<td>M</td>
<td>10.87</td>
</tr>
<tr>
<td>Y</td>
<td>M</td>
<td>3.5</td>
</tr>
<tr>
<td>Diameter</td>
<td>Mm</td>
<td>489</td>
</tr>
</tbody>
</table>

The flow rate of air, coal and biomass as well as the values of temperature and pressure are real values of the pipe measured during experiments conducted on 5th July 2009. The particle size of wood pellet fuels is dependent on pre-pelletization processing of the constituent wood products. The particle size ranging in this case is ~0.5-2 mm, hence the particles are approximately an order of magnitude larger in size than coal particles needed for the coal combustion. The table summarizes the operating conditions of the fuel pipe simulation.

Table 2.22 Operating conditions of the pipe simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate</td>
<td>kg/s</td>
<td>2.3542</td>
</tr>
<tr>
<td>Coal particle flow rate</td>
<td>kg/s</td>
<td>1.88</td>
</tr>
<tr>
<td>Wood particle flow rate</td>
<td>kg/s</td>
<td>0.12</td>
</tr>
<tr>
<td>Coal particle size range</td>
<td>μm</td>
<td>6 ~ 132</td>
</tr>
<tr>
<td>Wood particle size range</td>
<td>mm</td>
<td>0.5 ~ 2</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>70~80</td>
</tr>
<tr>
<td>Pressure at outlet</td>
<td>atm</td>
<td>1</td>
</tr>
</tbody>
</table>

Numerical results

Both one-way and two-way coupling were performed. Here is worth to provide the results of the two-way coupling as more representative. The fluid influences the particles via drag, turbulence and momentum transfer. The particulate phase influences the fluid phase via source terms of mass, momentum and energy. The simulation was conducted giving a particular attention also to wall interaction and deposition phenomena.

Figure 2.36 and Figure 2.37 show the particle traces coloured by density and by the particle diameter. Compared to the results obtained in the one-way coupling case, it is obvious that the
biomass gets squashed downward at the outlet of the pipe. Centrifugal forces and shape of the tube are not influenced by the mutual interaction of the motion field.

![Figure 2.36 Particle tracks colored by particle density [kg/m³]](image)

![Figure 2.37 Particle tracks colored by particle diameter [m]](image)

The fate of the particles once injected in fact is an important point to discuss. Particles that are travelling through the domain will inevitably find a wall and there is a number of different ways to model the interaction of particles with walls. The particle can escape, reflect on the wall or it can be trapped. When the particle strikes the wall in the context of the trapped option whatever volatile fraction is contained in the particle, it will be instantaneously converted to vapour. The dispersion of particles in a turbulent flow is due to turbulent fluctuations. The DPM model has associated a finite number of injections for any mass loading that is introduced in the system. So each individual injection does not represent an individual particle but an individual mass loading, divided equally amongst N number of tracks. FLUENT models the turbulent dispersion in two ways: the discrete random walk tracking and the particle cloud tracking. The discrete random walk tracking works by tracking each particle injection individually through the domain. Each injection is repeatedly tracked in order to generate a statistically meaningful sampling. The user specifies the number of attempts.

The cloud tracking is the second method and uses a statistical method to trace the dispersion of a particle about a mean trajectory. The cloud tracking calculates the mean trajectory from the ensemble average of the equations of motion for the particles represented in the cloud. The dis-
tribution of particles in this cloud is represented by a Gaussian probability density function. The stochastic tracking approach accounts for local variations of flow properties like temperature or concentration. Each particle trajectory that is released from a stochastic tracking point of view traverses the domain independently and counters the fluid flow properties of each cell as it tracks through. A large number of trails is needed to achieve a statistically significant sampling. Without enough trails there are convergence problems. Cloud tracking on the other hand, averages out local variations in the flow properties, like temperature. All the properties of the particles get distributed over that cloud diameter resulting in a smooth distribution of particle concentrations. One aspect of cloud tracking is that there is only one particle diameter per cloud. So, to model a distribution the introduction of a large number of clouds is necessary. For all these reasons the first approach was chosen and the result is that basically the particles at the wall result tracked or escape.

As regarding the particle deposition in the pipe, a model available in FLUENT 6.0 was used. The model solves continuity and momentum equations for the mixture and volume fraction equations for the secondary phases. Particle deposition in wall-bound flows has received considerable attention for more than four decades due to its practical relevance to many industrial applications. One of the earliest models of deposition is the one by Friedlander and Johnstone who proposed the so-called free-flight theory. The essence of this model is that particles are transported by turbulent motions to within one stop-distance of the wall, where they acquire sufficient inertia to coast through the viscous sublayer and deposit. This pioneering model was further improved by the work of many researchers.

As shown in Figure 2.36, the deposition phenomenon is not significant. Particles with small radii, approaching very close to the wall without depositing, are rarely lifted up by wall ejections.

To go deep in the deposition phenomena, a view of the particle tracks after the bends is presented in Figure 2.38, Figure 2.39, Figure 2.40, Figure 2.41 and Figure 2.42. The motion of particles is intimately related to the action of the vortices populating the near-wall region and related to the shape of the tube. The particle transfer mechanisms due to strong, coherent sweep and ejection events, specifically point out the effect of small stream wise vortices very close to the wall in promoting particle accumulation under the low-speed streaks.

Figure 2.38 Particle tracks coloured by particle density and indication of the sections analyzed
At any instant only a small fraction of particles have a high enough velocity to execute a free flight to the wall and to deposit, a majority of the particles near the wall are trapped in a region of very small wall-normal velocity fluctuations. Very close to the wall, the distance required by a particle to deposit is very small, but the probability of having large enough momentum to carry the particle across that distance is also extremely small.

Finally, a non-spherical particles analysis was conducted. Non-spherical particles are more difficult to treat than spheres because of the influence of particle orientation and the lack of a single unambiguous dimension upon which to base dimensionless group. The motion modeled is the motion of cylinders particles with a sphericity factor of 0.7. In the motion at high Reynolds number (>300,000), cylinders have a secondary oscillatory motion superimposed on their steady fall or rise. With a ratio of L/d>1 (this is the case), the axis oscillates in a vertical plane about the horizontal orientation and the trajectory oscillates about the mean path in the same plane as the cylinder “sideslips” when its axis is not horizontal. The results in Figure 2.43 and Figure 2.44 show that the trajectories of the particles slightly change from the spherical simulation. The shape of the particles in fact influence the drag force and the drag force influence the trajectories.
Figure 2.43  Particle tracks coloured by particle density [kg/m$^3$] – non-spherical

Figure 2.44  Particle tracks coloured by particle density, outlet – non-spherical

2.7.5 Conclusions and recommendations

In the fuel transport duct model the wood particles are effectively transported by primary air without significant circulation and deposition observed. However, wood and coal particles appear to mix poorly with air with particles segregation in the fuel pipe but both in one-way and in two-way coupling no “roping” phenomena occur. As far as concerns the deposition, the deposition of heavier particles was found to be higher at lower velocities and lower at higher velocities. The lighter particles were found to remain mostly suspended with homogeneous distribution. The larger particles clearly showed deposition near the bottom of the wall and this deposition was found to be pronounced at higher velocity due to a higher inertia.

In the future it will be important to perform a sensitive analysis of the rate flows (air, biomass and coal) and working on a CFD model of the mill as also the grinding and the thermal limitations control the capacity of the entire system.

2.8 WP8: Optimisation of numerical models for slagging/fouling

2.8.1 Problem definition

The existing park of the pulverized fuel (PF) boilers is basically designed to operate on coals of a fairly narrow quality range. Applying biomass to replace coals, results in a number of operational issues, both in the combustion zone, as well as further downstream. One of the main problems is the increase in the slagging (near-burner) and fouling of the boiler heat transfer surfaces, due to the altered fuel ash chemistry. In particular, the higher shares of volatile ash components, such as alkali metals, cause a number of undesired phenomena to occur both in the radiant as well as in the convective part of the boiler. These processes include both chemical interactions between conservative components of the coal and biomass ash (i.e. chemical reactions with aluminosilicates), as well as physical processes (condensation of the gas-phase alkali salts) leading to the formation of fine aerosols and coatings on the ash particles. The said processes have long been recognized as playing a key role in boiler fouling as well as emission issues. However, the exact details of each of these phenomena and the interaction of several processes are still insufficiently well understood, let alone integrated into predictive numerical models. Development for the long term of reliable co-combustion models is considered to be highly important to successfully expand the technology making use of a broad variety of green sources. This is the reason why a new, short and targeted study in this work package is presented.
2.8.2 Objectives

The objective of the investigation in this work package is to obtain further insight into and formulate a reduced chemical kinetics-based sub-model. This is aimed at the estimation of the partial pressures of free alkali components in the flue gas at the furnace exit, as a function of fuel quality (mineralogy, sulphur and chlorine contents) and operating conditions (air staging, temperatures etc.).

2.8.3 Approach

To understand the deposition behaviour inside the boiler, a model investigation is needed because measurements in a real boiler are often not possible or too challenging. The Ash Deposition Predictor (ADP) is a tool developed by ECN and TU Delft to model the main physical processes leading to deposition. So far, the ADP only considers fly ash particle deposition via inertial impaction, turbulent diffusion and thermophoretic attraction. For the future development of ADP the condensation mechanism of deposition will have to be included and added up. The aim of this study is to provide a concentration pool of gaseous inorganics species, for the future development of ADP, which are suspected as the main species released and are considered as the species with the highest impact if it condensed and deposited in the heat exchanging surface of the boiler during coal and biomass (co-)combustion. This concentration pool lead to respective values of gaseous inorganics partial pressure owing to the global gaseous composition known from the CFD result.

Six types of fuel (blends) are used in this study which are lignite, Russian coal, olive residue and the mixing between lignite and olive residue with mole ratio 70% : 30%, 50% : 50% and 30% : 70%, respectively. Lignite, Russian coal and olive residue will be used to model pure fuel combustion. The mixing fuels will be used to model the co-firing combustion between coal and biomass. The ultimate analyses of the fuels are processed and then used as an input to the combustion model in the FACTSAGE® software. The considered gaseous inorganics resulting from the combustion model are then used as input to the evolution model of gaseous inorganics as temperature decrease in CHEMKIN® software.

2.8.4 Results 2010 and discussion

Increased slagging (on walls and tube surfaces in the radiant part) and fouling (on heat exchangers in the convective section) during operation of PF boilers is observed when co-firing higher percentages of biomass with conventional fuels. Deposit formation is a complex function of the fuel properties and operating conditions. Deposition mechanisms involve inertial impaction, turbulent diffusion, thermophoretic attraction, vapor condensation and heterogeneous reaction between ash particles and deposition surfaces [Williamson and Wigley, 1993]. In previous years the Ash Deposition Predictor (a post-processor for CFD) was set up by ECN in a joint effort with TU Delft and used to model the main physical processes leading to deposition:

- inertial impaction,
- turbulent diffusion, and
- thermophoretic attraction.

Some simulations were made for pure coal fuels and blends. Here, only the reactor configuration of the LCS was modelled under air blown combustion conditions (Table 2.23) using the commercially available software CINAR Unstructured® [Lockwood et al., 2002]. The computational domain describing the Lab-scale Combustion Simulator (LCS) at the level of the deposition probe is shown in [Bertrand et al., 2010].
In the experiments as well as in the model, the probe temperature was kept at 560°C. Ash-related data are used as ADP specific input. These may be obtained from experiments or from the ash formation models and correspond to the physical properties of the already sampled ash particles after combustion. These are:

- Mean particle size (and standard deviation)
- Particle density
- Particle composition based on SiO\textsubscript{2} mole fraction
- The CaO/(CaO+Al\textsubscript{2}O\textsubscript{3}) mole ratio
- Particle visco-elastic properties based on the NBO/T ratio (ratio of non-bridging oxygen to tetrahedral oxygen oxides [Senior and Srinivasachar, 1995; Srinivasachar et al., 1992] and given by the general equation (1):

\[
NBO/T = \frac{FeO + CaO + MgO + K\textsubscript{2}O + Na\textsubscript{2}O - Al\textsubscript{2}O\textsubscript{3} - FeO\textsubscript{3}}{(SiO\textsubscript{2} + TiO\textsubscript{2})/2 + Al\textsubscript{2}O\textsubscript{3} + Fe\textsubscript{2}O\textsubscript{3}}
\]  
(Eq. 1)

where each term corresponds to the given oxide mole fraction in the formed fly ash.

- Young modulus: E (Pa) used in the expression of the restitution coefficients which are part of the complete energy balance on the particle when it reaches a wall [Losurdo, 2009].

Deposition modelling for Russian coal, Russian coal/shea meal blend, lignite and lignite/olive residue blend has been performed under air operating combustion conditions prevailing in the LCS experiments as outlined above. The conditions are summarized in Table 2.24, more details have been presented in [Glazer et al., 2010].

**Table 2.23** Ideal combustion gas composition formed in the LCS reactor tube under air tested operating conditions

<table>
<thead>
<tr>
<th>Deposit environment</th>
<th>Mass fractions [kg/kg\textsubscript{wet}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>O\textsubscript{2}</td>
<td>0.0300</td>
</tr>
<tr>
<td>N\textsubscript{2}</td>
<td>0.7438</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>0.1244</td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>0.1018</td>
</tr>
</tbody>
</table>

The deposition propensity is defined as the ratio of the ash collected on a deposit probe \(m_{\text{dep}}\) to the ash content in the fuel fed, \(m_{\text{ash}}\) as given by the proximate analysis of the fuel. The deposition propensity represents the capture efficiency on the probe and provides insight into the inherent deposition characteristics of the different fuels, as it normalizes the ash deposition in relation to the fuel ash content.
The measured and calculated values of the deposition propensity $DP$, calculated from Equation (1) are compiled in Table 2.25.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Experiments</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russian coal</td>
<td>0.20</td>
<td>0.34</td>
</tr>
<tr>
<td>Russian coal + shea meal</td>
<td>0.16</td>
<td>0.33</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td>Lignite + olive residue</td>
<td>0.12</td>
<td>0.30</td>
</tr>
</tbody>
</table>

The full analysis of the results as well as a parametric study of the performance of the deposition model in the ADP has been carried out by [Glazer et al., 2010]. So far, this is the highest difference encountered between measured and modelled deposition. As a matter of fact, the use of the LCS set up and ADP were coupled in many tests which revealed a minimum difference of -0.02 between the experimental and simulated deposition propensity while the maximum observed difference was of +0.065 [Zagorski, 2008].

A number of improvements for the ADP simulating tool have been identified:
- Particle tracking: the program spends 76% of the calculation time on particle location. An enhancement here could allow modelling of large systems with a large number of tracked particles.
- Visco-elastic properties set up per defined group of particles: the assignment of visco-elastic properties per defined group of particles would better reflect the reality. It could also allow a better description of liquid coalescence into sub-micron droplets. On the longer term, the system could be further improved describing the viscosity of biomass ashes in the SiO$_2$-CaO-K$_2$O system.
- The fly ash particle position and temperature could be read directly from the results of the CFD computations as it is done for the flow field variables.

The primary modifications mentioned above have a numerical aspect and are more related to programming issues which can be dealt with accordingly:
- If the knowledge and know-how of ADP are “re-integrated” in an existing CFD tool or
- If the ADP is simply still used as post-processor and further developed into a user tool.

On the contrary, condensation phenomena are deposition process-related improvements that are of particular importance in the case of biomass (co-)firing and could be integrated into the current ADP. With a simpler programming of the condensation phenomena, the resulting adapted program can also be used as support for the further developments related to coal firing and/or biomass co-firing slagging and fouling.

So far, the following actions were performed toward full implementation, which itself is outside the scope of this work and would require a four year PhD student project:
- The calculation of condensation has been activated in the General Input Condition file. It implies that Unsteady Particle Tracking option is selected for the calculations. An appropriate integration time step is also required. A tracking in a part of the domain only is advised.
- An input condensation file containing the required information on constant gaseous and inorganics species concentration (mol/s) and molecular weight (kg/mol) has been prepared and is provided to the main code for reading information that is processed and transmitted to the “Condensation Module”.

$$DP = \frac{m_{\text{dep}}}{m_{\text{ash}}} \times 100 \quad \text{(Eq. 2)}$$
A module “Condensation” has been coded and it is programmed for heterogeneous condensation onto particles according to the relationship of [Seinfeld&Pandis,1998]. The appropriate calls from/into the core program P3 and the other modules to the condensation subroutine have been made.

The “real” number of particles is estimated from the ashes injection rate and their properties at every “Particle Injection” then, the pool of inorganics available for heterogeneous condensation is readjusted to suit the new particle load injected at every “Particle Injection”.

The particle size, density and composition are expressed in terms of SiO$_2$ molar ratio and are adjusted according to the condensation taking place, the inorganic species condensing being transformed into K$_2$O and Na$_2$O equivalent.

Further in this work package a survey of the literature was made concerning a simplified chemical reaction scheme for alkali inorganics in the gaseous phase as combustion flue gas cools down. As a result, a detailed mechanism proposed by [Glarborg&Marshall,2005] was selected that comprises the formation of gaseous alkali sulphates based on the formation of HSO$_3^-$ as intermediate species. They give -based on a literature search or estimation- the complete set of kinetic reaction constants for the mechanisms including M/O/H/Cl/S containing basic elements. This was the first time that the authors encountered the treatment of both Na and K together. The reaction structure is extensive and will not be recalled here but the authors decided to model the sulphation reaction according to their proposed scheme Figure 2.45 although no differences of opinion among the researchers can be found for the sulphation reaction:

- Either KCl reacts with SO$_2$/SO$_3$ in the gas phase; two mechanisms are then suggested:
  - Overall sulphation reaction of MCl in the gaseous phase although MCl species are rather stable
  - Detailed theory and proposed mechanism of [Glarborg and Marshall,2005] with the intermediate species HSO$_3^-$ in the different M/O/H/Cl/S systems.

Or heterogeneous sulphation of MCl deposit on tubes as an earlier assumption from researchers. However, liquid/solid phase reactions are taking place at a much slower pace.

The literature review performed in the framework of this work package allowed the authors to devise a strategy for the determination of:

- the species formed from the elements released during combustion;
- a reduced scheme for the reaction taking place among a limited number of gaseous compounds as the temperature of the flue gas decreases.

It was decided to carry out the study with Russian coal (RC), lignite (L), olive residues (OR) and blends from lignite and olive residue. The focus was on ideal and typical pulverized fuel (PF) combustion, considering the species combustion field for the mentioned fuels at atmospheric pressure at 1900K with 3 %vol O$_2$ in dry flue gas. A reduced number of elements and species will be considered:

![Potential pathway diagram for potassium transformation](Glaborg and Marshall, 2005)
• For the flow field: \( \text{H}_2\text{O}, \text{CO}_2, \text{O}_2, \text{N}_2, \text{NO}_2, \text{SO}_2, \text{SO}_3 \)
• For the inorganics: (Ca, Mg, Na, K, Cl, S)
• For the compounds: hydroxides – KOH, NaOH-, (carbonates) , chlorides –KCl, NaCl, HCl-, sulphates, (oxalates), and alumino-silicates (Al\(_2\)O\(_3\),2SiO\(_2\))– KAlSi, NaAlSi.

The authors have formulated a model structure that links inorganics formation during combustion to their deposition within the chamber as depicted in Figure 2.46.

Figure 2.46 Pre-model structure

The first challenge consists of finding out which species are formed during combustion. Two ways can be devised to reach the results:

• **Path 1**: Knowing the fuels’ composition, the amount of elements formed after typical PF combustion is deduced from Shah’s correlation (Shah et al, 2010a). Then, their combination into compounds is deduced from a series of rules mentioned by researchers in the literature review above. Path 1 is a very empirical approach.

• **Path 2**: the species formed after combustion are calculated using the thermal equilibrium software FACTSAGE®. The conditions set for the reaction are atmospheric pressure and 1900K with 3 vol\% O\(_2\) in the flue gas (wet, very typical for PF boilers). It is assumed here that the high temperature within the combustion zone allows equilibrium to be reached in a very short residence time. This may not be true for particles for which heterogeneous reaction is an order of magnitude slower. Here the main interest lays in the gaseous phase components.

Some differences were observed in both approaches and it was decided to further continue with the equilibrium model data as combustion input. In this way a fraction of the results (gaseous species) is used as input to CHEMKIN®, a kinetic modelling software that relies on a number of known species, species concentration, reaction paths and reaction rates to calculate the formation and disappearance of compounds as function of residence time and temperature. A matrix, residence time– temperature, can then be created to study the behaviour of SO\(_2\), SO\(_3\), HCl, KOH, NaOH, KCl, NaCl, K\(_2\)SO\(_4\), Na\(_2\)SO\(_4\) as flue gas temperature decreases from 1700 to 900 K in a slightly over 2 s. A simplified reaction scheme can then be proposed; it constitutes the second challenge in the study. By knowing which species form where and when, condensation mechanisms of deposition can be studied and in turn modelled.

Correlations have been deduced from the results of the FACTSAGE® calculations. They have been derived for 100 g of fuels and were established from Russian coal, lignite, olive residues and two blends (70/30 and 30/70 lignite/olive residue) for a typical ideal PF flame at 1625°C with 3 vol\% O\(_2\) in the flue gases. The number of moles of elements such as S, Cl, K, Na present in 100 g of fuel are depicted on the horizontal axes. From use of the curve, the vertical axes will
give the corresponding gaseous species formed for a fuel. The curve may have to be adjusted in
the vicinity of the origin. The sequence is:
1. From S in the fuel (horizontal axis), one obtains the number of moles of SO$_3$ in the flue gas from Figure 2.47. SO$_2$ is then deducted according to: $\text{SO}_2 = S_{\text{fuel}} - \text{SO}_3$

![Figure 2.47 Correlation for SO$_3$ formation: (moles of SO$_3$ in the flue gases) =f (moles of S in 100 g of fuel)](image)

2. Neglect Fe and O species; the product not is yet sulphated; only Cl and SO$_2$ (HCO$_3$ and oxalates not considered);
3. If the number of moles of (Na + K) << the number of moles of Cl in the fuel then Na and K combine as chlorides
4. If the number of moles of (Na + K) >> the number of moles of Cl in the fuel then:
   - From the number of moles of Cl in 100 g of fuel and
   - Figure 2.48 obtain the amount of the number of moles of HCl in the flue gas resulting from the combustion of 100 g of fuel.

![Figure 2.48 Correlation for HCl: (moles of HCl in the flue gases) =f (moles of Cl in 100 g of fuel)](image)

- From the number of moles of Cl in the fuel and Figure 2.49 obtain the amount of mole of KCl in the flue gas resulting from the combustion of 100 g of fuel. NaCl is obtained
from deducting the number of moles of HCl and KCl from the original fuel Cl as:

\[
NaCl = Cl_{\text{fuel}} - HCl - KCl
\]

![Figure 2.49 Correlation for KCl: (moles of KCl in the flue gases) = f (moles of Cl in 100 g of fuel)](image)

- Combine the Al and Si in 100 g of fuel to form a number of moles of \(Al_2O_3 \cdot 2SiO_2\) (minimum of the number of moles of Si or Al). From this aluminosilicates in the fuels and Figure 2.50 deduce the number of moles of \(K_{\text{AlSi}}\). Deduce the number of moles of KOH in the gas phase for the combustion of 100 g fuel according to:

\[
KOH = K_{\text{fuel}} - K_{\text{AlSi}} - KCl
\]

![Figure 2.50 Correlation for potassium aluminosilicates: (moles of K-AlSi formed) = f(moles of Al\(_2\)O\(_3\) \cdot 2SiO\(_2\) in 100 g of fuel)](image)

- Almost no \(Na_{\text{AlSi}}\) is formed;
- Determine from the moles of Na in 100 g of fuel and Figure 2.51 which species other than NaOH and NaCl are formed; named as “Remaining” and deduce the number of moles of NaOH in the flue gas by subtracting the moles of NaCl previously calculated and “Remaining” one as:

\[
NaOH = Na - \text{Rem.} - NaCl
\]
Figure 2.51 Correlation for Na species other than NaOH and NaCl: (moles of Na species formed other than NaOH and NaCl) = f (moles of Na in 100 g of fuel)

A sequence of use of various correlations was proposed to determine empirically which species form during combustion. Please note that close to origin the correlations are undefined. This is a first attempt which would need to be complemented by FACTSAGE® calculations on other fuels and blends and, if possible, validated from experimental test or full scale measurements and observation.

The results from the calculation of the gaseous species formed during a typical PF combustion as obtained in FACTSAGE® are used as input for the simulation of the behaviour of these components as temperature decreases in the heat exchanging section of boilers. The simulations have been realized with the software CHEMKIN® with main input concerning residence time and temperature. The thermodynamic properties of the components considered the reactions between gaseous products and their respective reaction rates are also required as an input to the software. The thermodynamics properties were searched in literature and/or re-evaluated and implemented in the code. The mechanism of sulphation of [Glarborg and Marshall, 2005] was selected and also implemented in the code. In this respect, the study was carried out between temperatures ranging from 1700K to 900K under atmospheric pressure. This represents a residence time of over 2 s. At 700K the results were judged as physically non-realistic. The evolution of the flue gas was determined within the frame of a series of five well-stirred reactors (1700K, 1500K, 1300K, 1100K and 900K) with the output of the first high temperature reactor used as input to the next one in sequence. Russian coal, lignite, olive residue and the blends lignite olive residue were studied in the simulation. The full results are given in [Bertrand et al., 2010]. The evolution of the species as temperature decreases from 1700 to 900K after the combustion of lignite and olive residue are now extracted (See Figure 2.52 and Figure 2.53, respectively).
Figure 2.52  Evolution of gaseous components formed from lignite combustion as temperature decreases from 1700K to 900K and for the residence time quoted on each graph. Please note that condensation is not modelled at this stage
Figure 2.53  Evolution of gaseous components formed from olive residue combustion as temperature decreases from 1700K to 900K and for the residence time quoted on each graph. Please note that condensation is not modelled at this stage

The trends representing the species evolution were in line with the findings of [Christensen et al., 2000], except for HCl. In our case, condensation was not simulated. For the blends, the calculated trends of the various gaseous components’ evolution display a behaviour in between lignite and olive residue. The impact of reactor type for the chemical reactor model could be investigated as now a series of ideally stirred tank reactors was chosen. CFD simulations of a typical chosen PF boiler could help identify which mixing model combination could be most appropriate.

2.8.5 Conclusions and recommendations

The results obtained with the ADP are promising. One of the condensation modes has been implemented in the current ADP: heterogeneous condensation onto particles. It should be complemented by the others: heterogeneous condensation onto walls and homogeneous nucleation of inorganics species. A number of inputs are required for the ADP. Experiments carried out

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12 ADP including the development with condensation is the sole property of ECN.
using the Lab-scale Combustion Simulator of ECN provide information such as fly ash characteristics and inorganic compounds formed. Models developed by Shah and co-workers [Shah et al., 2010; Korbee et al., 2010] from LCS experimental tests and based on the Particle Population Model of Mitchel are now available.

One of the crucial questions remaining on the ADP is: which inorganic salts are actually generated during combustion and in which amount? The sequence of gaseous phase reactions, in which these inorganics are actually taking place as the flow cools down through the complete heat exchanging section of the boiler, is also of importance. This issue is particularly relevant when widely varying biomass is (co-)fired with coal in pulverized fuels systems. The topic was first tackled by [Shah et al., 2010a/b] who determined the partitioning of selected elements released during PF combustion.

Overall, whether the ADP is used as such or its knowledge incorporated in existing CFD software, a lot questions were raised, some answered, highlighting a further field of research and development as for instance the determination from experiments of the Young Modulus of ashes resulting from the combustion of many fuels and blends.

New correlations were proposed to define the species formed during ideal and typical PF combustion from the elemental fuels composition. Pure fuels and blends were studied. The species of interest are: SO$_2$/SO$_3$, HCl, KOH, NaOH, KCl, NaCl, K-AlSi. Their molar concentrations, for the combustion of 100g of initial fuel(s), were also predicted. This information will be used as input to determine, from a balance, the fate of species as temperature of the flue gas decreases. Indeed, a simplified reaction scheme simulating the evolution/combination of the components as temperature decreases was also proposed. Improvements of the proposed species formation and species evolution pattern are foreseen, i.e:

- The species formation correlations would need to be complemented with:
  - as many calculations of relevant co-firing fuels combustion as possible;
  - a detailed study of the gaseous calcium and magnesium elements combining with carbonates and oxalates at lower flue gas temperature.

- For the reduced reaction scheme:
  - A complete sensitivity analysis would need to be carried out.
  - The reaction rates corresponding to the different reaction would need to be expressed.
  - The results obtained would need to be compared and validated towards real boiler data, using an appropriate experimental set up.

This work is a crucial step towards implementation in a predictive tool e.g. the ADP. The work would allow to model not only the physical phenomena leading to deposition such as inertial impaction, turbulent diffusion and thermophoresis, but also, to consider deposition due to various condensation modes. The methodology applied was retained as a good compromise between simplicity, realism of predictions and equivalent calculation burden. A future model is proposed in Figure 2.54.
The work re-inforces the capabilities of the ADP as a step to predict the influence of condensation mechanisms on overall deposition behaviour. The realization of a full condensation model and its coding in the ADP is advised to be carried out within the scope of a future PhD project.
3. General conclusions and discussion

The following overall conclusions and observations of this study are made:

- **New/deeper insights have been obtained in the behaviour of (trace) elements.** The volatilisation behaviour of some elements in coal was found to be different than the volatisation behaviour of the same elements from biomass. Results from full-scale measurements indicate that an SCR installation can play a significant role, e.g. by increasing the conversion (oxidation) and therefore the removal of metallic mercury. Furthermore the obtained results have also shown that operational conditions affect speciation and behaviour of elements, like the oxidising conditions in the boiler as well as in the FGD. Results of a detailed analytical study on the deactivation of the SCR catalyst have indicated that co-firing may indeed lead to increased deactivation rates and hence may limit co-firing potential. However, for the presently used biomass (mainly wood), the effect is relatively small. Finally, in order to make all data and knowledge on speciation and co-firing conditions as found in the project available a speciation knowledgebase has been built.

- **In the field of technology development for indirect co-firing, the results of the technical-economic evaluation did not reveal clear advantages of the TORBED gasification concept over circulating-fluidised-bed (CFB) gasification, whereas the uncertainties in technical performance and costs are much larger.** Consequently, in consultation with the IAG it has been decided in 2008 to focus this work package on fluidized bed gasification. For low temperature gasification (<700°C) for difficult fuels as a co-firing option, the LT-CFB, Silvagas, Milena and FICFB concepts were assessed and selected as possible concepts. There is limited experience with operating biomass fluidized bed gasifiers at low temperature. To determine the actual potential for alkali load reduction, conversion efficiency and general operability of any of the fluidized bed gasifiers at low temperature, there is a need for experimental validation as no (public) experimental/practical data could be retrieved/is available. Taking Hemweg 8 power station as a case study, it is concluded that 20 % (e/e) co-firing reduces the overall efficiency with 1.3 percent points. With respect to indirect co-firing, the Hemweg case study indicates an additional efficiency reduction of 1.4 percent points for straw and 0.3 percent points for RDF. This results are based on data obtained from laboratory scale gasification experiments of straw and RDF performed in the 25 kWth indirect gasifier at ECN. These experiments also showed that indirect gasification can roughly reduce the alkali and chlorine load to the boiler by 80-95%.

- **On the ash recycling the overall conclusion is that recycling is in principle possible when the ashes are separately collected (not mixed with coal ashes).** In forestry, heavy metal contents of wood ash may prevent recycling. In agriculture, ashes can replace only part of the fertilizer used. Recycling has less environmental impact than land fill. A remarkable conclusion is that the best option is to use ashes as a raw material in local production of fertilizer. The reason is that it eliminates the environmental impact of long distance transportation. Finally, for biomass ashes mixed with coal ash, production of light-weight aggregates (LWA) was identified as the most promising bulk utilization. LWA test batches were produced and material properties were determined. LWA from co-firing ashes were found to be suitable for replacing gravel in concrete applications. The market is large enough to accommodate bulk production of LWA from co-firing ashes and the LWA have the lowest production cost of all feasible bulk applications, except for established applications in cement or concrete.

- **Under oxy-fuel firing conditions, an increase in the fouling propensities of coals, biomasses as well as their blends will occur.**

- **With respect to the aim of fouling monitoring, the prototype of the non-invasive steam flow meter has been designed, built and extensively tested on lab-scale, whereupon it was concluded that the sensitivity under the relevant high temperature conditions are more than satisfactory.** It was verified that the instrument is indeed capable of measuring small changes in
the flow of steam inside the steam tube under conditions relevant for the application in the full-scale power plant. After redesigning the instrument, allowing for clamp-on application on the existing steam tubes, the apparatus is ready for further testing in a power plant.

- On the study on the processing of wet biomass and heat utilisation of a power plant as most promising fuels, road side grass, organic wet/compostable fraction, digestates from digestion of agricultural residues and manures, animal manures and sewage sludge were identified. Anaerobic digestion, TORWASH, HTU\(^*\), WTA and thermal drying as the reference technology were selected. Most studied technology concepts considered have however few large-scale applications and are at the testing/demonstration phase. Belt drying and TORWASH with grass and HTU and anaerobic digestion with GFT have been assessed both technically and economically. Conventional drying techniques are calculated to be feasible at moderate cost by restricted steam consumption. The more innovative technologies as HTU and newest TORWASH technologies are more expensive in terms of steam use. However, especially the TORWASH technology may have significant process optimization possibilities, leading to a reduced specific cost.

The TORWASH experiments in a 20 l autoclave with hay indicate that the composition and characteristics of the product compare well with those of the material produced previously on a small-scale (0.5 litre autoclave) . Mechanical dewatering to a product with 65% dry matter content was achieved. The dissoluble salts (K, Cl, etc) are removed for more than 90%. The mass and energy yields are somewhat lower than on the small scale, but this can improve with optimization towards milder conditions. The grindability of the material is significantly improved compared to the feedstock. A test in ECN’s Lab-scale Combustion Simulator (LCS) showed that TORWASHed hay is highly reactive, better than high volatile coal, and therefore a suitable fuel for co-firing.

- On the modelling of the pneumatic behaviour of coal/biomass blends, the evaluation of the mill system in fact, led to the conclusion that mill capacity is not controlled by grinding or thermal limitations imposed by the wood pellet fuel or the mill itself. Mill capacity is most likely controlled by transport limitations within the mill and fuel duct. The results obtained show that in the fuel pipe transport model the wood particles are effectively transported by primary air without significant circulation and deposition observed. However wood and coal particles appear to mix poorly with air with particles segregation in the fuel pipe but “roping” phenomena does not occur. As far as concerns the deposition, the deposition of heavier particles was found to be higher at lower velocities and lower at higher velocities. The lighter particles were found to remain mostly suspended with homogeneous distribution. The larger particles clearly showed deposition near the bottom of the wall and this deposition was found to be pronounced at higher velocity due to a higher inertia.

- New correlations were proposed to define the species formed during ideal and typical PF combustion from the elemental fuels composition. Pure fuels and blends were studied. The species of interest are: \(\text{SO}_2/\text{SO}_3\), HCl, KOH, NaOH, KCl, NaCl, K-\(\text{AlSi}\). Moreover, a simplified reaction scheme simulating the evolution/combination of the components as temperature decreases was also proposed. This work is a step towards the implementation in a predictive tool e.g. the ADP. The work would allow to model not only the physical phenomena leading to deposition such as inertial impaction, turbulent diffusion and thermophoresis, but also, to consider deposition due to various condensation modes (heterogeneous onto walls and already existing particles as well as homogeneous nucleation). The methodology above was retained as a good compromise between simplicity, realism of predictions and equivalent calculation burden.

- Numerous results and insights have been generated in this project, resulting in a large number of dissemination activities, in the form of (confidential) reports, contributions to conferences and symposia, articles and book contributions. A dedicated symposium on biomass co-firing, attended by 60 people, was organised to present the results of the past four years. This symposium was well received by the audience. Besides a website has been set up to facilitate the knowledge dissemination.

- Overall, it is concluded that significant progress has been made and valuable insights have been obtained in the field of co-firing biomass in coal-fired power plants to reach and facili-
tate the long-term targets of the EOS-LT programme. Among others, the programme has contributed to a better, more realistic and more positive view at the technology of co-firing biomass, both from the public and from politicians. The combined knowledge and experience of the partners were experienced as valuable, where ECN has the emphasis of her activities on fundamental knowledge, experimental facilities and analytical facilities, KEMA in the field of consultancy for and modelling of power plants and TUD on the fundamental knowhow.
4. Joint valorisation and knowledge dissemination

4.1 Joint valorisation

In the third consortium year, discussions were held on the possible joint valorisation of the results generated by common effort of both partners. After a brainstorm session a number of possible candidates “joint commercial products” have been identified.

One such product stems from the co-operation within the WP 1 on the trace elements fate and speciation under biomass co-firing. It has been advanced that the jointly generated additional data on the specific influence of the SCR/DeNOx installations on the will be included in a knowledge base, which in future will form a separate “add on” module which can be accessed from within the TRACE tool, or used as a standalone piece of software. Extension of the database with results from new and additional measurements is the joint task of the consortium members the third consortium year, discussions were on the possible joint valorisation of the results generated by common effort of both partners. After a brainstorm session a number of possible candidates “joint commercial products” have been identified. One such product stems from the co-operation within the Work Package 1 on the trace elements fate and speciation under biomass co-firing. It has been advanced that the jointly generated additional data on the specific influence of the SCR/DeNOx installations on the speciation and further the emission of trace elements can possibly be integrated within the existing KEMA TRACE predictive tool. Finally it was agreed to develop a knowledge base, which forms a separate “add on” module, which can be accessed from within the TRACE tool, or used as a standalone piece of software.

In other work packages, the valorisation will have per definition a much less commercial character and will be basically limited to joint (public or limited) dissemination of knowledge. An example of such co-operation area is work package 3 on the utilization of biomass co-firing ashes.

4.2 Knowledge dissemination

Biomass co-firing symposium

On May the 27th, 2010 a symposium was held in Amsterdam to disseminate and discuss the knowledge gained by the research consortium. Around 60 people attended this event, mainly consisting of people related to the power industry. In the morning general back ground and issues of biomass co-firing were presented, while in the afternoon the results of the consortium were presented in separate presentations. The symposium was well received. All presentations are publicly available from the consortium co-firing website.

Biomass co-firing website

In order to facilitate the knowledge dissemination and to form an advertising platform for both the ECN/KEMA consortium as well as for the biomass co-firing as a sustainable energy generation option, a consortium website has been established. The chosen domain name “Biomasscofiring” has been registered by ECN (domain owner and primary responsible for the development and maintenance of this website) for the extensions .com, .eu, .org and .nl. Upon consultations with all partners and the IAG members, the website structure and graphical design (see Figure 4.1) has been agreed on.

As of September 2009, the first components of the website, including a general description of the consortium as well as the co-firing principles, have been put on-line. Further functionalities, including secure member access gate to confidential data generated within the project, but also a dedicated sub webpage for students and general public, have been successively added within the
fourth consortium year. To advertise the existence of the website to the broad public, it has also been used as the registration gate for the Biomass Co-Firing Symposium. Furthermore, presentations from the said event have also made available online via the consortium website.

Figure 4.1  Graphical design of the consortium website www.biomasscofiring.nl

Publications
There have been numerous publications generated by the consortium within the reporting period, by means of which the (public) results obtained within consortium have been disseminated. These are:

Reports
- Eijk, R.J. van and te Winkel, B.H.: ‘Fate of trace elements in biomass co-firing. Results of full-scale measurement campaign at MV2 power station in 2008’. Confidential report 50980611-TOS/ECC 10-4835. KEMA, Arnhem, 2010
- Eijk, R.J. van.: Concentrations of trace elements in biomasses of the future - additional data and analysis. Confidential report 50780586-TOS/ECC 08-9175, KEMA Arnhem, September 2008


- Magneschi, G., (KEMA), M. Cibiş (KEMA), J. Pels (ECN), EOS-LT WP6 Wet biomass processing and heat utilization, Phase 1: Selection of biomass types and evaluation of concepts, 50980611-Consulting 10-0297 Confidential, KEMA Arnhem, March 29 2010

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- Van der Ven, M.F. (KEMA), C.M. van der Meijden (ECN), B. Vreugdenhil (ECN), ‘Indirect-co-firing using fluidized bed gasification technologies’, Confidential report 50980611.200-consulting 10-1224, confidential, KEMA, Arnhem, June, 2010


Vreugdenhil, B.J., Alkali distribution for low temperature gasification, ECN-E-10-103, ECN, Petten, November 2010


Articles

Dyjakon, A.K., M.K. Cieplik, W.L. van de Kamp: Heat exchangers fouling during co-combustion of coal and biomass – development and application of a horizontal deposition probe for lab-scale tests (accepted for the publication “Overcoming Barriers to Bioenergy” – Biomass and Bioenergy Special Issue for Biomass Network of Excellence)


Stam et al., " Speciation of Cr, V, As, Se and Zn in Coal and Biomass co-combustion products" submitted to Env. Sci. Techn., 2011

Contributions to conferences and symposia

Bertrand, C., Fryda, L., Kalivodova, J., Leiser, S., Cieplik, M., Sobrino, C., Glazer, M. and de Jong, W.: Combining experiments and simulations...or how to tackle deposition phenomena in boilers, poster presented at the INFUB9 conference, Estoril, 26-29 April 2011, Portugal.

Cieplik, M.K., Verhoeff, F. (ECN) and Dyjakon, A. (TUD), ‘Karakterisering en monitoring van vervulingsgedrag in de ketel bij biomassa meestoken’, Presentation at the Biomassa Meestook Symposium, Amsterdam, 27 May 2010


characterisation, paper and oral presentation on fouling monitoring, Conference on Boiler Technology 2009, 13-15 October 2009, Szczyrk, Poland

- Dyjakon, A.K., Mariusz Cieplik and Willem van de Kamp. Deposition Probe for on-line Monitoring/Investigation of Slagging and Fouling Processes in the PF-boilers, in the proceedings of the 35th International Technical Conference on Clean Coal & Fuel Systems, June 6 to 10, 2010, Clearwater, USA


- Eijk, R. van (KEMA) and Cieplik, M.K. (ECN), ‘Richtlijnen sporenelementen’, Presentation at the Biomassa Meestook Symposium, Amsterdam, 27 May 2010

- Fryda et al., poster presentation ‘Oxyfuel combustion of coal/biomass blends’, IEA Oxyfuel Conference, Cottbus, Germany, 7-11 September 2009

- Fryda, L., Sobrino, C., Cieplik, M., Bertrand, C., Jong, W. de and Kamp, W.L. van de: Comparative Study of Ash Deposition under Air and Oxyfuel Combustion of Coal/Biomass Blends. European Combustion Meeting (ECM), Vienna, Austria, 14-17 April, 2009

- Fryda, Lydia (ECN). ‘The effects of biomass co-firing under oxyfuel conditions’ Presentation at the Biomassa Meestook Symposium, Amsterdam, 27 May 2010


- Kiel, Jaap (ECN), ‘Vergroening van kolencentrales Technische mogelijkheden en uitdagingen’, presentation at the Biomassa Meestook Symposium, Amsterdam, 27 May 2010

- Konings, Ton (KEMA), ‘Inzet ‘lastige’ brandstoffen in elektriciteitscentrales’, presentation at the Biomassa Meestook Symposium, Amsterdam, 27 May 2010

- Magneschi, G., Cremers, M., Wet biomass processing and heat utilization in co-firing applications, presentation at the STW COMBURA conference, including the contribution to the book of abstracts, 12-13 October 2010

- Pels (ECN), J.R., A.J. Sarabér (KEMA) and M.A.T. Cuperus (KEMA), Recycling of cacao ash – Can cacao ash replace fertilizer and close the nutrient cycle?, Poster European Biomass Conference, Lyon, 3-7 May 2010

- Pels, Jan (ECN), Angelo Sarabér (KEMA), ‘Management en toepassing van biomassaassen’, presentation at the Biomassa Meestook Symposium, Amsterdam, 27 May 2010

**Book Contributions**


**Miscellaneous**

5. Contribution to EOS-LT objectives

5.1 Contribution to sustainable energy infrastructure

The targets for the EOS-LT program for co-firing in 2020 are 25 % e/e biomass co-firing and 100 % utilization of conversion residues and in 2040 40 % e/e biomass co-firing. Co-firing of biomass is one of the most important renewable options in the Netherlands. It enables to produce renewable energy with a relatively low additional cost compared with many other renewable energy options. This is primarily due to the fact that it is feasible to a large extent in the existing pulverized-fuel (mainly hard coal) fired power generation infrastructure. The biomass co-firing consortium developed knowledge relevant for power plant operators to enable the long-term stable operation of their plants with high biomass co-firing percentages. Moreover this knowledge allows to assess and develop further attractive technologies for the utilization of low quality fuels, particularly wet biomass available locally in the Netherlands, to broaden the biomass fuel portfolio of the power plants.

In the overview below an indication is given, per work package, of the contribution to the (Dutch) sustainable energy infrastructure.

Work package 1: The fate of trace elements in biomass co-firing

This work provides necessary information to assess if extensive co-firing will result in negative environmental consequences e.g. environmental and public health hazards due to decreasing by product quality or air side emissions, particularly focusing on the existing Dutch coal-fired power industry. The analytical emission modelling and microscopic methodologies developed by ECN and KEMA within this work package consists amongst others of miniaturized, lab-scale characterization methods. It provides power plants operators with means to assess the impact of high-share co-firing on by product quality and applicability, air side dust and gaseous emissions, without the need to run costly and hazardous full-scale trials. In that sense the said methodologies and gathered data provide information for operators to operate their facilities in a more sustainable way. Furthermore, information is gathered on how to monitor, control or prevent technical issues that may limit increasing the co-firing percentage.

Work package 2: Development of indirect co-firing technology

The work package was aimed at the assessment of the possibility to increase the indirect co-firing percentages by gasification, which process can potentially utilize low quality and therefore more economically attractive fuels. These streams will broaden the portfolio of fuels to be used in power plants, particularly extending it by biomass locally available in the Netherlands. This can in turn reduce partially the need to import biomass and stimulate its local use to the full extent. Based on the case study indicated in this part of the work, when 20 energy% of the thermal input is indirectly co-fired, around 17-18% of the coal input can be replaced, next to the fossil fuel share already eliminated by direct co-firing. Extrapolating this to the 200 PJ of coal used annually in the current coal-fired power plants, this would result in 34-36 PJ/a. Whether this high amount can be realised in practice will be amongst others strongly dependent on the availability (price, volume) of the fuels for this application and total costs of production of power.

Work package 3: Sustainable ash management and development of new utilisation options

This work package contributed primarily to the EOS-LT targets on the utilisation of combustion residues by supplying information to assess if the application of high biomass percentages will result in problems considering the ash utilization. The results of the work package indicated that there are technically feasible options to utilize the residues, particularly in the construction industry. It was demonstrated that off-spec combustion residues from high biomass co-firing
could directly lead to the replacement of (fossil) fuel intensive or imported mineral constructing materials, upon an innovative pre-treatment.

**Work package 4: Biomass co-firing in oxy-fuel combustion**
This work package supplied information for biomass co-firing under the conditions of the so-called oxyfuel-fired boilers. This technology is considered as enabling for CO₂-capture, however the application of biomass co-firing is burdened with many technical challenges and unknowns, such as for example the consequences on fouling on the steam tubes. Knowledge generated within this work package supports the ultimate long term goal of a plant operated with high co-firing percentages of difficult biomass fuels, combined with full CO₂ capture. In this way, next to fossil fuel savings, this technology will result in a carbon dioxide sink.

**Work package 5: Fouling monitoring/boiler diagnostics**
The task of this work package was to improve the diagnostic quality and develop new tools to monitor on-line the extent of the fouling of the boiler tubes by the formation of ash deposits, particularly under high biomass co-firing percentages. Better insights into the localization and the extent of fouling can directly be translated into a better overall efficiency. Furthermore these insights can lead to the improvement of the reliability of the plant and also reduce costs/outage. The most valuable output of this work package is a novel sensor for the monitoring of the steam flow/capacity, which has been developed in close co-operation with a Dutch firm Hukseflux. The expected efficiency improvement, which might be realized by the application of an on-line monitoring system developed in the project and based on the above mentioned steam flow meter, is in the order of magnitude of 0.1 to 1 efficiency percent, depending on the conditions in the power plant. This corresponds to around 0.5 to 5 PJ/a saved based on 200 PJ/a fuel consumption in coal/biomass-fired power plants.

**Work package 6: Wet biomass processing and heat utilisation**
Necessary information has been derived for assessing the possibility to increase the co-firing percentage by using wet, low quality and cheaper fuels. This broadens the fuel portfolio of a coal-fired power plant. Estimated total availability of wet streams in the Netherlands is around 2 million tonne per annum on dry basis. This corresponds to a very rough estimate in the order of 27 PJ of potential coal replacement, assuming around 25% energy losses due to the wet biomass processing, mainly moisture evaporation.

**Work package 7: Hydrodynamic transport coal/biomass blends**
The aim of this WP was to obtain insight in the fundamentals of the hydrodynamic transport of biomass/coal mixtures in the transport system between the grinder and the burners in order to evaluate if the mill capacity is controlled by grinding, thermal limitations or transport limitations. The focus was on evaluation of the airflow and particle distributions in a real fuel transport duct at a Dutch power plant. Evaluation of the mill system in fact, led to the conclusion that mill capacity is not controlled by grinding or thermal limitations imposed by the wood pellet fuel or the mill itself. Mill capacity is most likely controlled by transport limitations within the mill and fuel pipe. The simulations performed using CFD have led to observation of segregation of coal/biomass, which needs attention when modelling the burners downstream and increasing diverse biomass shares for the future.

**Work package 8: Optimization of numerical models for slagging/fouling**
A literature study was performed on the state of the art concerning deposition mechanisms in co-firing coal and biomass. Simulations were performed using the ADP software for co-firing conditions and compared with LCS measurement data available from ECN. Work was started to come to implementation of condensation of species in ADP. For this it was necessary to understand the fate of alkali species during co-combustion of biomass. Both equilibrium calculations and a chemical reaction modelling were carried out, therewith the most important species were identified and their fate during a cooling trajectory typical for a PF boiler firing pure compounds (coals, biomass) and blends. The findings are promising as initial step towards coupling with the...
deposition modelling post-processor. This can be brought to further implementation in a follow up project (PhD student).

5.2 Strengthening the Dutch knowledge base

ECN, KEMA and TU Delft already have a strong position in the field of biomass co-firing and are the leading knowledge carriers and developers in the Netherlands. The results of this project have further strengthened their position and extended the experimental facilities park as well as the characterization capabilities of all parties in the field of:

- Development of new sampling and analytical methods to determine the speciation of elements in streams across the combustion process,
- Extending the data pool on the by-product composition, air side emissions of trace elements under biomass co-firing,
- New measurement data on the fouling behavior of biomass and biomass/coal blends under oxyfuel firing conditions,
- Development of lab-scale, miniaturized methods for the characterization of the behavior of elements under dynamic firing conditions and their subsequent chemical speciation in the combustion residues, including pH-static leaching tests in conjunction with LeachXS software package-aided data evaluation,
- Information on how to monitor, control or prevent technical issues that may limit increasing the co-firing percentage,
- Knowledge on the physical and chemical properties as well as utilization routes of biomass ashes,
- Knowledge and experience on the monitoring of fouling and development of a sensor to measure these phenomena on-line in the boiler,
- Knowledge and experience on measurement and modelling of the effects of co-firing under oxyfuel conditions on fouling,
- Knowledge and experimental facilities on low temperature gasification technology as a co-firing option in order to broaden the co-firing fuel portfolio, and
- Knowledge on the integration of power generation from coal/biomass with upgrading /pre-processing of wet biomass, in order to increase the efficiency as well as the co-firing fuel portfolio.
- Knowledge and modelling experience on transport hydrodynamics of biomass/coal blends.
- Development of knowledge concerning partitioning of alkali species, based on correlations developed and detailed chemical rate expressions integrated in a simplified reactor configuration simulating the flue gas cooling path in a co-firing PF boiler.

The above knowledge and experiences have been disseminated and shared within the primary target group of this consortium, namely: the Dutch power producers and Vliegasunie. Work performed in each work package has been carried out under the guidance of a mentor from the industry. Furthermore, the gained insights/knowledge were distributed in the form of numerous written reports amongst the members of the IAG. With a minimum of two project meeting per year with the IAG members, presentations and discussions were held on the progress and results of generated in each of the work areas. Also, the results were presented to and discussed with a broader audience during the public Biomass Co-firing symposium in May 2010 and other relevant conferences (see the section on dissemination for more details).
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Abbreviations

ADP  Ash Deposition Predictor
BEP  Bio Energy Plants
CapEx  Capital Expenditures
CFB  Circulating Fluidized Bed
CFD  Computational Fluid Dynamics
CGE  Cold Gas Efficiency
DEN  Duurzame Energie Nederland Subsidy Programme
DPM  Dispersed Particle Model
EARS  Early Agglomeration Recognition System
ECN  Energy Research Centre of the Netherlands
EOS-LT  Energy Onderzoek Subsidie Lange Termijn
ESP  Electostatic Precipitator
FGD  Flue Gas Desulphurisation
FGR  Flue Gas Recirculation
FICFB  Fast Internally Circulating Fluidized Bed
GFT  Groente, Fruit en Tuin afval
HTU  Hydro Thermal Upgrading
IAG  Industrial Advisory Group
LCS  Lab-scale Combustion Simulator
LT-CFB  Low Temperature Circulating Fluidized Bed
LWA  Light Weight Aggregates
NBO  Non Bridging Oxygen
OFA  Over Fire Air
OpEx  Operational Expenditures
PF  Pulverized Fuel
PSD  Particle Size Distribution
RDF  Refuse Derived Fuel
RFCS  Research Fund for Coal and Steel
SCR  Selective Catalytic Reduction
SEM  Scanning Electron Microscopy
TUD  Technical University of Delft
USC  Ultra Super Critical Conditions
WP  Work Package
WTH  Whole Tree Harvesting
XAFS  X-ray Absorption Fine Structure