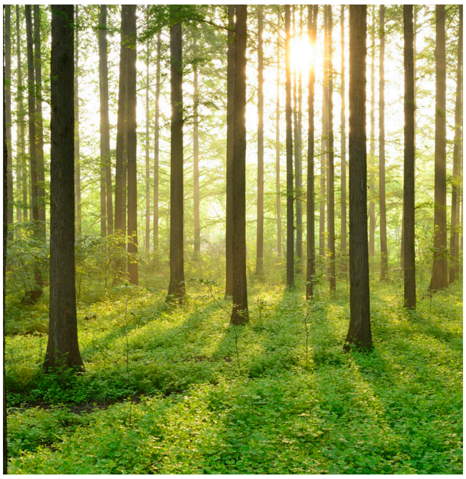
TECHNICAL AND ECONOMICAL POTENTIAL FOR COMBINED HEAT, POWER AND BIO-OIL PRODUCTION IN POWER PLANTS-CHPO

REPORT 2015:219



BRÄNSLEBASERAD EL- OCH VÄRMEPRODUKTION

Energiforsk

Technical and economic potential for combined heat, power and bio-oil production in power plants-CHPO

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Förord

Denna rapport är slutrapportering av projekt SYS 39209 Teknisk och ekonomisk potential för kombinerad värme, kraft och biooljeproduktion vid kraftvärmeverk – CHPO (Energimyndighetens projektnummer P 39209) som faller under teknikområde systemteknik inom SEBRA, samverkansprogrammet för bränslebaserad el- och värmeproduktion.

Projektet har följts av en referensgrupp bestående av

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SEBRA, samverkansprogrammet för bränslebaserad el- och värmeproduktion, är efterföljaren till Värmeforsks Basprogram och startade som ett samarbetsprogram mellan Värmeforsk och Energimyndigheten 2013. All forskningsverksamhet som bedrevs inom Värmeforsk ingår sedan den 1 januari 2015 i Energiforsk. Därför ges denna rapport ut som en Energiforskrapport.

Programmets övergripande mål är att bidra till långsiktig utveckling av effektiva miljövänliga energisystemlösningar. Syftet är att medverka till framtagning av flexibla bränslebaserade anläggningar som kan anpassas till framtida behov och krav. Programmet är indelat i fyra teknikområden: anläggnings- och förbränningsteknik, processtyrning, material- och kemiteknik samt systemteknik.

De bilagor, Appendix I och Appendix II, som refereras till i rapporten finns att hämta på Energiforsks webbplats.

Stockholm januari 2016

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Sammanfattning

En katalytisk snabbpyrolysprocess har integrerats med ett bio-baserat kraftvärmeverk på modelleringsbasis. Syftet i detta projekt är att producera värme, elektricitet och bio-olja, under realistiska förhållanden med mål att öka kapacitetsutnyttjandet hos bio-baserade kraftervärmeverk. Hörneborgsverket som ägs av Övik Energi AB, har använts som räknebasis i studien.

Snabbpyrolys av biomassa är ett sätt att producera flytande bränsle från biomassa. Nyckelfaktorn är snabb upphettning av den fasta biomassan och snabb kylning av de flyktiga ångorna. Därmed maximeras vätskeutbyte. Pyrolysoljan som erhålls är mörkbrun och trögflytande med hög densitet och hyffsat värmevärde (1.2 kg/liter respektive 16-19 MJ/kg). Syre från den ursprungliga biomassan finns dock kvar och gör att är vätskan instabil och oblandbar med andra petroleumråvaror.

Om ett katalysmaterial tillsätts i processen spjälkas mycket av syret bort. På KTH har dessutom ånga använts som tillsatsmedel, processen kallas då katalytisk ångpyrolys. Den bio-olja som då erhålls har:

- 12 % syreinnehåll
- låg O/C kvot
- ett värmevärde på 35.24 MJ/kg (torrbasis).

Därmed kan den användas som råvara i existerande oljeraffinaderier eller som bränsle. Data för den katalytiska snabbpyrolysprocessen kommer från ett tidigare forskningsprojekt på KTH.

Hörneborgsverket producerar i dagsläget el, fjärrvärme, fjärrkyla och processånga till intilliggande industrier. Kraftvärmeverket använder idag en bubblande fluidbäddspanna från Metso och en kondensturbin med flera steg, samt ett fjärrvärmekondensorsystem. Pannan har en nominell kapacitet på 130 MW som producerar ånga med trycket 140 bar och temperaturen 540°C. Ångturbinen har en nominell elektrisk effekt om 40 MW. Integrationen som gjorts innebär att en pyrolysanläggningen byggs på siten.

Pyrolysanläggningen och kraftvärmeverket har följande integrationspunkter (1) indirekt värme från ångpannan leds till biomasstorken före pyrolysen, (2) pyrolysgaserna leds till ångpannan för förbränning, (3) varma rökgaser från katalysregenereringen leds till ångpannan, och (4) kylvatten från bio-oljakondenseringen leds till matarvattensektionen i kraftvärmeverket.

Två huvudsakliga begränsningar identifierades:

1. Pannans maximala rökgasvolym, efter luftförvärmaren, som inte bör överskrida 80 Nm3/s. Detta begränsar hur stor kapacitet pyrolysanläggningen kan ha.
2. Pannans bränslemätningssystem, som inte kan hantera flöden under 7 kg/s. Detta begränsar hur låg lastgrad som kan köras med en given bio-oljaproduktion

Integrationen innebär också att pyrolysanläggningen kan utnyttja befintlig vattentillförsel och bränslehantering, vilket ger en lägre investeringskostnad. En ekonomisk analys genomfördes för att uppskatta produktionskostnaden av bio-oljan.

Aspen Plus som är en programvara för processmodellering användes för alla beräkningar. Tillvägagångssättet var att modellera pyrolysanläggningen och kraftvärmeverket separat. För pyrolysanläggningen användes en produktionskala på 5, 10, 20, 30 och 40 MW (LHV för producerad bio-olja). För kraftvärmeverket så användes följande lastfall 50, 60, 70 och 100 %. De enskilda anläggningarna integrerades och 20 scenarier simulerades. Det optimala fallet: 20 MW och 70 % last användes som referensfall.

<u>Slutsatser</u>

Studien har visat att:

- Den underutnyttjade panneffekten kan med fördel användas för bio-oljeproduktion under lågsäsong (sommartid), men även under högsäsong (vintertid).
- En bio-oljeproduktion om 20 MW är kompatibel med alla driftsfall som normalt sett används under året (utom 50 %).
- 20 MW motsvarar 26 000 ton bio-olja per år, med 30 % vattenhalt och ett värmevärde på 23 MJ/kg.
- Produktionskostnaden för bio-oljan, vid 20 MW och 70 % last, blir 4.7 SEK/kg (eller 752.1 SEK/MWh). Investeringen för 20 MW bio-oljakapacitet uppskattas till 276 MSEK. De årliga driftskostnaderna uppskattas till 98.4 MSEK.
- Det är möjligt att ha en större bio-oljeproduktion (>30 MW) med relativt små modifieringar i ångpannans rökgashanteringssystem vilket ger en lägre produktionskostnad.
- Produktionskostnaden av bio-oljan är mycken känslig för både pris på inköpt biomassa och hur fort katalysatormaterialet behöver ersättas med nytt.

Längre Sammanfattning

INTRODUKTION

Användning av biomassa för kombinerad kraft- och värmeproduktion har ökat markant i Sverige under de senaste årtiondena eftersom biomassa både kan produceras inom landet och anses koldioxidneutralt. För flerbostadshus i städer och tätorter är idag den huvudsakliga uppvärmningsmetoden fjärrvärme, och fortfarande finns potential för ytterligare utbyggnad av fjärrvärme i landet, då främst till villaområden. Vid kombinerad värme- och kraftproduktion kan en hög verkningsgrad uppnås, upp till 95 % av energiinnehållet i biomassan kan komma tillgodo som nyttig energi. I de norra delarna av halvklotet så har vi årstidsvariationer och därmed är efterfrågan på värme avsevärt lägre på sommarhalvåret. För kraftvärmeverken innebär detta att produktionen vid verket måste minska under sommarhalvåret. Samtidigt är också elpriserna lägre på sommarhalvåret än på vintern och sålunda kan inte elproduktionen utjämna det ekonomiska avbräcket som en minskad produktion innebär.

Ur både ekonomiskt och miljömässigt perspektiv skulle det kunna vara attraktivt att tillverka en tredje produkt vid kraftvärmeverk som ger ett högt anläggningsutnyttjande året runt. En möjlig sådan produkt är pyrolysolja som kan användas som bas för produktion av biodiesel. Detta skulle inte bara kunna ge direkta ekonomiska fördelar, utan även kunna bidra till ökad andel av förnybara drivmedel i transportsektorn, som idag är den sektor med högst användande av fossila bränslen. Vid avdelningen för Värme- och Ugnsteknik på Kungliga Tekniska Högskolan, KTH, har en katalytisk pyrolysteknik utvecklats som ger en dieselik produkt av hög kvalité från träråvara. Med hög kvalitét avses här att oljan har högt innehåll av organiskt kol, C och lågt innehåll av syre, O. Ett nästa steg är att se hur denna teknik kan integreras i ett existerande kraftvärmeverk. Det finns ett storskaligt exempel på en integrerad pyrolysreaktor i en kraftvärmeanläggning. Denna har Fortum tillsammans med Metso Power, UPM och VTT byggt i Joensuu i Finland år 2013. Här har en snabbpyrolysanläggning utan katalysator integrerats i den existerande kraftvärmeanläggningen och ska producera 50 000 ton bio-olja årligen. Snabbpyrolysreaktorn använder värme vid hög temperatur. Oljan som fås är relativt lågvärdig (lägre innehåll av organiskt kol C och högre innehåll av syre O än vad en katalytisk process kan ge) och kommer i det storskaliga exemplet att användas i oljepannor för uppvärmning som idag använder fossil olja, och som nu istället kan använda denna bio-olja. (Kohl mfl, 2014)

Fluidiserande snabbpyrolys med katalysator närvarande för att omvandla biomassa till bio-olja har tidigare testats kommersiellt av KiOR, ett USA baserat företag. I pyrolysanläggningen fanns även uppgradering av bio-oljan för den skulle passa för utblandning av bensin och diesel. Företaget gick dock i konkurs i november 2014 (Boust m.fl. 2015).

I en tidigare studie finansierad av Energimyndigheten (Benjaminsson m.f. 2013) gjordes en undersökning hur decentraliserad pyrolysteknik av biomassa skulle kunna vara del i det svenska energisystement. Både fristående och integrerade (t.ex. i massabruk eller kraftvärmeverk) pyrolysanläggningar studerades på en konceptuell nivå för att kunna bestämma produktionskostnaden bio- oljan. Denna beror på vilket teknik för pyrolys som används och om fristående anläggning eller integrerad anläggning används. Produktionspriset i denna studie uppskattades till 380-580 SEK/MWh bio-olja, där den högre kostnaden generellt gällde fristående anläggningar och de lägre kostnaderna för integrerade anläggningar. Det är alltså stor idé att fortsättningsvis studera produktion av bio-olja i integrerade koncept.

Syftet med det här projektet är att i detalj integrera den katalysiska pyrolystekniken i ett svensk kraftvärmeverk i ett trigenereringskoncept: kombinerad produktion av el, värme och bio-olja. Även kostnaden för produktionen skall uppskattas i projektet

MÅL

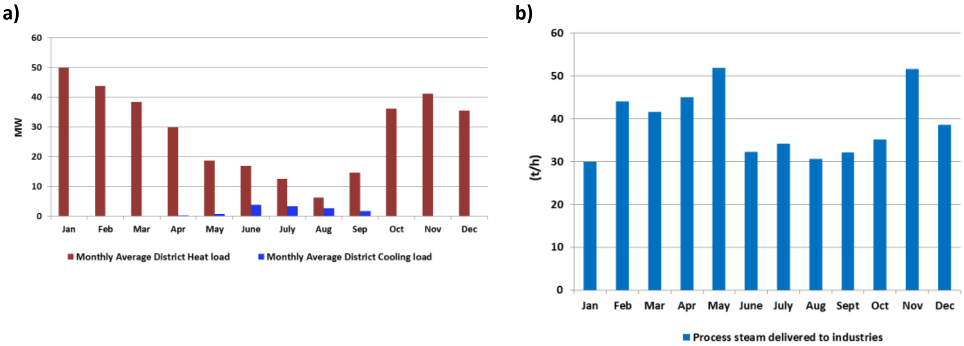
- med hjälp av teknisk integration och modelleringsverktyg, fastställa den ekonomiskt optimala samproduktionen av el, värme och biodiesel som funktion av säsongsvariation.
- klarlägga tekniska detaljer inför en realistisk integrering av pyrolysprocessen
- bygga upp ett systemtekniskt scenario, med hjälp av kommersiellt tillgängliga komponenter, för integrering av pyrolysprocessen samt implementering av detta i en modell i Aspen Plus.
- optimera driftsparametrar för att fastställa den optimala samproduktionen av el, värme och diesel på årsbasis.
- publicera minst en artikel i en vetenskaplig tidskrift eller som ett konferensbidrag
- sprida kunskap via rapporter, publikationer, seminarier och konferenser
- uppmärksamma kraftvärmeindustrin på integrationsmöjligheter av pyrolysprocessen för att samproducera en tredje produkt.

METOD

OM KRAFTVÄRMEVERKET

Den kraftvärmeanläggning som här studerats för pyrolysintegration är Hörneborgsverket i Örnsköldsviks kommun och ägs av Övik Energi AB. Verket som startade år 2009 har idag en kapacitet på 130 MW där 40 MW blir el och 90 MW blir värme och processånga. På ett år produceras 500 GWh ånga, 300 GWh el och 300 GWh fjärrvärme till en totalverkningsgrad av 88 %. Ångan levereras till bl.a. till Domsjö Fabriker, ett bioraffinaderi som tillverkar specialcellulosa, lignin och etanol. Återstod av biomassa som t.ex. bark går till Hörneborgsverket. Verket får även biomassa från en närliggande sågindustri. Den biomassa som idag används i kraftvärmeverket är av varierad typ: kvistmassa, bark, kutterspån, sågspån, torv, GROT-flis, torrflis och stamvedsflis. I medeltal matas pannan, som är en fluidiserande bädd från Metso Power, med en bränsleblandning där bark har en stor procentandel och det effektiva värmevärdet är 10,5 MJ/kg. Bränslefukthalten är ca 40 % och av inmatat bränsle blir ungefär 3 % utmatad aska. Fluidbäddspannan har en flexibel utformning för att kunna använda olika bränslen, bl.a. finns redan brännare för både biogas och olja integrerade i pannan.

Bränsle finns tillgängligt året runt, medan efterfrågan på fjärrvärme varierar under året, där lägst efterfrågan är under sommarmånaderna, något som idag påverkar hur driften av anläggningen sker. Figur 1 nedan presenterar månadsvis den genomsnittliga produktionen av a) fjärrvärme och fjärrkyla och b) processånga vid Hörneborgsverket för år 2014.



Figur 1a: Genomsnittligt produktion månadsvis av fjärrvärme och fjärrkyla (MW) och Figur 1b: genomsnittlig produktion månadsvis av processånga till kringliggande industrier (ton/h)

Vid en integration av en pyrolysanläggning är det av vikt att behålla produktion av fjärrvärme och processånga.

OM DEN KATALYTISKA PYROLYSPROCESSEN

Den katalytiska pyrolysprocessen som utvecklats på Värme- och Ugnsteknik, KTH, är byggd på snabbpyrolystekniken men har integrerats både med en katalysator och ånga som värmebärare och fluidiserande medium (Kantarellis, 2014).

Pyrolysreaktorn är en fluidbädd, som matas med överhettad ånga (500°C, 1.1 bar), biomassa och recirkulerad katalysator och bäddmaterial. Det katalyserande materialet består av zeolit med massförhållandet 28 av SiO_2/Al_2O_3. Tabell 1 visar en massbalans på pyroylsprocessen baserad på 1000 kg torr biomassa och de produkter som uppstår efter pyrolysen. Här ses att vid pyrolysen bildas förutom kondenserbara och icke-kondenserbara gaser även koks och träkol. Koks orsakar deaktivering av katalysatormaterialet genom deponering på ytorna. Därför måste katalyatormaterialet kontinuerligt regenereras, d.v.s. kokset bränns bort. Efter pyrolysreaktorn finns en cyklon som separerar den varma pyrolysgasen från det fasta materialet.

Tabell 1: Massbalans för den katalytiska pyrolysprocessen såsom erhållits vid labbskaleexperiment baserat på (Kantarellis, 2014). Inget inert bäddmaterial användes.

Komponent	Inkommande massa, kg	Utgående massa, kg
Torr biomassa, m_{fs_d}	1000	
Fukt i biomassa, m_{m_d}	98	
Katalysatormaterial, m_{cat_d}	500	500
Ånga, m_{st_d}	581	
Koks, m_{coke_d}		73,3
Träkol, m_{char_d}		180
Organisk vätska, m_{OL_d}		243,3
Gas, m_{gas_d}		212,7
Vatten, m_{wat_d}		969,7
Totalt	**2179**	**2179**

Gasen består både av kondenserbara och icke-kondenserbara produkter. Gasen leds till en kylanläggning för att kondensera ut bio-olja (Organisk vätska i tabell 1). Även vatten kondenserar. Resterande icke-kondenserbara gaser tas vidare. I labbskaleförsöken tas dessa till en gaskromatograf för mätning av sammansättningen. I vår integrerade modell tas dessa till biopannan i kraftvärmeverket, se vidare kapitlet om integrationen. Tabell 2 visar sammansättningen av den bio-olja som fås ur pyrolysprocessen och tabell 3 sammansättningen av den icke-kondenserade gasen. I tabell 3 ses att det finns en relativt hög andel av brännbar substans i den icke-kondenserade gasen.

Tabell 2: Representativ sammansättning den organsiska vätskan (bio-oljan) från den katalytiska pyrolysprocessen baserat på (Kantarellis, 2014).

Parameter	Värde	Huvudsakliga komponenter i den organiska vätskan	Viktsfraktion
Kol, C [vikt-% TS]	79,11	Karboxylsyror ($C_2H_4O_2$-1)	0,0341
		Ketoner (C_4H_8O)	0,0568
Väte, H [vikt-% TS]	7,66	Furaner ($C_5H_4O_2$)	0,2839
		Socker ($C_6H_{10}O_5$)	0,0057
Syre, O [vikt-% TS]	13,19	Fenoler (C_6H_6O)	0,1703
		Catechol ($C_{10}H_{14}O_2$)	0,0057
Effektivt värmevärde, LHV_{db} [kJ/kg]	33,85	Guaiacol ($C_7H_8O_2$-E1)	0,0125
		Alkohol (CH_4O)	0,0057
		Aromatiska kolväten (C_7H_8)	0.4255

Tabell 3: Sammansättning av icke-kondenserade gaser från den katalytiska pyrolysprocessen baserat på (Kantarellis, 2014).

Komponent	Vikts-%	Komponent	Vikts-%
H_2	0,76	C_3H_6	2,39
CH_4	5,26	C_2H_2	0,01
CO	44,8	iC_4H_{10}	0,02
CO_2	42,08	$1-C_4H_8$	0,08
C_2H_4	2,18	CH_3C_2H	0,04
C_2H_6	0,42	nC_6H_{14}	1,57
C_3H_8	0,38		

Det fasta materialet leds till en katalysatorregenerator som är en bubblande bädd. Här återaktiveras katalysatormaterial med hjälp av förbränning av koks och träkol. Katalysator och bäddmaterial matas tillbaka till pyrolysreaktorn och aska mats ut för vidare behandling. De varma förbränningsgaserna från regenereringen matas i vår integrerade modell vidare till biopannan i kraftvärmeverket. Den pyrolysreaktor som utvecklats på KTH är i labbskalemodell men eftersom den är baserad på fluidbäddstekniken kan den skalas upp till en fullskalig reaktor passande för ett kraftverk, och detta har antagits i denna studie.

BEGRÄNSNINGAR FÖR INTEGRATION

Det finns idag vissa både praktiska och anläggningsmässiga begränsningar för hur en integration av katalytisk pyrolys ska kunna göras. Det biobränsle som idag används vid Hörneborgsverket kommer från närliggande anläggningar och begränsas sålunda både till mängd och till sammansättning av de andra industrierna. En stor andel av bränslet är bark, och denna har både hög askhalt och hög fukthalt. Den katalytiska pyrolysprocessen har inte testats med bark som råvara utan med renare träslag. Av det bränslet som idag fås till Hörneborgsverket kan ca 17 % anses vara av sådan kvalitet att det efter torkning kan användas direkt i pyrolysprocessen. Ett alternativ skulle kunna vara att köpa in biomassa för att använda till pyrolysprocessen, men då biomassa har ett högt pris på dagens marknad kommer detta att ge stor ekonomisk påverkan vid en integration. Detta har tagits i beaktande vid de ekonomiska beräkningarna.

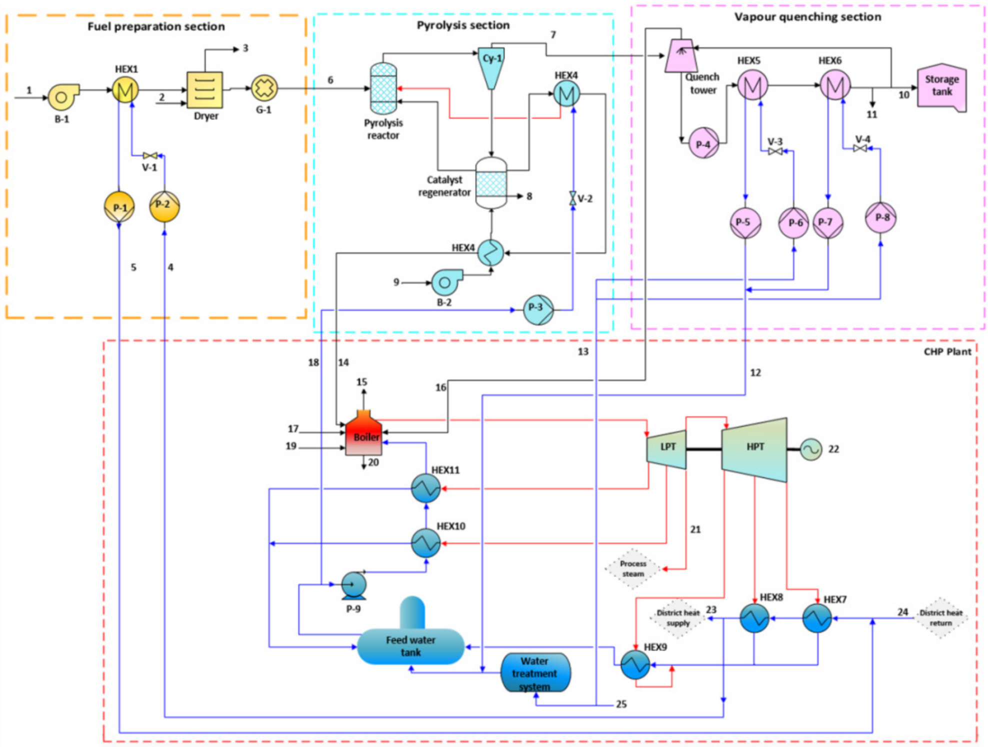
Andra begränsningar i integrationen är möjlig tillgång på ånga från ångpannan samt om viss utrustning som också ska användas efter pyrolysintegrationen har flödes- och temperaturbegränsningar. Vidare har begränsningen gjorts att separerat vatten från pyrolysprocessen antas kunna behandlas i existerande vattenreningsutrustning på kraftvärmeverket.

MODELL FÖR INTEGRATION

Integrationen av den katalystiska pyrolystekniken i det existerande kraftvärmeverket har genomförts i programvaran Aspen Plus. En förenklad schematisk bild för hela integrationen ses i figur 2 och flödesindikation i tabell 4.

De fyra huvuddelar som ingår i processintegrationen är:

- Förbehandling av bränsle
- Pyrolysreaktor med tillhörande cykloner, värmeväxlare och katalysatorregenerator
- Gasbehandling med kondensering och separation av icke-kondenserbara gaser och vatten
- Kraftvärmeverket med produktion av processånga, kraft och fjärrvärme



Figur 2. Förenklat integrationsschema i Aspen Plus för katalytisk pyrolysanläggning i Hörneborgs kraftvärmeverk

Tabell 4: Indikering av flöden i figur 2

Nr, figur 2	Beskrivning	Nr, figur 2	Beskrivning
1	Luft som tas till förvärmning för torkning av biomassa	11	Avloppsvatten
		12	Returvatten för kylning och rening
2	Biomassa med 31.8% fukthalt	13	Tillfört vatten för kylning och rening
		14	Rökgaser från katalysator-regeneratorn till pannan
3	Fuktig luft efter torkningsprocess	15	Rökgas till reningssektion
		16	Icke-kondenserade pyrolysgaser
4	Framledningsvatten till fjärrvärmenätet	17	Bränsle
5	Returvatten från fjärrvärmenätet	18	Vattentillförsel för ånggenerering via rökgaser från katalysatorregeneratorn
6	Biomassa med 1.4 mm partikelstorlek	19	Förbränningsluft till biopanna
7	Pyrolysgaser	20	Aska från biopannan
8	Aska	21	Processånga till industrier
9	Förbränningsluft via förvärmning till katalysatorregenerering	22	Elektrisk effekt
		23	Fjärrvärme framledning
		24	Fjärrvärme retur
10	Bio-olja med 30 % vatten	25	Färskvatten

Det finns flera integrationspunkter:

1. Bränsle till pyrolysreaktorn torkas med vatten från fjärrvärmesektionen i kraftverket
2. Pyrolysreaktorn försörjs med ånga från existerande biopanna
3. Icke-kondenserade gaser från pyrolysreaktorn leds till biopannan och förbränns i existerande biogasbrännare
4. Varma rökgaser från katalysatorregenereringen leds till biopannan
5. Kylvatten från kondenseringen av bio-olja leds till matarvattensektionen i kraftverket

Det som skiljer Hörneborgsverket från andra kraftvärmeverk är att detta levererar ånga till närliggande industrier som inte återkommer till kraftverket i kondenserad form. Kraftverket behöver därför hela tiden ett färskvattenflöde till ångproduktionen, vilket utnyttjas i integrationsschemat.

Utifrån både storlek på existerande kraftvärmeverk samt den tillförsel som idag sker och kan ske av biobränsle har följande storlekar på pyrolysanläggningen studerats (baserat på effektivt värmevärde av utmatad bio-olja med 30 % fukthalt): 5 MW, 10 MW, 20 MW, 30 MW och 40 MW. En styrande faktor i integreringen är att produkten av både processånga och fjärrvärme ska vara bibehållen, d.v.s. följa det varierande behovet under året. Detta gör att pyrolysanläggningen också kan behöva ha olika utbyten beroende på vilket last ordinarie biopanna har. Ett referensfall har tagits fram av de simuleringar som gjorts, och denna är då biopannan har 70 % last och pyrolysanläggningen producerar 20 MW bio-olja (motsvarar 26 000 ton årligen till ett värmevärde av 23 MJ/kg).

EKONOMISKA BERÄKNINGAR

För de ekonomiska beräkningarna har Fortums integrerade pyrolysanläggning i Finland använts som modell. Denna anläggning är designad att producera 30 MW bio-olja (motsvarar 50 000 ton årligen), dock fås en större mängd olja till ett lägre värmevärde än vad som uppnås med katalystisk pyrolys. Investeringskostnaden för Fortums anläggning var 30 MEuro. Eftersom den katalytiska pyrolysanläggningen som studeras i detta projekt är mindre används principen för skalekonomi för att uppskatta investeringskostnaden, Ekv 1 (Sadhukhan mfl. 2014):

$$\frac{\mathrm{COST_{size2}}}{\mathrm{COST_{size1}}} = \left(\frac{\mathrm{SIZE_2}}{\mathrm{SIZE_1}}\right)^{\mathrm{R}} \qquad \text{(Ekv. 1)}$$

Där:

- $\mathrm{SIZE_1}$ är kapaciteten för bassystemet
- $\mathrm{COST_{size1}}$ är kostnaden för bassystemet
- $\mathrm{SIZE_2}$ är kapaciteten för uppskalat/nedskalat system
- $\mathrm{COST_{size2}}$ är kostnaden för uppskalat/nedskalat system
- R är skalfaktor, här 0.7

I den ekonomiska analysen har indirekta kapitalkostnader och årlig drifts- och underhållskostnad integrerats. Den årliga drifts- och underhållskostnaden har delats in i fasta och rörliga kostnader. Fasta är t.ex. löner till anställda och rörliga är t.ex. inköpt bränsle och inköpt katalysatormaterial. Katalysatormaterialet är dyrt i nuläget 85 SEK/kg och nyinvesteringstakten antas vara 0.2% av katalysatormaterialsflödet per timme (Boust mfl 2015), som beror på permanent deaktivering samt en viss massflödesförlust vid regenereringen. Investeringskostnaden har periodiserats per helår utifrån en återbetalningstid på 15 år och en ränta på 6 %.

Produktionskostnaden per kg bio-olja beräknas enligt Ekv 2 (Sadhukhan mfl. 2014):

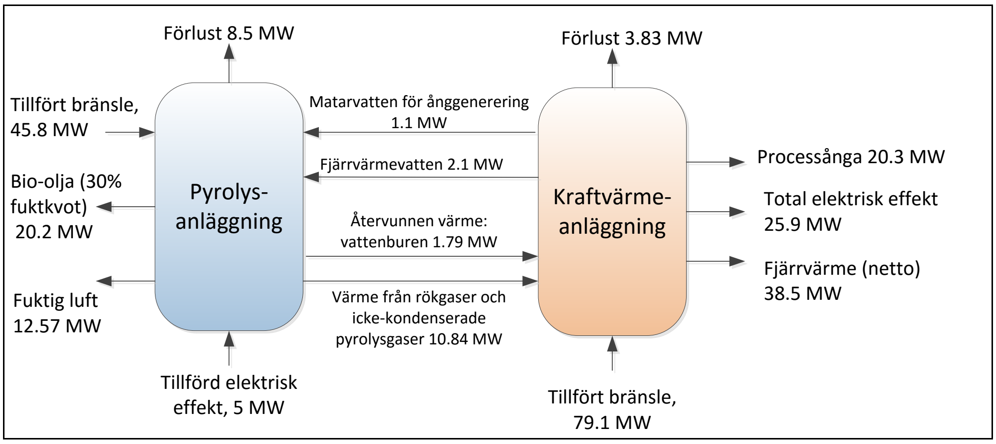
$$\frac{\text{SEK}}{\text{kg}}\text{bioolja} = \frac{Periodiserad\ kapitalkostnad + Årlig\ driftskostnad}{Årlig\ produktion\ bioolja} \qquad \text{(Ekv.2)}$$

Den ekonomiska analysen inkluderar endast kostnaderna för produktion av bio-olja och tar inte hänsyn till försäljning av producerad el, fjärrvärme och processånga från kraftvärmeanläggningen. Vidare antas att den elektricitet och fjärrvärme som behövs till pyrolysprocessen och torkning av biomassa för pyrolys inte debiteras internt utan fås gratis av kraftvärmeverket. På samma sätt så skickar pyrolysanläggningen brännbar pyrolysgas samt varma rökgaser till kraftvärmeverket, och inte heller detta debiteras utan ges gratis till kraftvärmeverket. Det driftsfall som studeras i den ekonomiska utvärderingen är det som hänvisas som referensfall, d.v.s. produktion av 20 MW bio-olja.

RESULTAT OCH DISKUSSION

ENERGIBALANS FÖR REFERENSFALL

Total energibalans för den integrerade pyrolysanläggningen visas i figur 3. Här ses det som är vårt referensfall, 20 MW oljeproduktion och 70 % last på biopannan. För att producera 20 MW bio-olja (med 30 % fuktkvot) behövs ca 46 MW biobränsle, en tillförd elektrisk effekt på ca 5 MW och tillförd fjärrvärme om 2,1 MW. Pyrolysprocessen tillsammans med katalysatorregenerering ger dock även upphov till högvärdig värme och brännbara gaser som kan återföras biopanna och utnyttjas för att producera elektricitet, processånga och fjärrvärme. Som ses i figur 3, så får pannan värme från pyrolysprocessen samt att biogasbrännarna utnyttjas för sameldning av pyrolysgaser och biomassa. I detta driftsfall fås ca 20 MW processånga, 26 MW elektricitet och 39 MW fjärrvärme. Här anges total elektricitet, d.v.s. utan avdrag för pyrolysprocessens behov, eftersom kraftverket kan välja att köpa in denna el som annan än grön el, och samtidigt försälja sin egenproducerade el som grön el. För fjärrvärmen finns dock ingen sådan lösning varför angiven fjärrvärme i figur 3 är netto till försäljning. Produktionen av fjärrvärme motsvarar här ungefär det behov som är under vår och höst. Under förutsättning att pyrolysanläggningen producerar under 11,5 månader per år (två veckor är kraftverket avstängt varje sommar för revision) kommer ca 26000 ton bio-olja att produceras i referensfallet.



Figur 3. Energibalans för den integrerade pyrolysanläggningen i Hörneborgs kraftvärmeverk

MASSFLÖDESBALANS FÖR REFERENSFALL

Tabell 5 indikerar massflödesbalansen och temperaturer av flödena för referensfallet enligt figur 2. Till torksektionen innan pyrolysreaktorn tillförs biomassa med ett flöde av 3,7 kg/s och en fukthalt av ca 32 %. För torkning av biomassan tillförs fjärrvärmevatten om 13,6 kg/s. Torkningen sker vid ett lägre tryck än atmosfärstryck. Efter torkning pyrolyseras biomassan och pyrolysprocessen genererar 3,6 kg/s av pyrolysgaser med en temperatur av 500°C. Av dessa gaser utvinns 0,9 kg/s bio-olja med 30 % fukthalt, med en sammansättning enligt tabell 2. Ett flöde av icke-kondenserade pyrolysgaser om 0,5 kg/s med sammansättning enligt tabell 3 tillförs biopannan. Övriga massflöden och temperaturer indikeras i tabell 5.

Tabell 5: Indikering av flöden enligt figur 2, deras massbalans och temperatur.

Sifferindikation i figur 2	Beskrivning	Massflöde (kg/s)	Temp. (°C)
1	Luft som tas till förvärmning för torkning av biomassa	52,1	0,8
2	Biomassa med 31.8% fukthalt	3,7	15
3	Fuktig luft efter torkningsprocess	53,0	26
4	Framledningsvatten från fjärrvärmenätet	13,6	82
5	Returvatten till fjärrvärmenätet	13,6	41
6	Biomassa med 1.4 mm i medelpartikelstorlek	2,8	24
7	Pyrolysgaser	3,6	500
8	Aska	0,01	700
9	Förbränningsluft via förvärmning till katalysatorregenerering	26,3	0,8
10	Bio-olja med 30% vattenhalt	0,9	25
11	Avloppsvatten	2,2	25
12	Returvatten för kylning och rening	8,7	57
13	Tillfört vatten för kylning och rening	8,7	4
14	Rökgaser från katalysatorregeneratorn till biopanna	26,9	398
15	Rökgas till reningssektion	95,7	167
16	Icke-kondenserade pyrolysgaser till biopannan	0,5	182
17	Bränsle	7,5	15
18	Vattentillförsel för ånggenerering via rökgaser från katalysatorregeneratorn	1,5	171
19	Förbränningsluft till biopanna	61	0,8
20	Aska från biopannan	0,2	182
21	Processånga till industrier	8,5	212
22	Elektrisk effekt	-	-
23	Fjärrvärme framledning	258,8	82
24	Fjärrvärme retur	258,8	42
25	Färskvatten	10,0	4

ANDRA DRIFTSFALL

Några driftsfall för övriga produktionsvolymer av bio-olja presenteras i tabell 6 nedan. Oberoende av hur mycket bio-olja som produceras vid en viss last på biopannan, behålls produktionen av processånga och elektricitet. Dock justeras fjärrvärmen något då högre produktion av bio-olja kräver mer fjärrvärmevatten till torkning av biomassa, och det blir sålunda mindre mängd fjärrvärme till försäljning. I tabell 6 ses också att mer elektricitet behövs för en högre produktion av bio-olja, och som tidigare nämnts kan denna antingen avräknas den totalt producerade elektriciteten eller inköpas separat. Driftsfallen i tabell 6 är teoretiska och det finns vissa praktiska begränsningar för några av fallen nedan med utgångspunkt från den utrustning som idag finns på kraftvärmeverket.

Två huvudsakliga begränsningar identifierades:

1. Pannans rökgasvolym, efter luftförvärmaren, som inte bör överskrida 80 Nm^3/s. Detta begränsar hur stor kapacitet pyrolysanläggningen kan ha.
2. Pannans bränslematningssystem, som inte kan hantera flöden under 7 kg/s. Detta begränsar hur låg lastgrad som kan köras med en given bio-oljaproduktion.

Om 20 MW bio-olja produceras vid 100 % pannlast istället som vid 70 % (referensfallet), fås ett högre rökgasflöde för en luftförvärmare än vad denna förvärmare är designad för. Detta gäller alla driftsfall för 100 % last på biopannan, och denna luftförvärmare måste i sådant fall bytas att klara 100 % last på pannan vid samtidig produktion av bio-olja. För alla driftsfall av 30 MW bio-olja fås en för hög rökgastemperatur för samma förvärmare ovan. För driftsfall med 50 % pannlast och en bio-olja produktion högre än 20 MW måste vatten tillsättas utöver vad nuvarande vattenanläggning klarar att producera per tidsenhet.

Tabell 6: Ett urval av övriga driftsfall, med olika lastfall på biopanna och produktion av bio-olja.

Energiström	100% Last biopanna Energibalans, MW				70% Last biopanna Energibalans, MW			50% Last biopanna Energibalans, MW		
Bio-olja 30% fuktkvot	5	10	20	30	5	10	30	5	10	30
Tillfört bränsle till panna	139,2	132,9	121,3	110,7	94,9	88,6	67,5	66,4	60,1	39
Tillförd våt biomassa till pyrolys	11,5	23,5	45,8	69,3	11,5	23	69,3	11,5	23	69,3
Fjärrvärme för torkning	0,6	1,2	2,4	4,1	0,6	1,2	4,1	0,6	1,2	4,1
Tillförd elektricitet pyrolys	1,2	2,4	5	7,2	1,2	2,1	7,2	1,2	2,1	7,2
Varma rökgaser till biopanna	2.5	5,3	10,6	16	2,5	5,1	16	2,5	5,1	16
Brännbar pyrolysgas till biopanna	0,2	0,4	0,7	1	0,16	0,3	1	0,16	0,4	1
Prod. Processånga	29,4	29,4	29,4	29,4	20,3	20,3	20,3	14,6	14,6	14,6
Prod. Elektricitet (totalt)	37,7	37,6	37,6	37,5	26	26	26	18,6	18,6	18,6
Prod. Fjärrvärme (netto)	58,3	57,5	56,3	54,6	40	39,9	36,5	28,5	28	25

EKONOMISKA RESULTAT

Tabell 7 visar ett summerat resultat från investeringsanalysen för en 20 MW pyrolysanläggning. Här ses att inköp av biomassa till pyrolysanläggningen är den största löpande kostnaden per år, men även en måttlig nytillsättning av katalysatormaterial bidrar till en hög rörlig driftskostnad. Produktionskostnaden för 1 kg bio-olja med 30 % fukthalt blir ca 4,70 SEK vilket motsvarar ca 752,1 kr/MWh. Denna kostnad är högre än vad som angivits i (Benjaminsson m.fl. 2013) men samtidigt har bio-oljan i vår studie en högre andel av organiskt kol än existerande kommersiella pyrolystekniker som studerats i referensen. Av denna produktionskostnad så hänförs 0,25 SEK/kg bio-olja till spenderandet av katalysatormaterial och den stora posten, inköp av biomassa är den som bidrar mest till priset på oljan: 2,70 SEK per kg bio-olja. Kan denna post sänkas, d.v.s. att biomassa fås till en billigare kostnad än marknadspriset, kan också kostnaden för produktionen av bio-olja sänkas kraftigt.

I denna ekonomiska sammanställning har det antagits att elektricitet fås gratis från kraftvärmeverket, men som tidigare nämnts kan denna behöva inköpas om verket väljer att sälja all sin producera el (grön el). Vidare har i denna ekonomiska sammanställning inte tagits hänsyn till att det vatten som separeras i efter kondensering av bio-olja från pyrolysgas eventuellt måste renas i en helt egen och ny vattenreningsanläggning. Vi har i vår studie antagit att existerande vattenreningsanläggning skulle kunna hantera detta.

Tabell 7: Ekonomisk analys av integration av katalytisk pyrolys

Investering	*MSEK*
Direkt kapitalkostnad	177,7
Indirekt kapitalkostnad	85,4
Arbetande kapital	13,1
Total projektinvestering	**276**
Drift och underhåll, fasta driftskostnader	*MSEK/år*
Underhåll	4,3
Personalkostnader	4,2
Övriga driftskostnader inkl skatt och försäkring	14,8
Totalt: fasta driftskostnader	**23,4**
Rörliga driftskostnader	*MSEK/år*
Biomassa till pyrolys	70,5
Katalysator	6,5
Vatten	2,2
Totalt: rörliga driftskostnader	**79**
Rörliga och fasta driftskostnader	*MSEK/år*
Totalt	**102,5**
Produktionskostnad bio-olja (SEK/kg)	**4,7**
Produktionskostnad bio-olja (SEK/MWh)	**752,1**

SLUTSATSER

I det här arbetet presenteras ett integreringskoncept för en katalytisk snabbpyrolysis process i en existerande kraftvärmeanläggning för att producera kraft, värme och bio-olja. Integrationen har utvecklats med hjälp av Aspen Plus. Resultaten visar att det är möjligt att integrera en pyrolysanläggning för produktion av bio-olja men vidare studier behövs för att i detalj studera de tekniska begränsningarna i det existerande kraftvärmeverket vid en sådan integration. I det här projektet dras följande slutsatser:

I det existerande kraftvärmeverket kan 20 MW bio-oljeproduktion eller lägre integreras. För en högre produktion finns i dagsläget vissa tekniska begränsningar på utrustning som utan modifiering inte klarar den temperatur och flöde av rökgas som uppstår samt tillförsel av vatten som behövs för den högre produktionstakten.

Ett referensfall har tagits fram om 20 MW och 70 % pannlast som ger maximal oljeproduktion utan att de begräsningar som finns i förvärmare och i vattentillförsel blir gällande. Årligen kan denna pyrolysanläggning producera ca 26 000 ton bio-olja, med en vattenhalt på 30% och ett på värmevärde 23 MJ/kg (total substans). Samtidigt produceras 20 MW processånga, 26 MW elektricitet och 39 MW fjärrvärme.

Produktionskostnaden för bio-oljan i referensfallet blir 4,7 SEK/kg (752,1 SEK/MWh), varav 0,25 SEK/kg är kostnaden för nytillsättning av katalysator och 2,70 SEK är kostnaden för inköpt biomassa.

REFERENSER

Thomas Kohl, Timo P. Laukkanen, Mika P. Järvinen; ”Integration of biomass fast pyrolysis and precedent feedstock steam drying with a municipal combined heat and power plant” Biomass and Bioenergy, Volume 71, 2014, Pages 413-430

G. Benjaminsson, J. Benjaminsson, N. Bengtsson, Gasefuels AB. Decentraliserad produktion av pyrolysolja för transport till storskaliga kraftvärmeverk och förgasningsanläggningar. Gasefuels AB (2013). Tillgänglig på: http://gasefuels.se/media/rapporter/Decentraliserad%20produktion%20av%20pyrolysolja%20f%C3%B6r%20transport%20till%20storskaliga%20kraftv%C3%A4rmeverk%20och%20f%C3%B6rgasningsanl%C3%A4ggningar.pdf . Besökt: November 2015

S. Boust, M Green, S. Machi, Fluidized Catalytic Cracking to Convert Biomass to Fuels , 2015 , University of Pennsylvania, Department of Chemical & Biomolecular Engineering. Tillgänglig på: http://repository.upenn.edu/cbe_sdr/72. Besökt: November 2015.

E. Kantarelis , Catalytic Steam Pyrolysis of Biomass For Production of Liquid Feed stock, Doktorsavhandling (2014).Kungliga Tekniska Högskolan,Institutionen för Materialvetenskap. ISBN 978-91-7595-023-5:_ Tillgänglig på: https://www.divaportal.org/smash/get/diva2:703293/FULLTEXT01.pdf.

Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez, " Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis", 2014 John Wiley & Sons, Ltd. Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries

Summary

In this report, the possibility of integrating a catalytic fast pyrolysis technology to an existing CHP plant with aiming at producing heat, power and bio-oil is studied. Here, the bio-oil is target as petroleum-like liquid with 12% of oxygen, which can be used as crude oil for the existing petroleum refinery, or as fuel oil. The Övik Energi AB CHP plant is used as an example for the study. Experimental data of catalytic fast pyrolysis process are used from the previous KTH research. A process model based on ASPEN Plus is developed.

It is known that the fast pyrolysis of biomass is one way to produce liquid from biomass. This is the most intensively investigated pyrolysis process at present. The key issues are rapid heating and rapid quenching in order to obtain liquid as much as possible. External heat generally is supported by sand in fluidized-bed reactors, or a hot wall such as ablative (vortex and rotating blade) reactor. The main heat transfer modes are conduction and convection. Pyrolysis oil is a dark-brown, free flowing liquid fuel that derived from plant materials such as biomass and waste. Its density is about 1.2kg/litre and heating value is 16-19 GJ/ton. A general problem encountered when using biomass pyrolysis to generated bio oil is that the 'oil' contains a high level of oxygen, including water and water –soluble components. This is not miscible with petroleum-based liquid. Further on, bio-oil generated by fast pyrolysis are very acidic and corrosive and often chemically unstable over time. A higher viscosity of bio-oil also makes it difficult pumping and handling. In order to increase the quality of bio-oil, catalytic fast pyrolysis is employed.

At KTH, a previous research of catalytic fast pyrolysis with steam has been conducted. Using the KTH developed catalysts and the process; it is possible to produce the organic liquid component of the bio-oil with low O/C ratio and having a higher heating value on dry basis of 35.24 MJ/kg.

The CHP plant considered in this study is Hörneborgsverket and it produces electricity, district heat/cooling, and process steam to nearby industries. The CHP plant uses a bubbling fluidized bed boiler from Metso Power and a multiple stage steam condensing extraction turbine with district heat water condenser system. The boiler has a nominal capacity of 130 MW with 540°C and 140 bar live steam parameters. The steam turbine has a nominal electricity output of 40 MW.

The methodology used for the simulation is that first standalone units are modelled using Aspen Plus simulation tool for both the pyrolysis and CHP plants. For the pyrolysis plant: the Bio-oil capacities considered are 5MW,10 MW,20 MW,30 and 40 MW on lower heating value (LHV) basis. For the CHP plant, the part load (PL) operations considered are: 50 %, 60 %, 70 % and 100 %. The standalone units are integrated and there are 20 scenarios simulated. Critical parameters during the integration are also investigated by examining the simulation results. The optimum possible scenario is selected based on the analysis of the critical parameters. A simplified economic analysis is also carried out in order to determine the minimum production cost of the bio-oil produced.

The study has shown that the underutilized boiler capacity of the CHP plant can be made use of during low production seasons as well as during winter at an optimum bio-oil production capacity of 20 MW. The integration process has its limitations and

possibilities as stated in this report and this needs to be further investigated by using the results from this study as an initial step.

Two main limitations were identified:

1. The boiler's flue gas after the air preheater, which should not exceed 80 Nm3/s. This limits how large capacity pyrolysis plant can have.
2. The boiler fuel handling systems which cannot handle flows under 7 kg/s. This limits how low loading degree which can be driven with a given bio-oil production.

The 20 MW bio-oil capacity integrated with the part load operations 60-100 % will enable the plant to run during the winter and part of the summer season if the case of 20 MW-50% PL is seen as a hindrance for integration. On the other hand, if the case of 20 MW-50% PL is seen as a minor problem, the plant will be able to maintain the existing operation hours per year. For higher capacities ≥30MW the critical parameters stated in the results section, have put a limit to the integration concept, however if the influence factors is minimized by further investing in small retrofit activities like in the flue gas condensing section and the need for additional water is also compensated by the added benefits from the integration, then it might be possible to consider higher bio-oil production integrated plant. The total investment cost based on the reference scenario results is 276 Million SEK. The bio-oil production cost and selling price are subject to different factors and the estimated production cost (4.7 SEK/kg or 752.1 SEK/MWh) is only indicative. For full load operation the limiting factor for integration is observed to be the flue gas flow after the air preheater. The bio-oil production cost is sensitive to the feed stock cost and the catalyst replacement rate.

List of content

1 Background

The Combined Heat, Power and Bio-oil (CHPO) is a new theoretical concept, which is based on the use of catalytic pyrolysis for bio-oil production integrated with an existing combined heat and power (CHP) plant. The idea is to improve the overall energy efficiency and increase added value of an existing CHP plant by introducing a third high grade product, Bio-oil, which is processed using fast catalytic pyrolysis process. The generated Bio-oil from this plan is a green fuel and can be used as bio-crude for the existing petroleum refinery and /or as fuel oil to replace fossil fuels. It can be a good candidate to meet the environmental goals in Nordic countries while at the same time serving as revenue generation for CHP plants. In this project, a CHP plant located in Sweden is considered as the case study plant and catalytic fast pyrolysis data coming from the previous work at KTH. It should be noted that the study carried out is theoretical and is subject to changes during practical applications of the results from this study.

1.1 PROBLEM FORMULATION

One big challenge that several lower capacity bio-fuel fired CHP plants located in Nordic countries have in common is that during summer seasons, the plants are forced to either shutdown or operate at very low part-load operations because during such seasons, the heat demand decreases. This means, there is a big boiler capacity that is left unutilized. Besides, regardless of the fact that such CHP plants use well established efficiency technologies that are also environmentally friendly, the increased use of biomass and its associated increased price is becoming a concern for the economy of the CHP plants. These facts alert the CHP industry owners and researchers to seek for other routes that enable utilizing the additional boiler capacities and also investigate for possibilities of producing another profitable product which is not season dependent in order to compensate for the revenue lost during the low part load operation season. The CHPO concept is thus suggested as one means to tackle this problem.

1.2 OBJECTIVES

The main objectives of the CHPO project are:

- Using technically reasonable integration and modeling tool, to determine the economically optimal cogeneration of electricity, heat and bio-oil as a function of seasonality.
- Clarify technical details before a realistic integration of the pyrolysis process
- Develop a technical system scenario for the integrated plant, using commercially available components of pyrolysis process, and implement this in a model using Aspen Plus.
- Optimize operating parameters to determine the optimal cogeneration of electricity, heating and bio-oil annually.
- Publish at least one article in a scientific journal or a conference papers
- Disseminate knowledge through reports, publications, seminars and conferences
- Give attention to the heat and power industry on the integration capabilities of the pyrolysis process to co-produce a third product.

1.3 PYROLYSIS PLANT

Pyrolysis is a thermochemical conversion of organic matter in an oxygen deprived and inert reaction atmosphere. The pyrolysis process produces three major products: a solid residue called char, gases (CO_2, H_2O, CO, C_2H_2, C_2H_4, C_2H_6, C_6H_6, etc) and liquid (tars, heavier hydrocarbons, and water). Depending on different factors like residence time, reaction rate, reaction temperature, etc., the pyrolysis process is categorized into three types: Slow, intermediate and fast/flash pyrolysis processes [1]. The slow pyrolysis process occurs under reaction rates of below 1°C/s, longer residence time and ~400°C. The main product from slow pyrolysis is charcoal. Intermediate pyrolysis occurs in temperature ranges of 300-700°C and residence time range of 10-30 seconds. On the other hand, fast/flash pyrolysis occurs in the reaction temperature range of 425 to 600 °C, heating rates of 1000 to 10,000 °C/s and short residence time <3s. A typical bio-oil yield from a fast/flash pyrolysis process is in the range of 70-75% of the total pyrolysis product [2]. On the other hand, for a biomass with high ash content, the oil yield can drop below 50% [3].

The heat required for fast pyrolysis is reported to be in the range of 1-2 MJ/kg of biomass with 10% moisture content [4]. The heat for pyrolysis is comprised of the sensible heat needed to raise the temperature of the biomass to the pyrolysis reaction temperature and the heat of the pyrolysis reaction.

Several pyrolysis reactors have been developed depending on the need for the type of product required. The modern pyrolyzers are concerned more on the gas and liquid products. The major classification of the different pyrolyzer are: Fixed or moving bed, bubbling fluidized bed (BFB), circulating fluidized bed (CFB), ultra-rapid, rotating cone, ablative and vacuum. For more explanation on the different pyrolzser designs the reader is referred to [2].

The commercial scale pyrolysis reactors in operation are BTG-BTL's Rotating Cone Reactor and Metso's Circulating Fluidized bed pyrolysis reactor [5]. Examples of commercial scale plants based on BTG-BTL's pyrolysis technology include, a 2 t/h (Emply Fruit Bunches as feed stock) fast pyrolysis plant located in Malaysia that produces 1.2 t/h of pyrolysis oil and the full commercial scale (5 t/h wood residue as feed stock) pyrolysis plant , Empyro in Hegelo, Netherlands [6]. The Empyro plant goal is to reach the annual maximum bio-oil production of over 20 million litres of pyrolysis oil [7].

The circulating fluidized bed pyrolysis reactor technology used by Ensyn involves a patented technology called Rapid Thermal Processing (RTP) technology and it has been widely used by Ensyn. The RTP process is similar to the Fluid Catalytic Cracking (FCC) process apart from the fact that Ensyn uses sand instead of catalyst during the pyrolysis of biomass to light liquid product [8].

Referring to industrial scale integrated pyrolysis-CHP units, Fortum's pyrolysis unit integrated with the CHP plant at Joensuu, Finland is the first of its kind in the world in an industrial scale integrated plant with an annual nominal production capacity of 50 000 tons [9]. The installation work had been done by the Finish company Metso which is also a supplier of circulating fluidized bed technologies.

Table 1 summarizes the reactor design types for biomass pyrolysis units worldwide including the capacities, products and owners.

Table 1 Worldwide biomass pyrolysis units [10]

Reactor Design	Capacity (Dry Biomass Feed)	Organization or Company	Products
Fluidized bed	400 kg/hr (11 tons/day)	DynaMotive, Canada	Fuel
	250 kg/hr (6.6 tons/day)	Wellman, UK	Fuel
	20 kg/ hr (0.5 tons/day)	RTI, Canada	Research / Fuels
Circulating Fluidized Bed	1500 kg/hr (40 tons/day)	Red Arrow, WI Ensyn design	Food flavorings / chemicals
	1700 kg/hr (45 tons/day)	Red Arrow, WI Ensyn design	Food flavorings / chemicals
	20 kg/hr (0.5 tons/day)	VTT, Finland Ensyn design	
Rotating Cone	200 kg/hr (5.3 tons/day)	BTG, Netherlands	Research / Fuels
Vacuum	3500 kg/hr (93 tons/day)	Pyrovac, Canada	Pilot scale demonstration / Fuels
Other Types	350 kg/hr (9.3 tons/day)	Fortum, Finland	Research / Fuels

A general problem encountered when using biomass pyrolysis to generated bio oil is that the 'oil' contains a high level of oxygen, including water and water –soluble components. This is not miscible with petroleum-based liquid. Further on, bio oil generated by fast pyrolysis are very acidic and corrosive and often chemically unstable over time. A higher viscosity of bio-oil also makes it difficult pumping and handling.

Therefore, an upgrading process of this kind of oil is needed. Upgrading biomass-derived oils to hydrocarbon fuels requires oxygen removal and molecular weight reduction. This requires that hydrogen is added in the process to increase the H/C ratio of the product and to remove excess oxygen as water. A larger number of conversion processes that utilize heating of the biomass in different types of reaction media with the aim of producing higher quality oil have already been explored, for example, hydro processing in which water or steam acts as the reaction medium and also as a hydrogen donor to some degree. Generally, the process using gaseous hydrogen with different catalysts has been employed. However, there is still lack of efficient route for upgrading needed to produce a motor fuel.

It is obviously that the hydro deoxygenation (HDO) must be emphasized. An efficient and fast HDO process to upgrade biomass-derived oils is the key issue of cost efficient production of bio-oil for produce renewable liquid motor fuel.

The idea of combing the normal pyrolysis process and HDO process into one reactor, i.e., in situ catalytic pyrolysis, is attractive since a petroleum-like oil is produced.

This idea had already been tested by Anellotech and KiOR. Antellotech uses fluidized-bed reactor for the conversion process and a catalyst. KiOR is US based company that had been using Fluid Catalytic Cracking (FCC) type system for producing gasoline and diesel until it recently went bankrupt in November 2014 [11]. GTI (Gas Technology

Institute) has recently introduced a new pilot size catalytic pyrolysis plant using IH²® technology. The thermochemical catalytic process of IH²® technology enables to produce high quality and cost-effective liquid transportation fuel from any type of non-food biomass feed stock. The IH²® pilot plant processes 50 kgs of dry biomass per day[12].

Researchers at KTH also started this work from 2010 under the financial supported by Energimyndigheten (projektnummer 33284-1). Positive results from their research led to the idea of combining of biooil production with heat and power production.

Here it would be nice to highlight for the fast pyrolysis process of biomass, if the final product is diesel ($CH_{1.2}$), the theoretical yield of the diesel depending on very much if extra *hyodgren* is used. This can be described as below.

If the biomass is considered as $C_6H_{12}O_6$, , then the pyrolysis process can be described as:

$$C_6H_{12}O_6 \rightarrow 4.615\ CH_{1.2} + 1.385\ CO_2 + 3.231\ H_2O$$

Where, the biodiesel is represented as $CH_{1.2}$. From this reaction, it can be seen that the maximum yield of oil is 82.89% from energy point of view; this number is 33.85% from mass conversion point of view. The maximum carbon conversion efficiency is 76.69%.

If additional hydrogen is added, then the reaction is changed as

$$C_6H_{12}O_6 + 3.6\ H_2 \rightarrow 6\ CH_{1.2} + 6\ H_2O$$

In this case, the maximum yield of oil is increased till 107.75% from energy point of view; this number is 44% from mass conversion point of view. Then the carbon conversion efficiency is 100%.

For traditionally pyrolysis, the yield of the biooil is much higher, but it is only an intermediate product to diesel.

1.3.1 Experimental facility at KTH

Existing fast catalytic pyrolysis experimental setup at KTH (which had been used during a PhD project [13]) is composed of three major process sections: feeding and pyrolysis reaction, char and vapor separation, vapor quenching and product collection. The type of pyrolzer is bubbling fluidized bed reactor and a cyclone is used for char-vapor separation. The vapor quenching is carried out by means of venture scrubber. The fast pyrolysis process considered uses ZSM-5 zeolite with a SiO_2/Al_2O_3 ratio of 28 and the catalytic material accounts for 0.17% of the bed material. The results of the catalytic steam fast pyrolysis experimental runs have indicated that it is possible to produce the organic liquid component of the bio-oil with low O/C ratio and having a higher heating value on dry basis of 35.24 MJ/kg [13]. The C,H and O compositions in percentages obtained for the weight hourly space velocity (WHSV) of 2 are:- C:9.10±0.61, H: 8.08±0.008 and O:12.82±0.60 [13].

The experimental results from fast pyrolysis experimental facility based from this work [13] are used as input in this study. The inputs used are discussed in detail in section 3.1. . As mentioned earlier, the pyrolysis process considered in this project is a fast pyrolysis process that uses catalyst and steam. The assumed pyrolysis unit is discussed in section 1.3.2.

1.3.2 The assumed pyrolysis unit concept

The general process description for the assumed steam catalytic fast pyrolysis is discussed below. Figure 1 illustrates the simplified schematic diagram of the system.

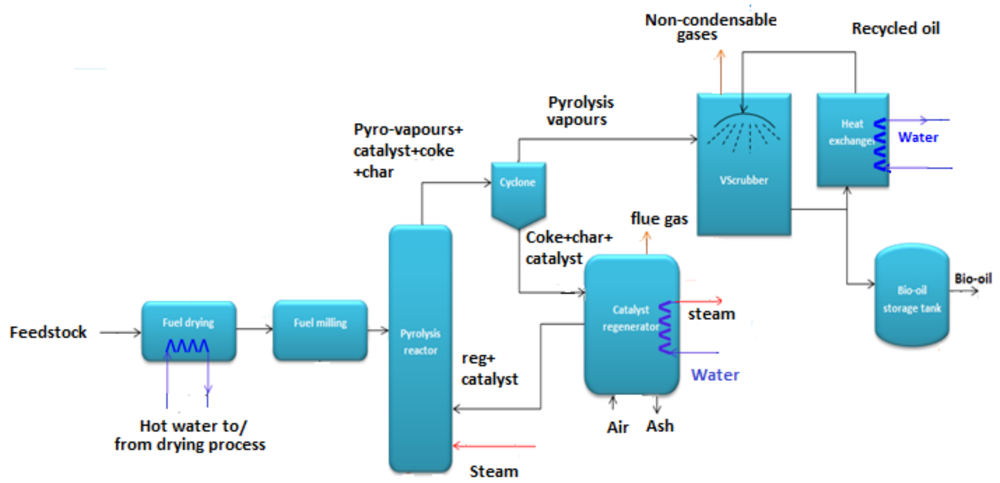


Figure 1 Simplified block diagram of stand alone pyrolysis unit

Referring to Figure 1, the feed stock preparation unit comprises of fuel drying and size reduction sub-units. The fuel drying process can make use of low grade waste heat. The moisture content of the dried feed stock can be in the range of 5-10%. The size reduction section involves grinding/milling process where the goal is that the particle size of the dried feed stock is below 3 mm. The pyrolysis reactor (here considered as circulating fluidized bed), consists of pyrolyzer along with its cyclone. The optimum reaction temperature in the pyrolyzer is 500°C and the pressure is 1.1 bar. The input streams to the pyrolyzer are dried feedstock, steam and regenerated catalyst. The main product streams from the pyrolyzer are pyrolysis vapors and solids (char, coke and spent catalyst). In the cyclone, the pyrolysis vapors are separated from the solid streams and the solids are sent to the catalyst regenerator (which is bubbling fluidized bed reactor) to burn-off the coke from the catalyst surface as well as burn the char. The pyrolysis vapors are led to the vapor quenching section.

In the catalyst regenerator, the combustion of coke and char takes place in the presence of combustion air. The catalyst regenerator's maximum temperature is 700 °C. The main products and byproducts from the catalyst regeneration process are, regenerated catalyst, flue gas and ash. The pyrolysis vapors contain both condensable and non-condensable components. The condensable vapors upon condensation in the vapor quenching tower, become bio-oil. The non-condensable gases also called permanent gases still contain combustible components and can be recycled back to the regenerator or after compressing them, they can serve as fluidizing agent in the pyrolyzer.

1.4 COMBINED HEAT AND POWER (CHP) PLANT

The CHP plant considered as a case study plant is the Övik Energi AB's Hörneborgsverket started year 2009. The CHP plant produces electricity, district heat/cooling, and process steam to nearby industries. Övik Energi AB is a subsidiary under the ownership of Rodret I Örnsköldsvik which is owned by the Örnsköldsvik Municipality. All the street and highway lighting in the Municipality of Örnsköldsvik (amounting 18 300 lighting points) is covered by the production service Övik Energi Nät AB. The process steam and electricity are sold to the nearby industries: Domsjö Fabriker, Akzo Nobel and SEKAB. District cooling customers includes boutiques, hospital and ice-skating courts.

Figure 2 illustrates a simplified schematic diagram of the CHP plant. The preparation of the fuel takes place is done by mixing fuel having high moisture content (like bark) with low moisture content fuel such as saw dust and wood chips. The nominal fuel lower heating value of the mixed fuel is 10.5 MJ/kg with average moisture content of 40%. About 3 % of the fuel feed is removed as ash.

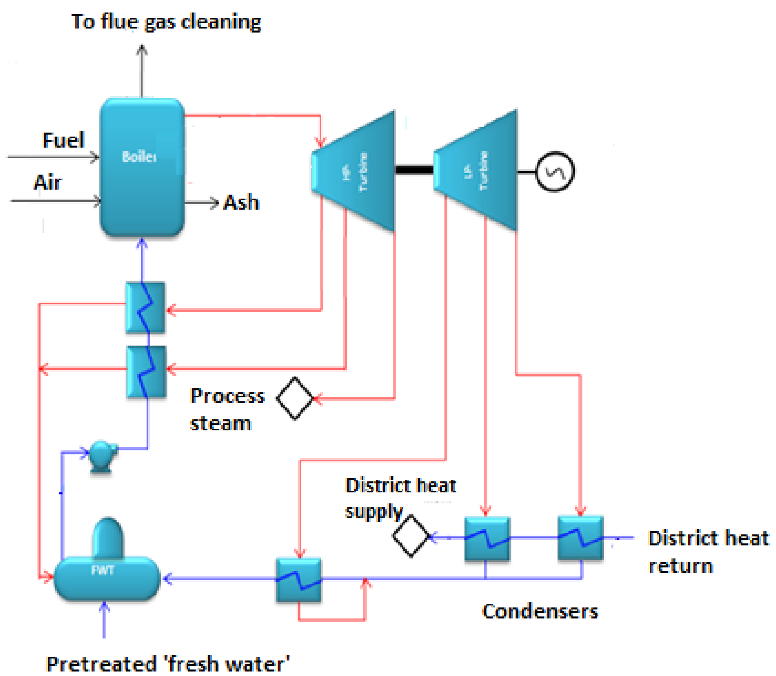


Figure 2 Simplified block diagram of Hörneborgsverket CHP plant

The Hörneborgs CHP plant among others is equipped with a bubbling fluidized bed boiler from Metso Power (see Figure 3) and a multiple stage steam condensing extraction turbine with district heat water condenser system. The boiler has a nominal capacity of 130 MW with 540°C and 140 bar live steam parameters. The boiler bed temperature is regulated using flue gas recirculation system and the goal is to keep it around 700-900°C. The fluidization velocity is about 0.7-1.5 m/s, so that sand particles (except those less than 0.3 mm) do not leave with the flue gases. The fluidized bed boiler has biogas and oil burners integrated in it.

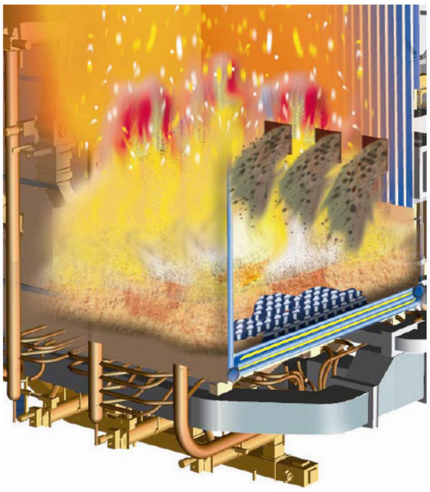


Figure 3 Bubbling fluidized bed boiler

The steam turbine has a maximum capacity of 40 MW electricity productions. The process steam and the district heat together account for 90 MW nominal capacity of the plant. The fuel type used include: bark, woodchips, sawdust, willow and fuel oil for startup or as a back-up fuel. The annual nominal fuel consumption is 1.3 TWh. The operation duration of the CHP plant is 11.5 months per year. The overall efficiency of the CHP plant is 88% and the investment cost is 1 140 MSEK.

The feed water system comprises of the feed water preheaters (i.e., low pressure preheater, feed water tank and the high pressure preheaters). The high pressure feed water preheaters are placed in series and are of vertical type. They utilize two different medium pressure steam extractions (14.8 bar(g) and 26.8 (bar)) for the feed water preheating which at full load operation attains a temperature of 230°C and at a flow rate of 53.7 kg/s. The condensate from these is led to the feed water tank.

The low pressure feed water preheates the feed water before economizer. The feed water system is responsible for delivering dearated feed water to the boiler. The feed water streams entering the feed water tank are: condensates from feed water preheaters dump condenser and the boiler. Demineralized makeup water and also steam is also added to compensate for losses. The feed water tank is kept at saturated state (171 °C and 7.1 bar (g). The district heating system has designed conditions of 16 bar and 120°C.

Annual average operational parameters for the Hörneborgsverket in the year 2014 are discussed below. Figure 4 shows the monthly average values of district heating and cooling loads over a year. It can be seen that for the months April to September the demand for the district heat is quite low.

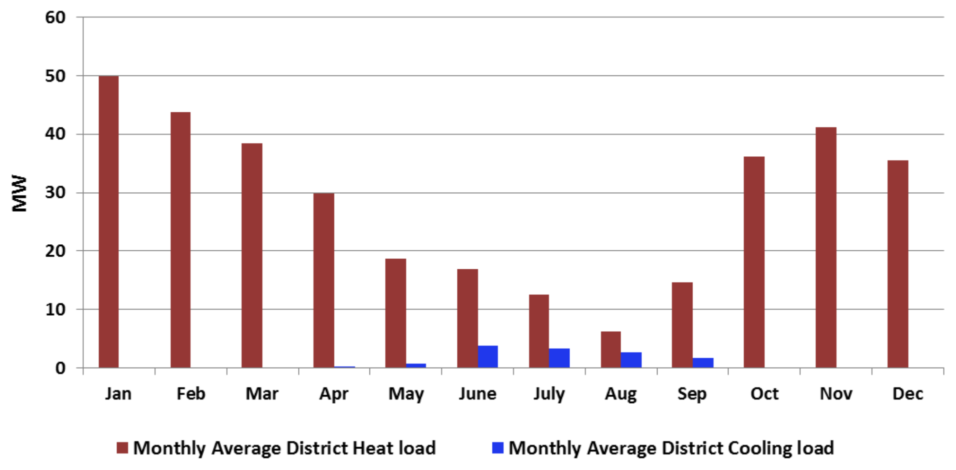


Figure 4 Monthly average district heating/cooling load profile

Figure 5 shows the monthly average values of the district heat supply and return temperatures and it can be seen that the average supply temperature lies in the range of 70-95°C while the average return temperature lies in the range of 40-49°C

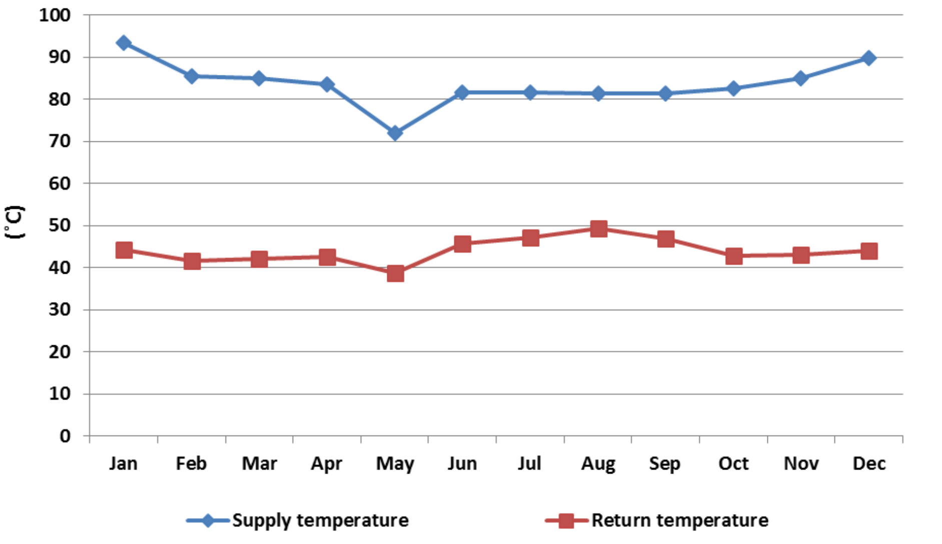


Figure 5 Monthly average values of supply and return temperatures of district heat

Figure 6 shows the monthly average district water volumetric flow over a year along with the average values of the outside temperature. Again the pattern of the water flow is in line with the district heat profile depicted in Figure 4.

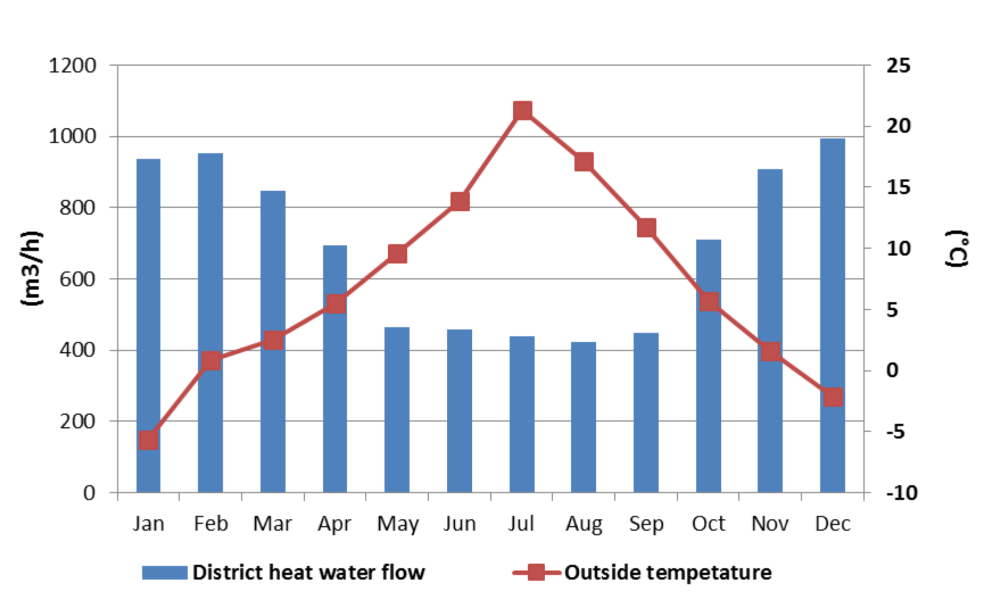


Figure 6 Monthly average district heat water flow and outside temperature

Figure 7 depicts the monthly average values of the boiler thermal power (QB) over a year. Again for the months April to September, the boiler's capacity is underutilized due to the lower district heat needs during these months.

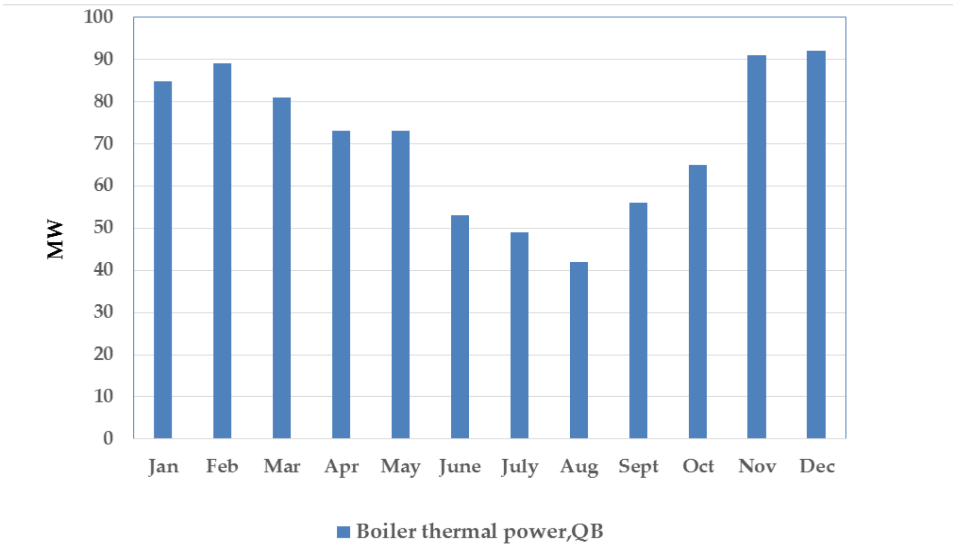


Figure 7 Monthly average values of boiler thermal power

Figure 8 shows the monthly average values of the net electrical power output over a year. The electric power need is also lower during the months April-September similar to the district heat demand.

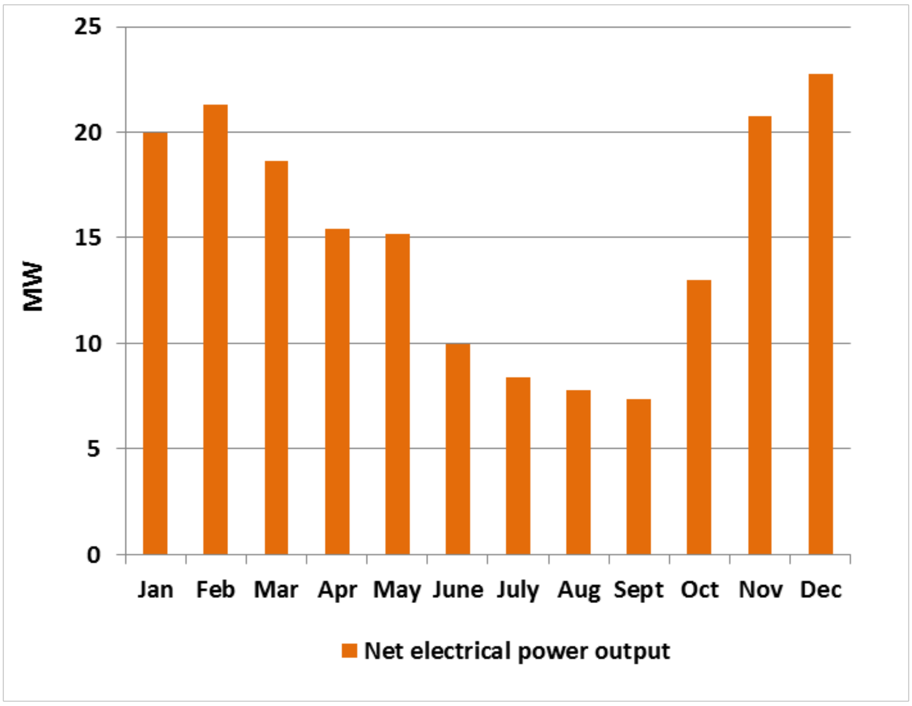


Figure 8 Monthly average values of net electrical power output

Figure 8 shows the monthly average values of the process steam that is delivered to the nearby industries. The delivery of the process steam varies over a year and depends on the demand of the industries' process.

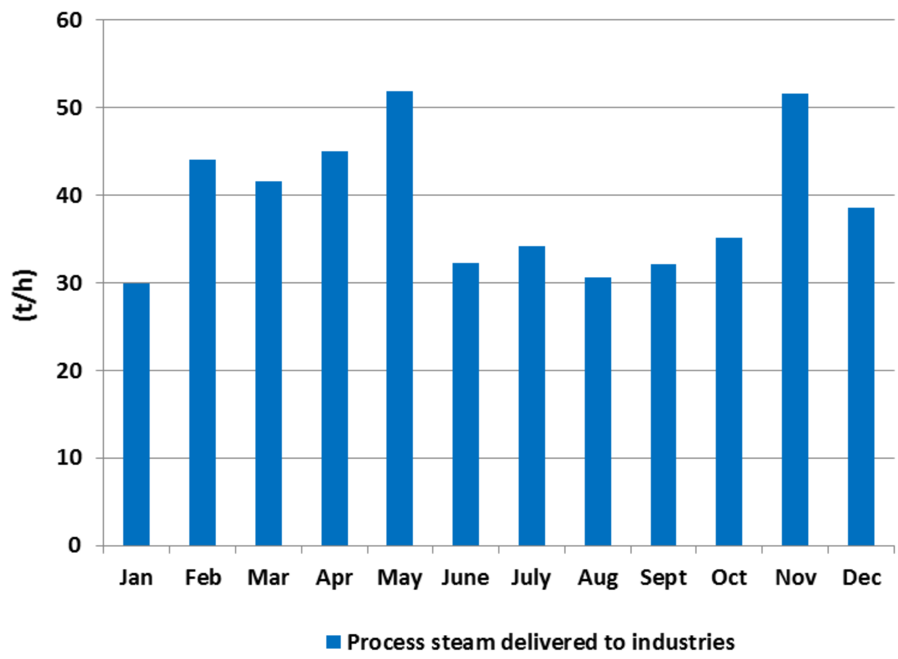


Figure 9 Monthly average values of process steam delivered to industries

1.5 INTEGRATION CONCEPT

The integrated scheme of the pyrolysis and CHP plant is illustrated in Figure 10. The labels in the flowsheet are described in Table 2**.** As can be seen from Figure 10, there are four major blocks of the integrated plant, three of them belonging to the Pyrolysis plant and the remaining representing the CHP plant. For the purpose of simplification and clarity, the CHP plant is not divided into sub-sections. However, this is done for the Aspen Plus simulation flowsheet.

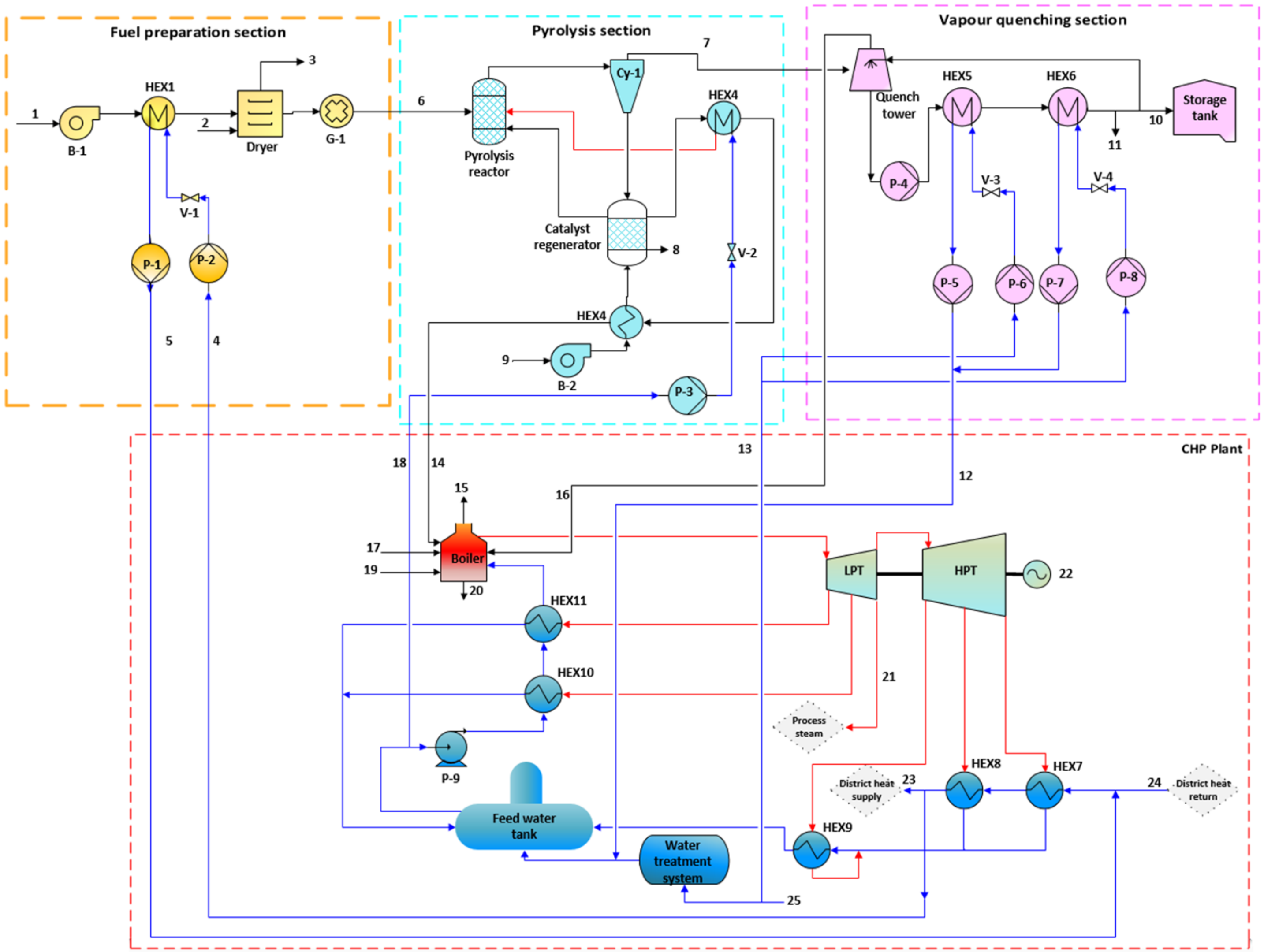


Figure 10 Integrated scheme of pyrolysis and CHP plant

The pyrolysis plant is composed of three main sub-sections: Fuel preparation, pyrolysis and vapor quenching & product cooling sections. The fuel preparation process starts with the ambient air (stream '1') entering the blower and transported to the dryer's heat exchanger section where it is preheated with incoming district heat water. The preheated air further goes to the drying section where the wet feed stock (stream '2') to be dried also enters. The dried feed stock is sent to the grinder for particle size reduction while the moist air (stream '3') is let to the atmosphere. The dried and milled feed stock (stream '6') then enters the pyrolysis section to undergo fast pyrolysis process in circulating fluidized bed reactor in the presence of catalyst and steam. The steam is generated by the heat recovered from the flue gases produced after the combustion (catalyst regeneration) that takes place in a bubbling fluidized bed reactor.

The water for recovering the heat from the flue gases is obtained from the CHP plant's feed water line after the feed water tank. The flue gas after steam generation process is used for preheating the combustion air used in the catalyst regenerator. The final flue gas is then sent to the boiler of the CHP plant to provide oxygen and heat. After the pyrolysis reaction the products (solids and vapor) are sent to cyclone for separating these two streams. The solids contain the spent catalyst, coke and char. These are sent to the catalyst regenerator where combustion process takes place using the air supply at stream '9'.

The ash after the combustion process in the catalyst regenerator is fed out at stream '8'. The pyrolysis vapors (stream '7') continue to the next sub-section: vapor quenching and product cooling. Here the condensable components of the pyrolysis vapors condense to form organic liquid and water which becomes bio-oil. Stream '11' represents waste water that is separated from the bio-oil while (stream '10') is the bio-oil with 30% moisture content. The vapor quenching process takes place in two steps: condensation of the vapor at 80 °C and further condensing them down to 50 °C. The product at 50 °C is then cooled down to 25 °C and the non-condensable gases are sent to the boiler of the CHP plant. The quenching and cooling media is water that is obtained from the CHP plant. This water is returned back to the CHP plant after the quenching process.

The integration points in the schematic diagram are indicated by shaded rows in Table 2. The corresponding labels in Figure 10 for the integration points are: 4, 5, 12, 13, 14, 16 and 18. The overall description for the CHP plant is as discussed earlier in section 1.4. A more detailed process description is presented in section 3.

Table 2 Description of stream labels in the integrated scheme (coloured fields represent the integration points)

Stream labels in Figure 10	Description
1	Feedstock drying air to preheating
2	Feedstock at 31.8 % moisture content
3	Moist air after the drying process
4	Supply water to district heat network
5	Return water from district heat network
6	Feedstock at mean particle size of 1.4 mm
7	Pyrolysis vapors
8	Ash (pyrolysis process)
9	Combustion air to preheating
10	Bio-oil at 30 % moisture content
11	Waste water
12	Return quench and cooling water
13	Supply quench and cooling water
14	Flue gas to boiler
15	Flue gas to scrubbing unit
16	Compressed non-condensable gas to boiler
17	Fuel
18	Water supply for steam generation using flue gas from catalyst regenerator
19	Combustion air to boiler
20	Ash (CHP plant)
21	Process steam to industries
22	Electrical power output
23	District heat supply point
24	District heat return point
25	Fresh water

Potential limiting/critical parameters for integration

When integrating the pyrolysis unit with the CHP plant the most important thing to investigate what design limitations exist (specially related to the boiler). The critical parameters during the integration are obtained after running the simulation for the different scenarios considered. Some of them will be directly reported by Aspen Plus and some are observed by comparing with maximum/minimum design values discussed below:

- **Maximum boiler effect:** 158.5 MW when run 110% on Biomass and 82 MW with EO5 (100% load).
- **Maximum steam flow**: 57.8 kg/s when run 110% on Biomass and 36.5 kg/s with EO5 (100% load).
- **Maximum pressure in the boiler drum**: 154 bar(g) when run 110% on Biomass and 144.5 bar (g) with EO5 (100% load). Tertiary superheater (Max:169 bar).
- **Maximum feed water temperature to the boiler**: 230 °C
- **Maximum flue gas flow including recirculation at 110% load operation:** 80.1 Nm^3/s
- **Maximum air flow:** 52.5 Nm^3/s
- **Maximum fuel flow to the boiler:** 15.1 kg/s
- **Minimum fuel flow to the boiler:** 7.03 kg/s

In addition to the above maximum design parameters, possible limitations for the integration can be need for additional quench water for higher bio-oil production capacities, flue gas flow combined with temperature and fuel flow to the boiler.

2 Methodology

The methodology followed in building Aspen Plus simulations is outlined as follows: The starting step is data collection from the experimental results of the pyrolysis process from literature [13] and registered actual operation parameters of the CHP plant (obtained from field study and e-documents from the factory) which are used as input for the modelling task. Standalone units are modelled using Aspen Plus simulation tool for both the pyrolysis and CHP plants. For the pyrolysis plant: the Bio-oil capacities considered are 5 MW, 10 MW, 20 MW, 30 MW and 40 MW on lower heating value (LHV) basis. For the CHP plant, the part load (PL) operations considered are: 50 %, 60 %, 70 % and 100 %. The standalone units are integrated as 100 % PL with each bio-oil capacity (5 simulations), 70 % PL with each bio-oil capacity (5 simulations), 60 % PL with each bio-oil capacity (5 simulations) and 50 % PL with each bio-oil capacity (5 simulations). Critical parameters during the integration are also investigated by examining the simulation results. The optimum possible scenario is selected based on the analysis of the critical parameters. A simplified economic analysis is also carried out in order to determine the minimum production cost of the bio-oil produced.

2.1 BOUNDARY ACCOUNT

The study does not consider the simulation or analysis of the following areas:

CHP plant: Fuel preparation system, flue gas cleaning process, ash handling system and the treatment of the cooling water system.

Pyrolysis plant: Flue gas cleaning, ash handling and waste water separation and treatment of the pyrolysis plant.

3 Process model descriptions

In this section, the Aspen Plus model description of the integrated scheme of pyrolysis and the Övik Energi CHP plant are presented.

3.1 PYROLYSIS MODEL DESCRIPTION

In this section, the Aspen Plus model description of the pyrolysis unit is presented.

3.1.1 Experimental data obtained for the pyrolysis unit

The mass balance obtained from experimental result is summarized in Table 3.

Table 3 Pyrolysis unit mass balance obtained from experiment. No inert bed material was used.

Stream name	Incoming streams [kg]	Outgoing streams [kg]
Dry feedstock,m_{fs_d}	1000	
Moisture, m_{m_d}	98	
Catalyst, m_{cat_d}	500	500
Steam, m_{st_d}	581	
Coke, m_{coke_d}		73.3
Char, m_{char_d}		180
Organic liquid, m_{OL_d}		243.3
Gas, m_{gas_d}		212.7
Water, m_{wat_d}		969.7
Total	**2179**	**2179**

The values in Table 3 are the basis for all the pyrolysis model simulation. Since the values for the different streams are obtained per 1 ton of dry feedstock, it is necessary to transform the values for feedstock, catalyst and steam into values per unit of time as these values are manually input in the Aspen Plus simulation. This is discussed in the section 3.1.2. As can be seen in Table 3, the conversion efficiency on mass basis of the organic liquid is close to 25%. On the other hand, the low oxygen level in the organic liquid permits the its use as crude oil for the existing petroleum refinery, or as fuel oil. The compositions of the feed stock and char along with their heating values are shown in Table 4. The feed stock for the pyrolysis process is wood chip with a moisture content of 31.8 % before the drying process. After the drying process, the moisture content considered is 8.9 %.

Table 4 Dry basis compositions and heating values of feedstock and char

Parameters	Ultimate analysis [wt_{db}%] Feedstock	Ultimate analysis [wt_{db}%] Char	Parameters	Proximate analysis [wt_{db}%] Feedstock	Proximate analysis [wt_{db}%] Char
Ash	0.31	1.72	Ash	0.31	1.72
Carbon, C	50.55	85.24	Fixed carbon, FC	16.69	16.69
Hydrogen, H	6.4	3.24			
Oxygen, O	42.74	9.8	Volatile matter, VM	83	81.59
LHV* [kJ/kg]$_{db}$	19.2	31.4			

*The lower heating value (LHV) is calculated using the ultimate analysis .

The lower heating values are calculated from the higher heating value using the following equations

The dry basis higher heating value, HHV_d is calculated from

$$HHV_d = 0.341 \cdot C + 1.322 \cdot H - 0.12 \cdot O - 0.12 \cdot N + 0.0686 \cdot S - 0.0153 \cdot Ash \left[\frac{MJ}{kg}\right]$$

The dry basis lower heating value, LHV_d is calculated from

$$LHV_d = HHV_d - 8.936 \cdot \frac{H}{100}\left[\frac{MJ}{kg}\right]$$

The wet basis lower heating value, LHV_d is calculated from

$$LHV_w = LHV_d \cdot \left(1 - \frac{MC}{100}\right) - 2.443 \cdot \frac{MC}{100}\left[\frac{MJ}{kg}\right]$$

Where MC is the moisture content in percent.

$LHV_{dry} = HHV_{dry} - 2.443 \cdot 8.936\ H/100[MJ/kg]$

The C, H and O compositions of the organic liquid along with its components is shown in Table 5.

Table 5 Organic liquid components and compositions

Parameters	Wt_{db} [%]	Major Components in the organic liquid	Estimated wt-fractions
Carbon, C	79.11	Carboxylic acids ($C_2H_4O_2$-1)	0.0341
		Ketons (C_4H_8O)	0.0568
Hydrogen, H	7.66	Furans ($C_5H_4O_2$)	0.2839
		Sugars ($C_6H_{10}O_5$)	0.0057
Oxygen, O	13.19	Phenols (C_6H_6O)	0.1703
		Catechol ($C_{10}H_{14}O_2$)	0.0057
LHV [kJ/kg]$_{db}$	33.85	Guaiacol ($C_7H_8O_2$-E1)	0.0125
		Alcohol (CH_4O)	0.0057
		Aromatic (C_7H_8)	0.4255

The weight fractions shown in Table 5 of the major components in the organic liquid are estimated based on the information obtained from experimental measurement and the reader is referred to the reference Table 9.3 (pp.123 for the case WHSV 2). The summarized data was also shown in Figure 9.5 (pp. 114). It should be noted that the summarized values listed in the Table 9.3 and Figure 9.5 do NOT add up to 100% as some of them were not detected due to the limitation of instrument or time.

The permanent gas (Non-condensable gas) composition is summarized in Table 6.

Table 6 Non-condensable gas compositions

Components	Wt.%	Components	Wt.%
H_2	0.76	C_3H_6	**2.39**
CH_4	5.26	C_2H_2	**0.01**
CO	44.8	iC_4H_{10}	**0.02**
CO_2	42.08	$1\text{-}C_4H_8$	**0.08**
C_2H_4	2.18	CH_3C_2H	**0.04**
C_2H_6	0.42	nC_6H_{14}	**1.57**
C_3H_8	0.38		

3.1.2 Estimation of mass flow rates of other streams in Table 3

As stated earlier, the estimation of the mass flowrate is considered only for streams that are input in the Aspen Plus. These are dry feedstock, catalyst and steam. The starting point for the estimation of the mass flow rates is the assumed values of bio-oil production capacities represented as Q_{BO} (all on LHV basis) : 5 MW,10 MW,20 MW,30 MW, 40 MW and the LHV of bio-oil (@ 30% [1]MC). The bio-oil flow rate, $\dot{m}_{BO}$ is determined from the relation:-

$$\dot{Q}_{BO} = LHV_w \cdot \dot{m}_{BO}$$

Since the assumed organic liquid component of the bio-oil has 70 % share, its flow rate, $\dot{m}_{OL}$ is determined by multiplying $\dot{m}_{BO}$ by 0.7. The dry feed stock flowrate for the different bio-oil production capacities considered is calculated from the equation:-

$$\dot{m}_{fs\_d} = \frac{\dot{m}_{OL}}{\left(m_{OL\_d} / m_{fs\_d} \right)}$$

For each of the bio-oil capacities considered, the corresponding dry feedstock flowrates are calculated and from these, the wet basis feedstock flow rate (before drying process) is obtained using the relation,

$$\dot{m}_{fs\_w} = \frac{\dot{m}_{fs\_d}}{(1 - MC)}$$

Catalyst flow rate, $\dot{m}_{cat}$ is calculated using

$$\dot{m}_{cat} = m_{cat} \cdot \dot{m}_{fs\_d}$$

The catalyst is Zeolite with ratio of SiO_2 to Al_2O_3 equal to 28.

The steam flowrate $\dot{m}_{st}$ is calculated using

$$\dot{m}_{st} = m_{st} \cdot \dot{m}_{fs\_d}$$

The other flowrates of the streams in Table 3 (except that of the feedstock, catalyst and steam) are obtained from the simulation.

3.1.3 Aspen Plus component and block specification for standalone pyrolysis unit

The two major categories of components defined in the simulation are conventional and non-conventional. All other components except the feed stock, char and ash are defined as conventional components. For the non-conventional components, component attributes are input in the form of fuel composition (ultimate, proximate and moisture content. Table 28 in Appendix I[1] illustrate the components for the pyrolysis model as defined in Aspen Plus. The stream class MCINCPSD is selected for all the simulation streams as there are both conventional and non-conventional solid streams with particle size distribution.

PYRO-100: Feedstock preparation section

The feedstock preparation section consists primarily of drying, milling processes. Figure illustrates the feedstock preparation section for the pyrolysis unit. Table 7 summarizes the stream and block numbers in Figure 11 as well as their description.

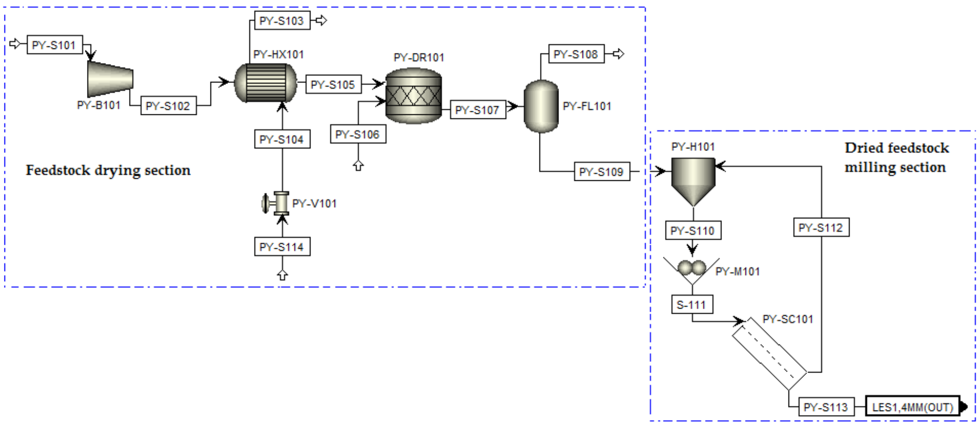


Figure 11 Feedstock preparation section (PYRO-100)

Referring to Figure 11 and Table 7, the drying section consists of air blower, air preheating with district heat water, feedstock drying and flash separation of moist air from the dried feedstock. The milling section contains transportation of the dried feedstock to the mill after which it is sent to a screen where the desired particle size of the dried feedstock is sifted. The coarse particles are led to the hopper for further grinding. The required particle size of the feedstock for the pyrolysis reaction is 1.4 mm.

The RStoic reactor block is modelled to represent the dryer section where the preheated air and the wet feed stock enter and the fortran statement 'PYRFUEL(NCPSD) --> 0.0555084 H2O(MIXED)' is specified for the Rstoic block in order to tell Aspen Plus the conversion factor of the water available in the wet fuel (with the component name 'PYRFUEL').

[1] The Appendix is available for donwloading at www.energiforsk.se

Table 7 Stream and block numbers with description for process section PYRO-100

Stream number	Description	Block number	Description
PY-S101	Fresh air	B-101	Blower
PY-S102	Air to dryer	HEX-101	Heat exchanger
PY-S103	District heat water –return	Dry-101	Dryer
PY-S104	District heat water-supply	Flsh-101	Flash drum
PY-S105	Preheated air	H-101	Hopper
PY-S106	Wet feedstock entering dryer	M-101	Mill
PY-S107	Dried feedstock + moist air	SCR-101	Screen
PY-S108	Moist air		
PY-S109	Dried feedstock		
PY-S110	Fine + coarse		
PY-S111	Ground feedstock to screen		
PY-S112	Coarse		
PY-S113	Feedstock with 1.4 mm particle size		
PY-S114	District heat water supply		

PYRO-200: Pyrolysis section

The pyrolysis unit consists of decomposition of the prepared feedstock, catalyst regeneration, combustion air preheating, steam generation for pyrolysis process (see Figure 12).

The decomposition of the feedstock is simulated using the Ryield block. It was specified that the reaction temperature is 500 °C and pressure is 1.1 bar. As the catalyst is considered inert, the yield distribution of the products is specified in terms of the non-inert feed components as shown in Table 8.

Table 8 Yield distribution specified for Ryield block (PY-DE201)

Component	Wt.fraction	Component	Wt.fraction
H2	0.000975	NC6H14	0.00049
CH4	0.006706	CHAR	0.1072
CO	0.05712	COKE (CIPSD)	0.04366
CO2	0.003046	H2O	0.5777
C2H4	0.05339	CARB-ACI	0.004937
C2H6	0.001069	KETONES	0.008228
C3H8	0.000484	FURANS	0.04114
C3H6	0.003046	SUGARS	0.000823
C2H2	1.00E-05	PHENOLS	0.02469
IC4H10	2.00E-05	CATECHOL	0.000823
1-C4H8	9.80E-05	GUAIACOL	0.00181
CH3C2H	5.27E-05	FURANS	0.04114
ALCOHOL	0.000823		
AROMATIC	0.06166		

The solid components (char, coke and spent catalyst) from the Ryield block are separated from the vapor components in the cyclone (PY-CY201) . The char is decomposed in PY-DE202 block which is also RYIELD block in order to create a stream containing only solid Carbon which is sent to the catalyst regenerator together with the coke (modelled as pure Carbon) and the spent catalyst. Table 9 shows the specification of the char decomposition block.

Table 9 Yield distribution specified for Ryield block (PY-DE202)

Components	Wt.fraction
CARBON (CIPSD)	0.8524
H2	0.0324
O2	0.098
ASH	0.0172

The flue gas from the char decomposition process is sent to the catalyst regeneration process. The catalyst regeneration process is simulated using the Rstoic block and the air flow to the block is manipulated such that the reactor temperature reaches 700 °C. The reactions specified are listed in Table 10.

Table 10 Reaction specification for PY-CO201

Reaction number	Reactions
1	CARBON(CIPSD) + O2(MIXED) --> CO2(MIXED)
2	CARBON(CIPSD) + 0.5 O2(MIXED) --> CO(MIXED)
3	CARBON(CIPSD) + CO2(MIXED) --> 2 CO(MIXED)
4	2 CO(MIXED) + O2(MIXED) --> 2 CO2(MIXED)
5	COKE(CIPSD) + O2(MIXED) --> CO2(MIXED)
6	COKE(CIPSD) + 0.5 O2(MIXED) --> CO(MIXED)
7	COKE(CIPSD) + CO2(MIXED) --> 2 CO(MIXED)
8	2 CO(MIXED) + O2(MIXED) --> 2 CO2(MIXED)
9	H2(MIXED) + 0.5 O2(MIXED) --> H2O(MIXED)

The flue gas from the combustion process in the catalyst regenerator is then used for steam generation in the heat exchanger block PY-HX201. The heat exchanger is specified to have operation temperature of 500 °C. The steam is then sent to the Ryield reactor (PY-DE201). The flue gas is further used to preheat the combustion air entering the heat exchanger PY-HX202. The heat exchanger is specified to have 200 °C. The flue gas from the PY-HX202 is then sent to the CHP plant’s boiler.

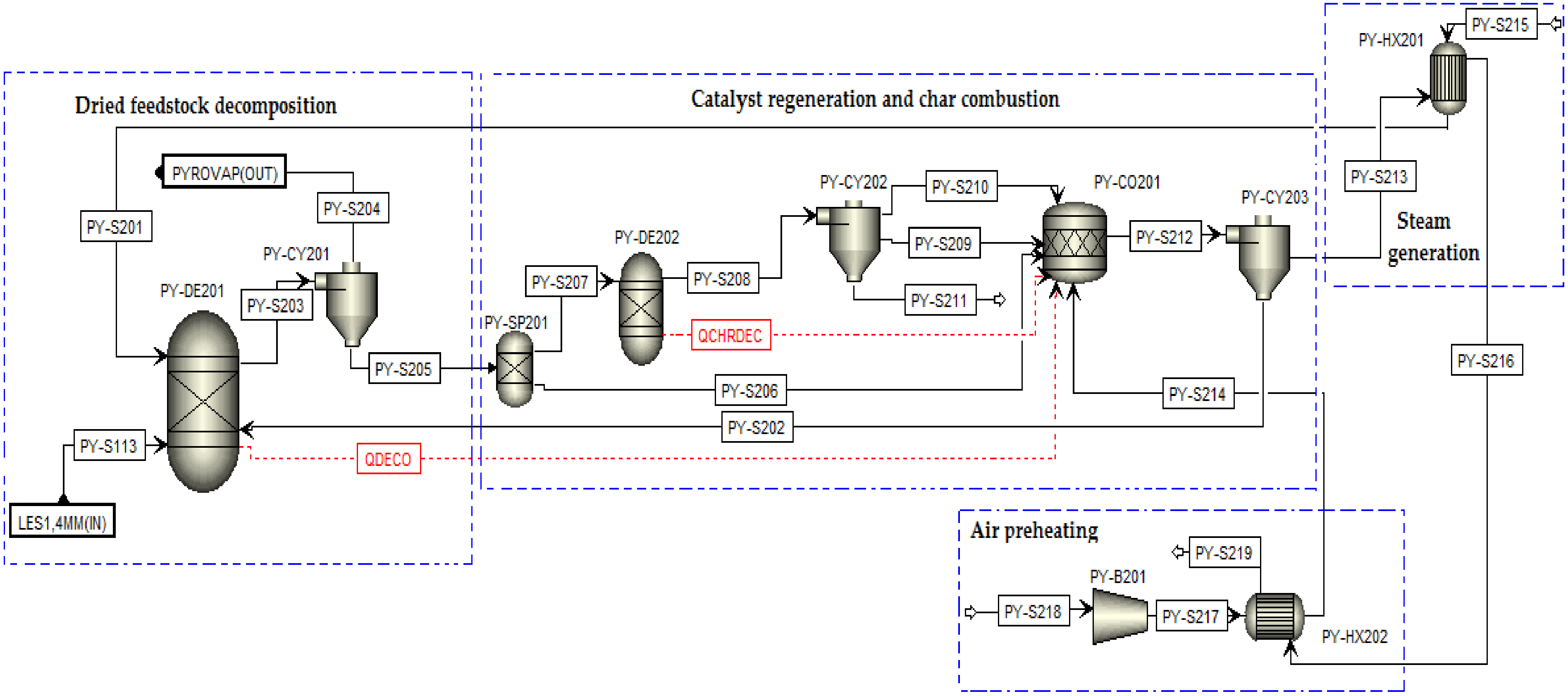


Figure 12 Pyrolysis process section (PYRO-200)

Table 11 summarizes the stream and block descriptions for PYRO-200 depicted in Figure 12.

Table 11 Stream and block numbers with description for process section PYRO-200

Stream number	Description	Block number	Description
PY-S201	Steam to pyrolyzer	PY-DE201	Dried feedstock decomposer
PY-S202	Regenerated catalyst	PY-CY201	Cyclone for separating pyrolysis vapors from solid components
PY-S203	Pyrolysis products	PY-SE201	Separation of the streams 'Char' and 'Catalyst+coke'
	-Bio-oil vapor components -Char -Coke -Catalyst -Non-condensable vapors	PY-DE202	Char decomposer
PY-S204	Pyrolysis vapors	PY-CY202	Cyclone for separating ash, Carbon and oxygen+hydrogen
	-Condensable vapors -Non-condensable vapors	PY-CO201	Combustor for char and coke (catalyst regeneration)
PY-S205	Solid components -Char -Coke -Catalyst	PY-CY203	Cyclone for separating catalyst from fluegas
PY-S206	Spent Catalyst and Coke	PY-HX201	Heat exchanger :Flue gas-Water
PY-S207	Char	PY-HX202	Heat exchanger: Flue gas-Air
PY-S208	Char components -Carbon -Hydrogen -Oxygen		
PY-S209	Flue gas from Char -Hydrogen -Oxygen		
PY-S210	Carbon component of Char		
PY-S211	Ash		
PY-S212	Combustion products from Catalyst regenerator		
PY-S213	Flue gas from catalyst regenerator		
PY-S214	Preheated air to catalyst regenerator		
PY-S215	Water for steam generation		
PY-S216	Flue gas to air preheater		
PY-S217	Air to preheater		
PY-S218	Fresh air to blower 2		
PY-S219	Flue gas to boiler		

PYRO-300: Vapor quenching and product cooling

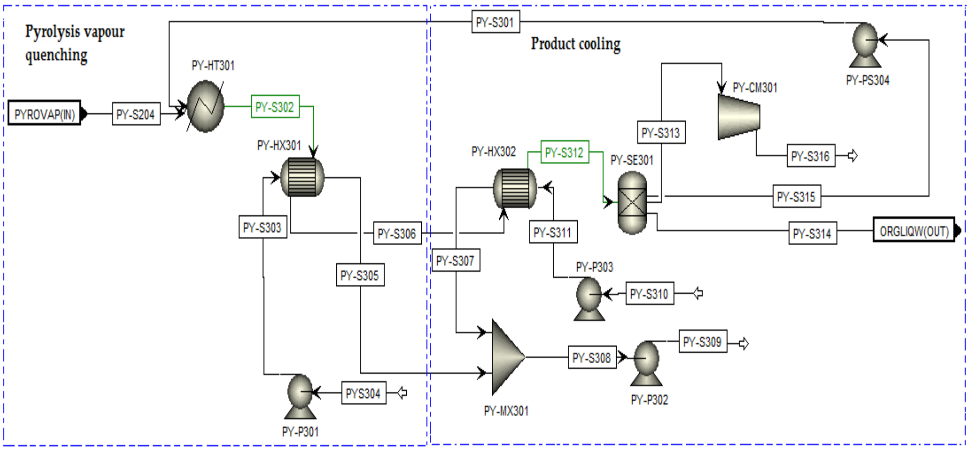


Figure 13 Vapor quenching and product cooling section (PYRO-300)

The vapor quenching of PYRO-300 is simulated as a cooler block PY-HT301 (with the temperature set as 80°C) and heat exchanger PY-HX301 (specified to have countercurrent flow and 50°C). The cooler block receives an already cooled recycled bio-oil having a temperature of 25°C in order to condense the condensable pyrolysis vapors down to 80°C. After the heat exchanger block PY-HX301, the product (containing organic liquid, gas and water) is sent to the product cooling process where the heat exchanger PY-HX302 (specified to have countercurrent flow and 25 °C) is used for the cooling. The non-condensable components (gases) are then compressed and sent to the CHP plant's boiler. The compressor is specified to have a discharge pressure of 4 bar. Table 12 summarizes the stream and block descriptions for PYRO-300 shown in Figure 13.

Table 12 Stream and block numbers with description for process section PYRO-300

Stream number	Description	Block number	Description
PY-S204	Pyrolysis vapors from PYRO-200	PY-HT301	Quench tower
PY-S301	Recycled bio-oil after pump	PY-HX301	Condensor
PY-S302	Partially condensed hot vapors + recycled bio-oil (80 °C)	PY-P301	Pump for quench water supply
PY-S303	Vapor quench water after pump	PY-HX302	Bio-oil cooling heat exchanger
PY-S304	Quench water, before quenching process	PY-MX301	Tank for return cooling and quench water streams
PY-S305	Quench water, after quenching process	PY-P302	Pump for returned cooling and quench water streams
PY-S306	Condensed bio-oil vapors + non-condensable gases (50 °C)	PY-P303	Pump for cooling water supply
PY-S307	Return cooling water	PY-SE301	Separator for gas, bio-oil, recycle bio-oil
PY-S308	Mix of return cooling water and quench water before pump	PY-CM301	Gas compressor
PY-S309	Mix of return cooling water and quench water after pump		
PY-S310	Cooling water before pump		
PY-S311	Cooling water after pump		
PY-S312	Bio-oil (80% MC) and gases at 25 °C		
PY-S313	Non-condensable gases at 25 °C		
PY-S314	Bio-oil with 80 % MC and at 25 °C		
PY-S315	Recycled bio-oil before pump		
PY-S316	Compressed gas		

PYRO-400: Product storage section

The product storage section PYRO-400 is simulated as a waste water separation block PY-SE401 and a storage tank PY-ST401 (see Figure 14). The separator is specified to have a mass fraction of 0.3 for the stream PY-S402 which represents bio-oil with 30% moisture content. The stream PY-S401represents the waste water from the separation process and its treatment or handling is outside the scope of this study and thus not addressed in the analysis.

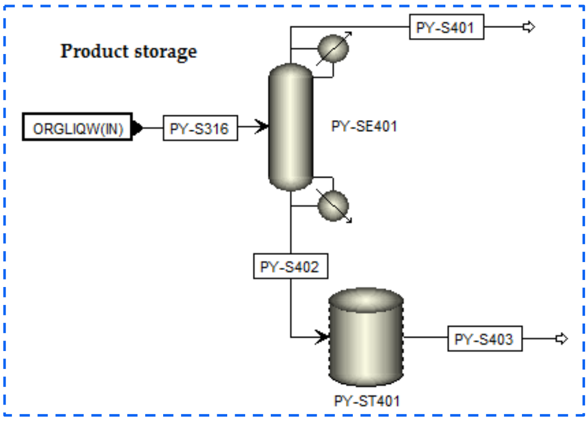


Figure 14 Product storage (PYRO-400)

Table 13 Stream and block numbers with description for process section PYRO-400

Stream number	Description	Block number	Description
PY-S401	Waste water	PY-SE401	Separation unit for Bio-oil and wastewater
PY-S402	Bio-oil with 30 % moisture content to storage	PY-ST401	Bio-oil storage tank
PY-S403	Bio-oil to end users		

3.2 CHP PLANT MODEL DESCRIPTION

In this section, the Aspen Plus model description of the CHP unit is presented. Table 14 shows the dry basis compositions of the fuel to the CHP plant. The moisture content of the fuel entering the boiler is 40%.

Table 14 Dry basis compositions and heating value of fuel to CHP plant

Parameters	Ultimate analysis [wt_{db}%]	Parameters	Proximate analysis [wt_{db}%]
Ash	4	Ash	4
Carbon, C	52	Fixed carbon, FC	16
Hydrogen, H	6		
Nitrogen, N	0.5	Volatile matter, VM	80
Chlorine, Cl	0.04		
Sulfur, S	0.03		
Oxygen, O	37.43		
Lower heating value, LHV_{db}[kJ/kg]	20.5		

Table 15 shows the selected part load operations of the standalone CHP plant and other average actual operation parameters for the selected part load operations. The values presented in the table are taken from actual registered data for the selected dates: Jan 24th (100 %PL), Apr 10th (70 %PL), May 9th (60 %PL) and July 16th (50 %PL). In the integrated plant, the value of the input parameter fuel flow, $\dot{m}_f$ is lowered as flue gas and non-condensable gas streams from the pyrolysis plant are sent to the boiler.

Table 15 Selected part load operation of the standalone CHP plant and average actual operation data

Part loads [%]	T_{amb} [°C]	$T_{DH\text{-}sup}$ [°C]	$T_{DH\text{-}ret}$ [°C]	$\dot{m}_{ps}$ [kg/s]	P_{el} [MW]	$\dot{m}_{DH}$ [m³/h]
100	-14.7	108.43	48.56	11	35.6	1273
70	0.78	86.8	42.5	15	20.7	878.29
60	4.5	82.3	42.2	12	16.3	705.12
50	19	81.8	46.7	13	12.4	420.72

Some selected boiler design parameters (as obtained from the boiler manufacturer's design document) at different part load operations of the CHP plant are presented in Table 16.

Table 16 Selected boiler design parameters

Parameters	Part load operations				
	100 %	80 %	70 %	60 %	50 %
$T_{fg,SH}$ [°C]	1050	985			815
V_{fg} [Nm³/s]	74.1	62.8			50.1
Q_B [MW]	130	104	91	78	65
Q_f [MW]	144	115.2	100.8	86.4	72
$\dot{m}_f$ [kg/s]	13.8	11.04	9.66	8.28	7
$\dot{m}_{st}$ [kg/s]	54.2	43.4	37.94	32.52	27.1
$T_{fg,eco}$ [°C]	291	281			272
Ratio (fluegas recirculation)	18.9	28.8			31.3

3.2.1 CHP-100: Boiler section (fuel decomposition, combustion, flue gas and steam side)

The CHP-100 section contains the fuel decomposition, combustion and air preheating processes. Figure 15 shows the stream and block numbers for CHP-100.

Fuel decomposition

The decomposition of the wet fuel (stream CHP-S101) to the CHP plant is simulated using the Ryield reactor block (DECO-101). The yield distribution of the fuel components is summarized in Table 17. The stream CHP-102 consists of the decomposed components along with their flow rates and is sent to the combustion section.

Table 17 Component yields for Ryield reactor specified in Aspen Plus (DECO-101)

Component	Yield, wt-fraction
ASH	0.024
C	0.312
H2	0.036
N2	0.003
CHLOR	0.00024
S	0.00018
O2	0.22458
H2O	0.4

Combustion

The combustion process is modelled using RGibbs block (COMB-101) and the possible products (H_2O, CO_2, NO_2, SO_2, Chlor, C, H_2, N_2 and O_2) were specified. All these components except C (which is specified as a 'PureSolid' sub-stream) are specified as 'Mixed' sub-streams. The stream CHP-103 which contains the combustion products (flue gas and ash) is sent to the cyclone block CYC-101 for separating the solid component ash (stream CHP-S107) from the flue gas (CHP-S106). The streams PY-S219 and PY-S316 from the pyrolysis process are connected to the combustion block and represent one of the integration points to the CHP plant.

Flue gas and steam sides of the boiler

The boiler section is modelled such that the fluegas side and steam side sub-parts are separately modelled inorder to be able to see the critical parameter behaviours associated with the boiler.

The flue gas side of the boiler is simulated using the heater block 'HT-101' with the outlet stream CHP-S109 representing the flue gas flow after the economizer. The outlet temperature (T_{fg_eco}) for the block is specified based on the boiler design data (Table 16) for the different PL operations. The part of the fluegas stream CHP-S109 is then recirculated (stream CHP-S111) using recirculation fan (in this simulation it is only the outlet temperature that was of interest so this is represented by block SPL-103 and a heater block (HT-103) with a temperature specified at 195 °C). The recirculated flue gas stream is then mixed with an incoming air stream CHP-S113. The purpose of the recirculation is to allow controlling the boiler's sand bed temperature so that it does not to exceed 870°C. The remaining part of the flue gas stream CHP-S123 is sent to the air preheating process. The steam side of the boiler is simulated using the heater block HT-106 and the heat stream QB from the flue gas side is connected to this heater to represent the heat supply from the flue gas to the incoming feed water stream CHP-S125. The stream CHP-124 is the live steam generated after the heat exchange between the flue gas and feed water streams. The heater block HT-106 is specified to have an outlet steam temperature of 540°C and pressure of 140 bar.

Air preheating

The combustion air preheating process starts from the outside air being sucked by fans and blowed to the air canal. The temperature of the outside air is set in the simulation based on the data provided in Table 15. The stream CHP-S119 has its temperature specified as 25 °C and is sent to the block SPL-102 for splitting the air stream into CHP-

S120 and CHP-S121. The split ratio for stream CHP-S120 is 40 %. These two streams are then sent to the air preheating process which is done in two main steps: air preheating using steam and then flue gas. The economizer (not simulated in this project) and the air preheater recover the heat from the flue gas so that the fluegas end temperature before it enters the flue gas scrubber section (not simulated in this project) is 168 °C at full load. The air stream CHP-S120 is preheated using steam in the heater block HT-104 using the heat stream Qair1 which represents the heat provided by the steam. The preheated air stream CHP-S114 is then sent to the exchanger block HEX-101 to further get preheated using the flue gas stream CHP-S115. The heat exchanger is specified to have a countercurrent flow and an outlet temperature of the hot stream as 166 °C. The preheated air stream CHP-S112 from HEX-101 block is then mixed with flue gas (stream CHP-112) and led to the combustor block COMB-101. The flue gas stream CHP-S116 is finally sent to the flue gas scrubbing section which is not considered in this simulation.

The air stream CHP-S121 is preheated first using the heat from steam in stream Qair2 in the heater block HT-105. The preheated air stream CHP-S122 is then led to the heat exchanger block HEX-102 for further preheating using the flue gas stream CHP-S123. The heat exchanger is specified to have a countercurrent flow and an outlet temperature of the hot stream as 168 °C. The final flue gas stream CHP-S117 is then sent to the scrubbing section which is not considered in this simulation.

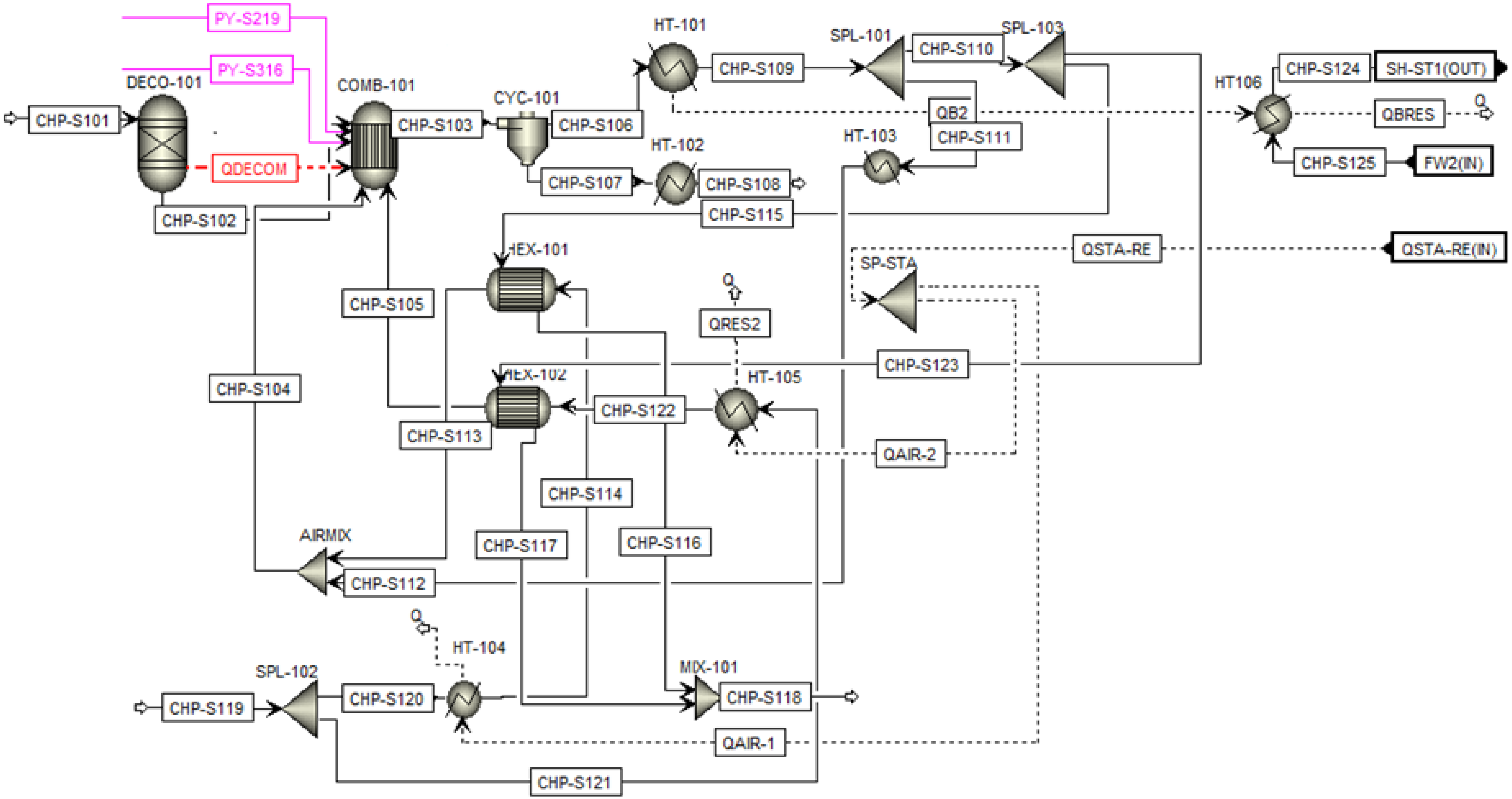


Figure 15 Boiler section CHP-100

Table 18 shows the steam and block names for CHP-100 along with their descriptions.

Table 18 Stream and block names with description (Section CHP-100)

Stream name	Description	Block name	Description
CHP-S101	Wet fuel	AIRMIX	Mixer for fluegas and air
CHP-S102	Components after fuel decomposition	COMB-101	Combustor
CHP-S103	Combustion products	Cyc-101	Cyclone
CHP-S104	Preheated air +flu e gas	DECO-101	Decomposer
CHP-S105	Preheated air	HEX-101	Heat exchanger (air-fluegas)
CHP-S106	Flue gas after cyclone	HEX-102	Heat exchanger (air-fluegas)
CHP-S107	Ash after cyclone	HT-101	Heater
CHP-S108	Final ash out	HT-102	Heater
CHP-S109	Flue gas after heater block HT-101	HT-103	Heater
CHP-S110	Flue gas for air preheating	HT-104	Heater
CHP-S111	Flue gas for mixing with air (before HT-101 block)	HT-105	Heater
CHP-S112	Flue gas for mixing with air (after HT-101 block)	HT-106	Heater
CHP-S113	Air after HEX-101 block	MIX-101	Flue gas stream mixer
CHP-S114	Air to HEX-101 block	SPL-101	Flue gas stream splitter
CHP-S115	Flue gas to HEX-101	SPL-102	Air stream splitter
CHP-S116	Flue gas after HEX-101	SPL-103	Flue gas stream splitter
CHP-S117	Flue gas after HEX-102	SP-STA	Steam stream splitter
CHP-S118	Total flue gas stream to scrubber unit		
CHP-S119	Fresh air from outside (total flow)		
CHP-S120	Air stream (40 % of total air flow)		
CHP-S121	Air stream (60 % of total air flow)		
CHP-S122	Steam preheated air to HEX-102 block		
CHP-S123	Flue gas to HEX-102		
CHP-S124	Superheated steam		
CHP-S125	Feed water (total flow)		

3.2.2 CHP-200: Feed water system

The feed water system in section CHP-200 of the simulation mainly consists of fresh water supply sub-system, district heat water preheating, and boiler feed water preheating stages. Figure 16 illustrates the flowsheet of the CHP-200 section and the description of the stream labels in the figure is summarized in Table 19.

As can be seen in Figure 16, the fresh water supply stream CHP-S201 is divided into three streams where the lines in pink color represent the integration points with the pyrolysis vapor quenching and product cooling processes. The fresh water temperature is set to be 4°C for all the part load operations of the CHP plant simulations. The stream CHP-202 enters water demineralization system where its temperature is raised and is sent to the de-ionization tank which is before the feed water tank. The feed water from the deionizationtank undergoes preheating process steps. For the purpose of simplification, the detailed simulation of these systems is not considered in the simulation however the possible outlet temperature of the feed water (coming from these sub-systems) before it enters the feed water tank is set to be 77 °C in the simulation. Similarly, the outlet temperature for the demineralization system is set to be 50 °C.

The high pressure feed water preheater blocks HEX-201 and HEX-202 are specified to have countercurrent flows and for the first heat exchanger, the hot stream outlet vapor fraction is set to be zero while for the second heat exchanger , the hot outlet-cold inlet temperature difference is set to be 5.1 °C.

The low pressure feed water preheater block HEX-203 is specified to have Hot / cold outlet temperature approach as 10 °C with countercurrent flow direction. For the dump condenser HEX-204 and the two district heat water condensers (HEX-205 and HEX-206), the hot stream outlet vapor fraction is set as zero to represent an outlet stream of saturated liquid water.

The two major incoming stream categories of the feed water tank are condensates (from high pressure feed water preheaters, low pressure feed water preheater, district heat water preheating system) and the fresh water system. The feed water tank is designed to have operation conditions of 171 °C and 8.1 bar and so in the simulation, under the 'flash options', the estimated temperature is input as 171 °C.

The rest of the specifications (if not specified in Table 19) either for streams or blocks is dependent on the part load operations and are provided during the description of the models.

Table 19 Stream and block names with description for section CHP-200

Stream	Description	Stream	Description	Block	Description
CHP-S201	Fresh water 4°C	CHP-S223	Steam extraction to HEX-202 block,328°C and 27.8 bar	HEAT-201	Demineralization unit, 50 °C
CHP-S202	Water to demineralization unit	CHP-S224	Steam for air preheating entering HEAT-204	HEAT-202	De-ionizationsystem,77 °C and 11.5 bar
CHP-S203	Preheated clean water to deionization tank	CHP-S225	Stream at 200 °C and 9 bar entering steam side of air preheater HEAT-205	HEAT-203	Heater block, 197 °C and 8.1 bar
CHP-S204	Mixture of water from pyrolysis unit and stream	CHP-S226	Steam extraction at 139 °C and 3 bar to feed water preheater HEX-203 block	HEAT-204	Steam side of air preheater, 200 °C and 9 bar
CHP-S205	Mixture of water from pyrolysis unit and stream	CHP-S227	Condensate from HEX-203 block	HEAT-205	Steam side of air preheater, 9 bar
CHP-S206	Feed water from Deionization system	CHP-S228	Mixture of two condensate lines from district heat network system	HEX-201	High pressure feed water preheating heat exchanger 1
CHP-S207	Condensate from district heating network	CHP-S229	Condensate to MIX-205 block	HEX-202	High pressure feed water preheating heat exchanger 2
CHP-S208	Condensate from feed water preheater HEX-203	CHP-S230	Condensate from HEX-205 block	HEX-203	Low pressure Feed water preheater before feed water tank
CHP-S209	Feed water stream after MIX-202	CHP-S231	Condensate from HEX-206 block to MIX-205	HEX-204	Dump condensor
CHP-S210	Condensate from feed water preheaters HEX-201	CHP-S232	Preheated district heat water entering HEX-205 block	HEX-205	District heat water preheater
CHP-S211	Steam extraction to feed water tank	CHP-S233	Low pressure steam extraction to HEX-205 block	HEX-206	District heat water preheater
CHP-S212	Condensate from steam used for air preheating	CHP-S234	Preheated district heat water entering dump condensor	MIX-201	Mixing point for return streams CHP-S203 and PY-S309
CHP-S213	Total flow of feed water	CHP-S235	Final district heat water to district heat distribution network	MIX-202	Mixing point for condensates and feed water streams
CHP-S214	Heat stream to air preheating	CHP-S236	Extracted steam with reduced pressure entering block HEX-204	MIX-203	Feed water tank
CHP-S215	Feed water entering feed water pump	CHP-S237	Steam extraction to dump condensor	MIX-204	Mixing point for streams CHP-S219 and CHP-S218
CHP-S216	Feed water to preheater HEX-201 block	CHP-S238	Exhaust steam entering block HEX-206	MIX-205	Mixing point for condensates from blocks HEX-205 and HEX-206
CHP-S217	Steam extraction,261°C and 16 bar	CHP-S239	District heat water total flow (including PY-S103) to block HEX-206	MIX-206	Mixing point for return water streams from district heat network
CHP-S218	Condensate from HEX-201 block	CHP-S240	District heat water return from existing users (other than the pyrolysis unit)	PUMP-201	Dejonat system pump,11.5 bar
CHP-S219	Condensate from HEX-202 block	CHP-S241	District heat supply to existing users (other than the pyrolysis unit)	PUMP-202	Feed water pump, 140 °C,79 % efficiency
CHP-S220	Preheated feed water from HEX-201 block			SPL-201	Split point for fresh water streams
CHP-S221	Final preheated feed water to boiler			SPL-202	Split point for feed water streams (PY-S215 and CHP-S215)
				SPL-203	Split point for supply water streams to district heat network
				V-201	Valve, 3.17 bar

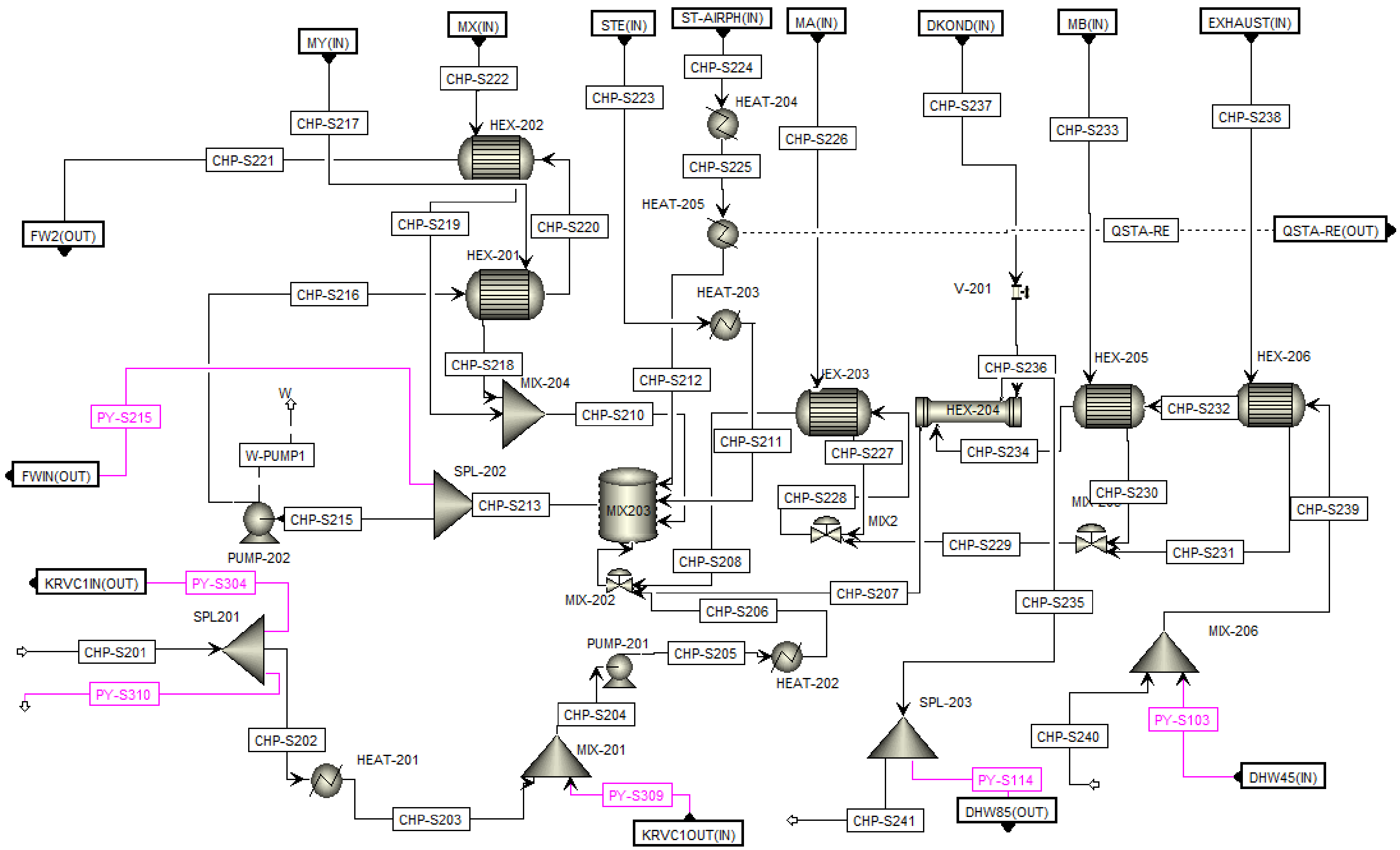


Figure 16 Feed water system (section CHP-200)

3.2.3 CHP-300: Electric power generation system

This section describes the power generation unit of the CHP plant. The turbine is a multi-stage steam extraction condensing turbine simulated as illustrated in Figure 17. The stream and block numbers in Figure 17 are presented in Table 20.

The turbine has six extraction stages and due to limitation of availability of a turbine block with such multiple stages, the simulation is done by modelling individual turbine stages as small turbines with steam extractions. The electrical power outputs from the individual small turbines is then sent to a mixer inorder to obtained the sum of the individual power outputs.

The simulation is such that the first three turbines (blocks T-301,T-302 and T-303) represent the high pressure stages of the big turbine and the remaining three (blocks T-304,T-304 and T-306) represent the low pressure stages. The high pressure staged turbines are specified to have an isentropic efficiency of 87 % and mechanical efficiency of 98 % whereas the low pressure staged turbines are specified to have an isentropic efficiency of 62 % and mechanical efficiency of 98 %.

Specification of high pressure turbine stages
Block T-301 represents the first stage of the big turbine and it is specified to have a pressure of 28.34 bar. Block T-302 represents the second stage of the big turbine and is specified to have a pressure of 16.35 bar. Block T-303 represents the fourth stage of the big turbine and is specified to have a pressure of 9.48 bar.

Specification of low pressure turbine stages
Block T-304 represents the fourth stage of the big turbine and it is specified to have a pressure of 4.15 bar. Block T-305 represents the fifth stage of the big turbine and is specified to have a pressure of 1.46 bar. Block T-306 represents the sixth stage of the big turbine and is specified to have a pressure of 0.85 bar.

Specification of the split blocks connected to the turbines
Block SPL-301 is specified to have a split fraction of 0.062 for stream CHP-222. Block SPL-302 is specified to have a split fraction of 0.05234 for stream CHP-S217. Block SPL-303 is specified to have the split fractions: 0.4041, 0.1123, 0.07858 and 0.05613 for the streams: CHP-S307, CHP-S223, CHP-S237 and CHP-S224 respectively. Block SPL-304 is specified to have a split fraction of 0.09331 for stream CHP-S226. Block SPL-305 is specified to have a split fraction of 0.5663 for stream CHP-233.

Table 29 in Appendix I[2] illustrate the components for the integrated model as defined in Aspen Plus. For the CHP plant, all components except the fuel and ash are specified as conventional components.

[2] The Appendix is available for donwloading at www.energiforsk.se

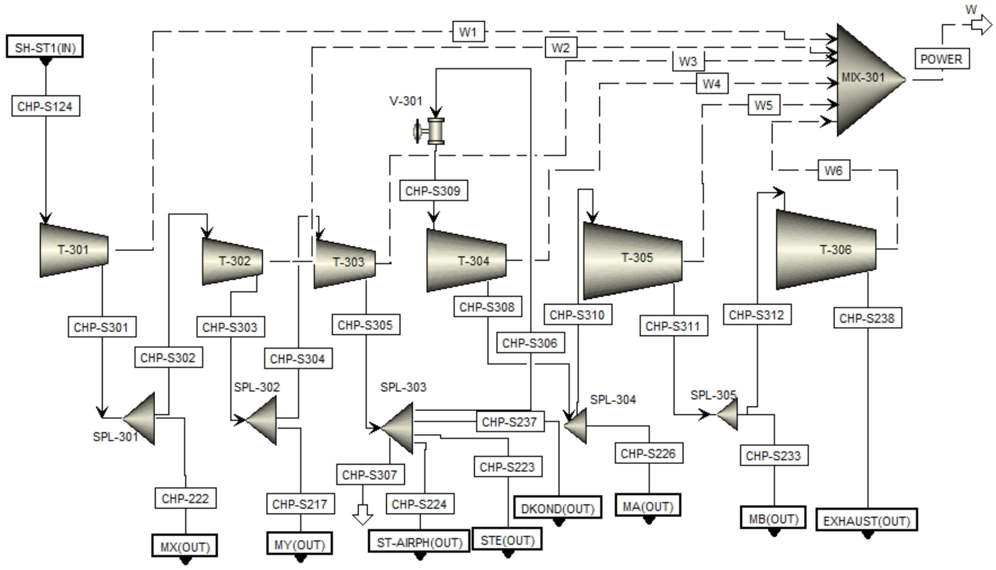


Figure 17 Power generation section (CHP-300)

Table 20 Stream and block descriptions for CHP-300

Stream name	Description	Block name	Description
CHP-S301	Exhaust steam from 1st turbine stage	Mix-301	Mixing point for the individual electrical power generated from each stage of the turbine
CHP-S302	Incoming steam to 2nd turbine stage	SPL-301	Splitter for stream CHP-S301
CHP-S303	Exhaust steam from 2nd turbine stage	SPL-302	Splitter for stream CHP-S303
CHP-S304	Incoming steam to 3rd turbine stage	SPL-303	Splitter for stream CHP-S305
CHP-S305	Exhaust steam from 3rd turbine stage	SPL-304	Splitter for stream CHP-S308
CHP-S306	Incoming steam to 4th turbine stage before block V-301	SPL-305	Splitter for stream CHP-S311
CHP-S307	Process steam delivered to nearby industries	T-301	1st stage high pressure turbine section
CHP-S308	Exhaust steam from 4th turbine stage	T-302	2nd stage high pressure turbine section
CHP-S309	Incoming steam to 4th turbine stage after block V-301	T-303	3rd stage high pressure turbine section
CHP-S310	Incoming steam to 5th turbine stage	T-304	4th stage high pressure turbine section
CHP-S311	Exhaust steam from 5th turbine stage	T-305	5th stage high pressure turbine section
CHP-S312	Incoming steam to 6th turbine stage	T-306	6th stage high pressure turbine section
		V-301	Valve

4 Economic analysis

The economic analysis is carried out by considering the reference case scenario results. The major Components of the pyrolysis unit are listed in Table 21.

Table 21 Major components of the pyrolysis unit

Section	Major Components	
PYRO-100	B-101	Blower
	HEX-101	Heat exchanger
	Dry-101	Dryer
	Flsh-101	Flash drum
	H-101	Hopper
	M-101	Mill
	SCR-101	Screen
PYRO-200	PY-DE201	Dried feedstock decomposer
	PY-CY201	Cyclone for separating pyrolysis vapors from solid components
	PY-SE201	Separation of the streams 'Char' and 'Catalyst+coke'
	PY-DE202	Char decomposer
	PY-CY202	Cyclone for separating ash, Carbon and oxygen+hydrogen
	PY-CO201	Combustor for char and coke (catalyst regeneration)
	PY-CY203	Cyclone for separating catalyst from fluegas
	PY-HX201	Heat exchanger :Flue gas-Water
	PY-HX202	Heat exchanger: Flue gas-Air
PYRO-300	PY-HT301	Quench tower
	PY-HX301	Condensor
	PY-P301	Pump for quench water supply
	PY-HX302	Bio-oil cooling heat exchanger
	PY-MX301	Tank for return cooling and quench water streams
	PY-P302	Pump for returned cooling and quench water streams
	PY-P303	Pump for cooling water supply
	PY-SE301	Separator for gas, bio-oil, recycle bio-oil
	PY-CM301	Gas compressor
PYRO-400	PY-SE401	Separation unit for Bio-oil and wastewater
	PY-ST401	Bio-oil storage tank

4.1 ESTIMATION OF THE PRODUCTION COST OF BIO-OIL

The methodology for the estimation of the production cost of the bio-oil is discussed below:

Capital cost estimation

The capital cost estimation is done using economies of scale calculation. The assumption is that the equipment or unit operations of an existing system can be scaled up or down. A scaling factor R = 0.7 is used in the following relation:

$$\frac{COST_{size2}}{COST_{size1}} = \left(\frac{SIZE_2}{SIZE_1}\right)^R$$

Where **$SIZE_1$** is the capacity of the base system

$COST_{size1}$ is the cost of the base system

$SIZE_2$ is the capacity of the system after scaling up/down

$COST_{size2}$ is the cost of the system after scaling up/down

R is the scaling factor.

The base system used in this project is Fortum's fast pyrolysis-CHP integrated plant at Joensuu in Finland.

The nominal bio-oil production capacity of this plant is 30 MW and the annual production rate is 50 000 tons. The capital investment cost of this plant is €30 million. In the integrated plant Övik Energi, the annual bio-oil production capacity could be 26 231 tons, considering the reference case. It is assumed that the pyrolysis plant operates year round as the existing stand-alone CHP plant (i.e. 11.5 months per year).

Indirect capital costs

Contingency (3% of direct capital cost), construction (25% of direct capital cost) and Field expenses (20% of direct capital cost)

Working capital is 5% of the sum of Direct and Indirect capital costs.

Operating costs

These are categorized as fixed and variable costs. The considered fixed costs are: Maintenance (5% of indirect capital costs), Labour cost (see result summary sheet for the cost break down and the salary supplement is considered to be 55 %), Laboratory costs (20% of labour cost), Supervision (20 % of Labour cost), Plant overheads (50% of labour costs), Capital charges (10% of indirect capital costs), Insurance (1 % of indirect capital costs) and Tax (2 % of indirect capital costs).

The variable costs are Feedstock cost (186 SEK/MWh or at 31.8 % MC becomes 637 SEK/t), Fresh catalyst amounting 75 712kg per year (at 85.2 SEK/kg and an assumed replacement rate of 0.2% every hour). The cooling water used for the pyrolysis unit is obtained from the existing cooling water circuit in the CHP plant and for the reference case, no additional water is accounted for except for the stream used to recover heat from the catalyst regenerator.

Notes:

Feed stock flow (at 31.8 % MC): 3.72 kg/s (or 110.6 Million kg every year)

Catalyst flow: 1.27 kg/s. Thus, 75 712kg fresh catalyst needs to be supplied as replacement annually. The cost of Zeolite catalyst is $10/kg [10] and the assumed catalyst replacement rate is 0.2% every hour [10].

Water used for steam generation (pyrolysis unit): 1.476 kg/s (or 44 Million kg every year)

Cost of production = (Annualized capital cost + Annual operating cost)/Production rate

The annualized capital cost is calculated by multiplying the capital cost in Table 22 by the capital recovery factor 0.08 (considering 15 year's loan at 6% interest rate). The capital recovery factor, CR is calculated from

$CR = \frac{i \cdot (1+i)^n}{(1+i)^n - 1}$ Where n is the number of years and i is the interest rate.

4.2 SENSITIVITY ANALYSIS

The sensitivity analysis is carried out to see how the bio-oil production cost varies with feed stock cost , contingency and catalyst replacement rate. The feed stock price between 600 SEK/t and 800 SEK/t. The Contigency is varied from 3% to 10 %. The catalyst replacement rate is varied from 0.2% per hour to 1% per hour.

4.3 MARKET

In this project, the primary goal with the end use is in the transportation sector. Several literatures have expressed that the bio-oil has a potential to replace heavy fuel oil in boilers. The wide ranges of applications of bio-oil are discussed in different literature. Combined heat and power plants are one application area and substitution of hydrocarbon fuels has been tested but not yet commercialized. The cost of bio-oils is relatively higher than fossil based fuels.

The bio-crude oil from conventional fast pyrolysis processes needs to be upgraded to get higher value transportation fuel. Unlike the case of the organic component of the bio-oil produced using conventional fast pyrolysis process, the type of organic liquid component considered in this study is considered a higher grade fuel which makes it a good candidate for transportation sector specially in more advanced technologies (like internal combustion engines) where the quality of the fuel is very critical. In contrary to the high quality that the organic liquid obtained from the steam catalytic fast pyrolysis process, the other challenge in handling the bio-oil is the large amount of water that comes as a product. This large amount of water is mainly due to the steam used initially and the separation of the water as a waste water stream incurs additional costs. As mentioned previously this analysis is outside the scope of this project.

The most recommended route in order to upgrade bio-oil to higher grade fuel that can be used in the transportation sector involves de-oxygenation and reforming processes which can result in higher heating value. The organic liquid considered in this study is assumed to have a relatively lower oxygen content and the higher heating value on dry basis is in the order of 35 MJ/kg. Thus, the quality of the organic liquid is undoubtedly competent as any other fuel in the transportation sector. The only challenge will be the separation of the waste water. Overviews of these applications are provided below. Some pilot scale experimental studies have indicated the huge potential that bio-oil has in becoming fuel input in combustion processes ,diesel engines, turbines, etc. with minor modification of the existing units. It is thus possible to consider the bio-oil from catalytic steam fast pyrolysis process to have even bigger application areas than the conventionally produced bio-oil.

According to the information provided in [10], the production cost for the different plant capacities lies in the range of $0.1-0.6 per kg. On the other hand, a study done on seven standalone pyrolysis processing plants has indicated that the production cost of bio-oil per MWh bio-oil is in the range of 400-600 SEK/MWh [5]. The price for biomass derived oils like vegetable oils ranges between 560-900 SEK/MWh. The cost for EO5 is 480 SEK/MWh and heavy bio-oils is 560 SEK/MWh [5].

5 Results and discussion

The simulation results for the different scenarios considered in this project are presented in the following-sections where the first section summarizes the results for the reference case scenario and the second section summarizes the results for the remaining scenarios.

5.1 RESULTS OF REFERENCE CASE SCENARIO

The results of the reference case scenario (i.e., 20 MW_{LHV} bio-oil plant integrated with 70 % part load CHP plant) are summarized in Tables 21 and 22.

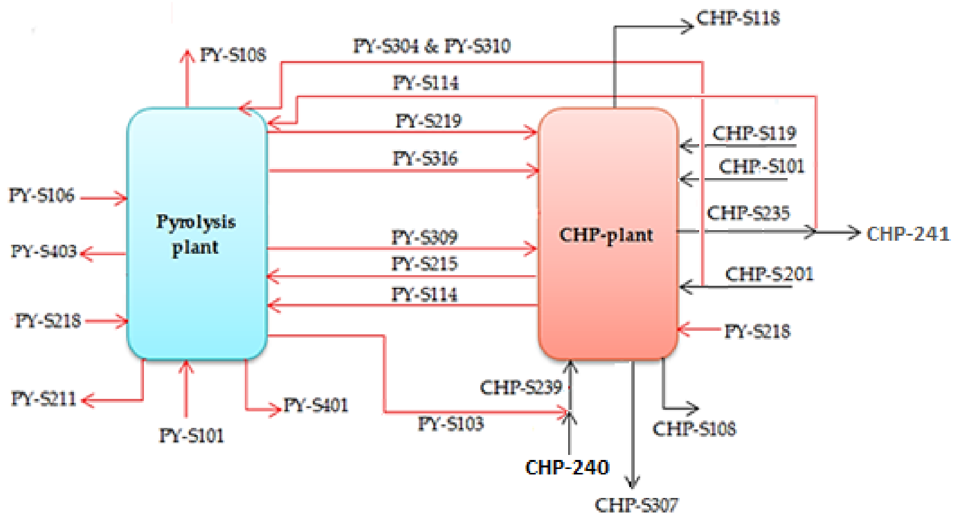


Figure 18 Simplified scheme diagram for the integrated plant (for mass balance)

Table 22 summarizes the mass balances in accordance with the stream labels in Figure 10.

Table 22 Overall mass balance for Reference case scenario. MF is Mass flow.

Inlet stream			Outlet stream			Intermediate stream		
Id	**Note**	**MF, kg/s**	**Id**	**Note**	**MF, kg/s**	**Id**	**Note**	**MF, kg/s**
PY-S106	Wet fuel (@ 31.8 MC)	3.72	PY-S211	Ash	0.01	PY-S304	Incoming quench water	5.22
PY-S101	Fresh air (to drying section)	52.05	PY-S108	Moist air	53	PY-S310	Incoming product cooling water	3.48
PY-S218	Fresh air (to Catalyst regeneration)	26.25	PY-S401	Waste water	2.20	PY-S114	District heat supply (to drying section)	13.59
			PY-403	Bio-oil (@ 30% MC)	0.88	PY-S219	Flue gas to boiler	26.88
CHP-S239	Return district heat (total)	251.93	CHP-S118	Flue gas (to cleaning section)	95.7	PY-S316	Compressed gas to boiler	0.54
CHP-S201	Fresh water (FW system)	10	CHP-S108	Ash	0.2	PY-S103	District heat return (from drying section)	13.59
CHP-S119	Fresh air (boiler)	61	CHP-S307	Process steam	8.5	PY-S309	Return stream (quench and cooling water)	8.70
CHP-S101	Wet fuel (CHP)	7.5	CHP-S235	District heat supply (total)	251.93	PY-S215	Water for steam generation (pyrolysis section)	1.48
CHP-240	Return district heat (existing customers)	238.34	CHP-241	District heat supply (existing customers)	238.34			

The simulation result in Table 23 is summarized based on the labels on Figure 10 found under section 1.5. For detailed Aspen Plus result report the reader is referred to Appendix II.[3]

[3] The Appendix is available for donwloading at www.energiforsk.se

Table 23 Mass flow results for Reference case scenario based on labels in Figure 10

Stream Label	Stream description	Mass flow (kg/s)	T (°C)
1	Fresh air to feedstock drying section	52.1	0.8
2	Wet feedstock to drying section (@ 31.8 %MC)	3.7	15.0
3	Moist air	53.0	25.7
4	District heat water supply to drying section	13.6	79.6
5	District heat water return from drying section	13.6	41.2
6	Prepared feed stock to pyrolysis reactor (1.4 mm particle size and 8.9% MC)	2.8	23.7
7	Pyrolysis vapors to quenching section	3.6	500.0
8	Ash (Pyrolysis)	0.01	700
9	Fresh air to air preheating (pyrolysis section)	26.3	0.8
10	Bio-oil (@ 30% MC)	0.9	25.0
11	Waste water	2.2	25.0
12	Quench water return	8.7	57.3
13	Quench water supply	8.7	4.0
14	Flue gas from pyrolysis section to boiler	26.9	398.1
15	Flue gas to flue gas cleaning unit	95.7	167.3
16	NCG to boiler	0.5	181.6
17	Fuel to boiler	7.5	15.0
18	Feed water to steam generation in pyrolysis section	1.5	170.9
19	Combustion air (Boiler)	61	0.8
20	Ash (Boiler)	0.2	182
21	Process steam	8.5	211.8
23	Total district heat supply point	258.8	82
24	Total district heat return point	258.8	42.4
25	Fresh water	10.0	4.0

The results of the energy balance for the reference case scenario is illustrated in Figure 19 below.

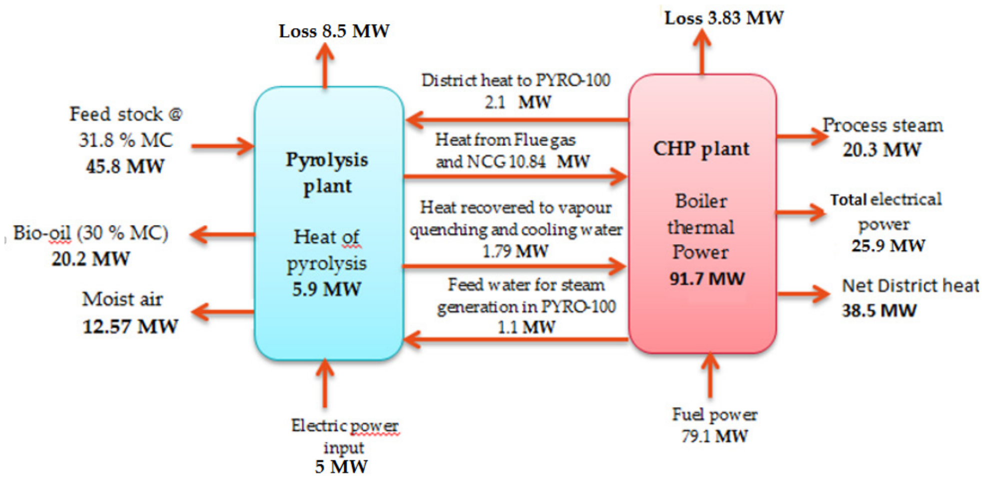


Figure 19 Overall energy balance for Reference case scenario

The overall plant efficiency of the reference case plant (calculated by dividing the sum of the outlet streams-electric power, bio-oil, process steam and district heat by incoming streams-fuel power and feedstock thermal powers) in Figure 19, gives and overall efficiency of 86.8 %. The losses indicated for the pyrolysis plant consist of heat losses associated with combustion, pyrolysis, feed stock drying, and losses at the integration points. For the CHP plant the losses are mainly associated with flue gases.

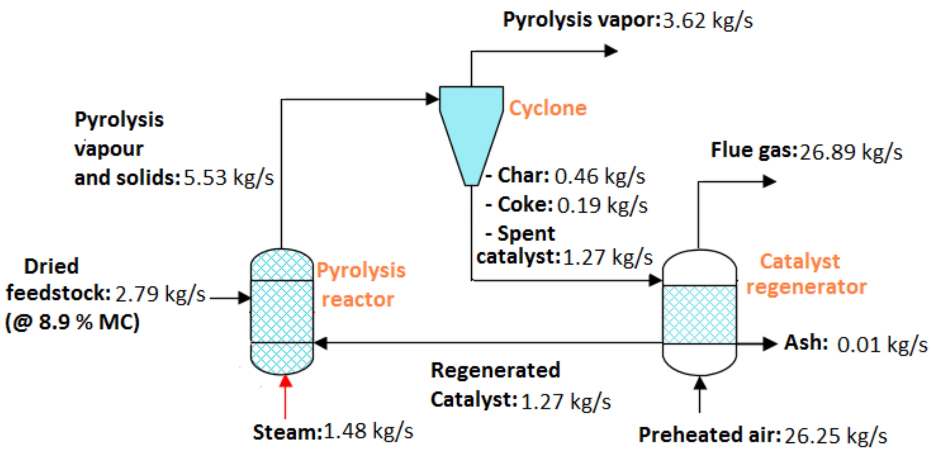


Figure 20 Mass balance for pyrolysis reactor and catalyst regenerator

Figure 20 illustrates the mass balance for the pyrolysis and catalyst regeneration processes. As mentioned earlier, the pyrolysis reactor is Circulating Fluidized type thus uses cyclone for separating the vapor phase streams from solids that consists of char, coke and spent catalyst. The steam, in addition to creating a favorable environment for the catalytic reaction, it also serves as a fluidizing agent in the pyrolyzer. The catalyst generator is Bubbling Fluidized Bed reactor and though not shown in the figure, it makes use of cyclones to separate the flue gas from the solid streams. The bed material in this work is considered catalyst only; other bed materials such as sand is not included in the proposed system. This does not affect the energy balance of the whole integrated system.

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5.2 RESULTS OF OTHER SCENARIOS

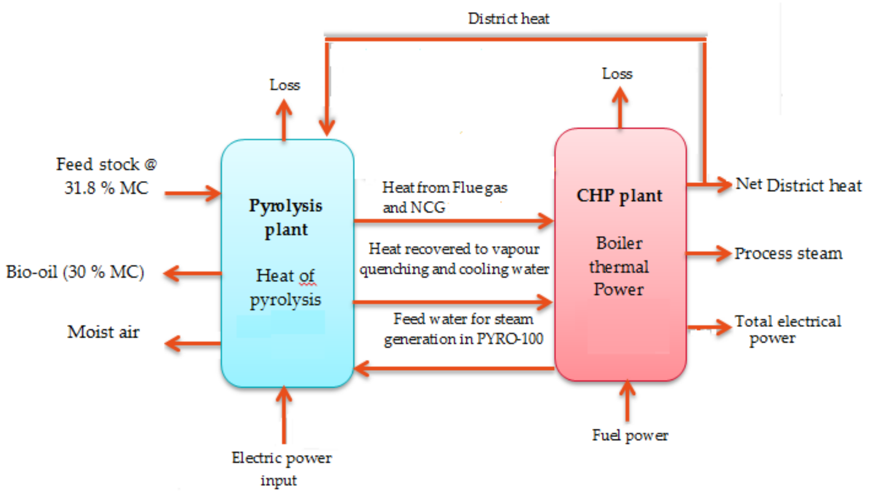

Figure 21 Overall schematic diagram for the integrated plant (for energy balance)

Table 24 and 25 summarize the mass and energy balance results respectively of the 100 % PL, 70 % PL, 60 % PL and 50 % PL integration scenarios based on the overall schematic diagram in Figure 18. The electricity input for the pyrolysis plant includes the power consumptions of pumps (taken from simulation result), non-condensable gas compressor (taken from simulation result) and the grinder (taken as 50 kWh/t of ground material [10]).

Table 24 Summary of mass balance results for the other scenarios

Scenarios		100 % - 5MW	100%- 10MW	100%- 20MW	100%- 30MW	100%- 40MW	70%- 5MW	70%- 10MW	70%- 20MW	70%- 30MW	70%- 40MW	60%- 5MW	60%- 10MW	60%- 20MW	60%- 30MW	60%- 40MW	50%- 5MW	50%- 10MW	50%- 20MW	50%- 30MW	50%- 40MW
Streams		Mass flow (kg/s)					Mass flow (kg/s)					Mass flow (kg/s)					Mass flow (kg/s)				
PY-S106	Wet fuel (@ 31.8 MC)	0.9	1.9	3.7	5.6	7.4	0.9	1.9	3.7	5.6	7.4	0.9	1.9	3.7	5.6	7.4	0.9	1.9	3.7	5.6	7.4
PY-S101	Fresh air (to drying section)	13.0	26.0	52.1	78.8	104.1	13.0	26.0	52.1	78.3	104.1	13.0	26.0	52.1	78.3	104.1	13.0	26.0	52.1	78.3	104.1
PY-S218	Fresh air (to Catalyst regeneration)	6.6	13.2	26.3	43.0	57.2	6.6	13.1	26.3	39.5	52.6	6.6	13.1	26.3	39.5	52.6	6.6	13.1	26.3	39.5	52.6
CHP-S201	Fresh water (FW system)	12.7	13.0	13.8	14.5	15.3	8.9	9.3	10.0	10.7	11.5	7.7	8.1	8.8	9.5	10.3	6.5	6.8	7.6	8.3	9.1
CHP-S119	Fresh air (boiler)	83.0	78.0	84.0	80.0	65.7	60.0	52.0	61.0	45.0	32.0	51.0	54.0	52.0	31.0	25.0	45.0	40.0	36.0	25.0	10.0
CHP-S101	Wet fuel (CHP)	13.2	12.6	11.5	10.5	9.8	9.0	8.4	7.5	6.4	5.5	7.7	7.2	6.2	5.0	4.2	6.3	5.7	4.7	3.7	2.8
CHP-240	Return district heat (existing customers for stand alone CHP plant)	343.3	343.3	343.3	343.3	343.3	238.3	238.3	238.3	238.3	238.3	191.4	191.4	191.4	191.4	191.4	113.7	113.7	113.7	113.7	113.7
PY-S211	Ash (pyrolysis)	0.002	0.004	0.010	0.012	0.020	0.002	0.004	0.010	0.012	0.020	0.002	0.004	0.008	0.012	0.016	0.002	0.004	0.008	0.012	0.016
PY-S108	Moist air	13.2	26.5	53.0	79.7	106.0	13.3	26.5	53.0	79.7	106.0	13.3	26.5	53.0	79.7	106.0	13.3	26.5	53.0	79.7	106.0
PY-S401	Waste water	0.6	1.1	2.2	3.3	4.4	0.6	1.1	2.2	3.3	4.4	0.6	1.1	2.2	3.3	4.4	0.5	1.1	2.2	3.3	4.4
PY-403	Bio-oil (@30% MC)	0.2	0.4	0.9	1.3	1.8	0.2	0.4	0.9	1.3	1.8	0.2	0.4	0.9	1.3	1.8	0.2	0.4	0.9	1.3	1.8
CHP-S118	Flue gas (to cleaning section)	102.8	104.0	122.7	135.0	135.2	75.6	86.1	95.7	92.5	92.3	65.4	75.0	87.8	77.2	84.0	58.0	59.4	68.2	70.2	71.1
CHP-S108	Ash (CHP)	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1
CHP-S307	Process steam	12.3	12.3	12.3	12.3	12.0	8.5	8.5	8.5	8.5	8.5	7.3	7.3	7.3	7.3	7.3	6.1	6.1	6.1	6.1	6.0
CHP-241	District heat supply (existing customers for stand alone CHP plant)	343.3	343.3	343.3	343.3	343.3	238.3	238.3	238.3	238.3	238.3	191.4	191.4	191.4	191.4	191.4	113.7	113.7	113.7	113.7	113.7

Table 25 Summary of energy balance results for the other scenarios

	100 % - 5MW	100%- 10MW	100%- 20MW	100%- 30MW	100%- 40MW	70%- 5MW	70%- 10MW	70%- 20MW	70%- 30MW	70%- 40MW	60%- 5MW	60%- 10MW	60%- 20MW	60%- 30MW	60%- 40MW	50%- 5MW	50%- 10MW	50%- 20MW	50%- 30MW	50%- 40MW
Parameter (MW)																				
Fuel power (CHP)	139.22	132.89	121.29	110.74	103.36	94.92	88.59	79.10	67.50	58.01	81.21	75.94	65.39	52.73	44.30	66.44	60.12	49.57	39.02	29.53
Wet feedstock (pyrolysis)	11.5	23.5	45.8	69.3	91.6	11.5	23.0	45.8	69.3	91.6	11.5	23.0	46.1	69.3	91.6	11.5	23.0	46.1	69.3	92.2
District heat input (Pyrolysis)	0.62	1.2	2.4	4.13	4.64	0.6	1.2	2.1	4.1	4.6	0.61	1.2	2.6	4.01	4.7	0.6	1.2	2.5	4.13	4.7
Electric power input (pyrolysis)	1.2	2.1	5	7.17	9.82	1.2	2.1	5	7.17	9.82	1.2	2.1	5	7.17	9.82	1.2	2.1	5	7.17	9.82
Moist air	3	6.1	12.2	18.3	24.5	3.1	6.18	12.57	18.6	24.45	3.0	6.20	12.6	18.7	24.3	2.8	6.18	12.5	18.7	24.3
Bio-oil(@30%MC)	5	10	20	30	40	5	10	20	30	40	5	10	20	30	40	5	10	20	30	40
Heat input from flue gas	2.5	5.3	10.6	16	21.3	2.5	5.1	10.2	16	21.3	2.5	5.1	10.2	16	21.3	2.5	5.1	10.2	16	21.3
Heat input from non-condensable gas	0.2	0.39	0.68	1.02	1.35	0.16	0.3	0.65	1.03	1.4	0.16	0.39	0.68	1.02	1.35	0.16	0.40	0.68	1.02	1.36
Total district heat	58.9	58.7	58.7	58.7	58.7	40.6	41	40.6	40.6	40.6	34.84	34.84	34.84	34.84	34.84	29.12	29.12	29.12	29.12	29.12
Total electrical power	37.66	37.54	37.6	37.54	37.54	26.0	26.2	26.0	26.0	26.0	22.3	22.3	22.3	22.3	22.3	18.62	18.62	18.62	18.62	18.62
Net district heat	58.26	57.50	56.26	54.56	54.06	39.97	39.87	38.47	36.47	35.97	34.23	33.66	32.28	30.82	30.14	28.52	27.94	26.66	24.99	24.42
Process steam	29.4	29.4	29.4	29.4	29	20.3	20.3	20.3	20.3	20.3	17.4	17.4	17.4	17.4	17.4	14.6	14.6	14.6	14.6	14.3
Heat of Pyrolysis	1.6	2.9	6.2	9.4	10.7	1.6	3.1	5.9	9.4	10.7	1.6	3.1	5.9	9.4	10.7	1.6	3.1	5.9	9.4	10.7
Boiler thermal power	131.0	130.7	131	131.0	131	90.6	91.0	91.7	91.0	91.0	78.0	78.1	78.0	77.9	78.1	64.8	65.1	65.0	64.9	65.0
FW for steam generation	0.27	0.5	1.1	1.58	2.1	0.27	0.5	1.1	1.58	2.1	0.27	0.5	1.1	1.58	2.1	0.27	0.5	1.1	1.58	2.1
Heat recovered to vapor quenching and product cooling water	0.45	1.04	1.79	2.83	3.5	0.45	0.90	1.79	2.83	3.5	0.45	1.04	1.79	2.83	3.5	0.45	1.04	1.79	2.83	3.5
Loss (Pyrolysis plant)	2.4	4.5	8.9	14.2	17.1	2.3	4.2	8.5	13.9	17.1	2.4	4.0	9.2	13.0	17.4	2.6	4.0	9.2	13.1	18.0
Loss (CHP plant)	16.2	13.5	7.6	3.4	2.5	10.9	6.9	3.9	-1.0	-4.7	9.5	7.4	2.4	-3.6	-6.2	7.0	3.8	-1.1	-5.0	-8.4

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The simulation result for the different scenarios has indicated the major critical parameters limiting the integration: These are either reported by Aspen Plus as error points or are identified by comparison with the CHP plant's design parameters. Such critical parameters are detected for integrated schemes beyond 20 MW. On the other hand, the simulation result of the 50 %-20 MW integrated plant, has indicated that at such lower part load operations, 20 MW bio-oil capacity may not be an option due to the need to decrease the fuel flow to the boiler much below the minimum design fuel flow. However, if there is a possibility for operating the boiler below the minimum design fuel flow (7 kg/s) and the flue gas temperature after air preheating can be accommodated by the existing flue gas condensing unit, there is a possibility that the 20 MW bio-oil production can be pursued year round. The choice of the reference case scenario is using this assumption. Table 26 summarizes the major critical parameters identified either by Aspen Plus or by observation. As can be seen in the table, the flue gas temperature after the air preheater increases way beyond the desired 168 °C for integration capacities ≥ 30 MW (except for the 50% PL operation discussed above). Compared to the potential benefit obtained from the integration of the CHP plant with the pyrolysis unit, a retrofit on the flue gas condensation unit (with the aim of accommodating higher flue gas temperature) can be considered a minimum investment.

The other critical parameter identified for integration capacities ≥30 MW is the additional water used for the quenching and product cooling process. As can be seen in Table 26, the need for this additional water starts at the integration scenario where 70% PL CHP and 20 MW bio-oil capacity pyrolysis plant are integrated. The water flow almost doubles as the capacity increases from 30 MW to 40 MW for a certain part load operation of the CHP plant. If Övik Energi AB considers the cost due to this additional water and its treatment after wards is not a big investment as compared to the integration benefits, higher capacity integration schemes (30-40 MW) plant can be considered assuming also the retrofit on the fluegas condensation unit is implemented. On the other hand, the boiler fuel flow has been observed to be one possible limiting factor for the integration. The last column on Table 26 shows the fuel flows for the scenarios (20-40 MW integrated with the different CHP PL operations) below the minimum design fuel flow (7 kg/s) for the stand alone plant. This lower fuel flows are not reported as errors by the simulation, however, it is clear that there is a certain margin below which the boiler cannot be operated using biomass. The result indicates that the integration of the 50% PL CHP with capacities beyond 20 MW requires lowering the boiler fuel flow as low as 2.8 kg/s indicating about 65 % lower capacity operation. In table 26, the limiting values are indicated with red colour. The moisture content of the flue gas after the air preheating unit is also summarized in Table 26. The performance of the flue gas cleaning system is affected by this moisture values among other factors. In general, the result shows that, as the capacity of the bio-oil production increases the dryer the flue gas gets.

Table 26 Major critical parameters identified

	Flue gas temperature[a] after air preheater (°C)					Flue gas mass flow after air preheater (kg/s)					Additional water for and product cooling (kg/s)		
	5 MW	10 MW	20 MW	30 MW	40 MW	5 MW	10 MW	20 MW	30 MW	40 MW	5 MW	10 MW	20 MW
100 % PL	167.3	167.3	167.3	177.4	197.1	102.8	104.0	122.7	135	134.8	0	0	0
70 % PL	167.3	167.3	167.3	188	213	75.6	73.9	95.7	92.5	92.3	0	0	0
60 % PL	167.3	170	170	202	220	65.4	74.8	85.5	77.1	83.9	0	0	0
50 % PL	168.6	167.3	179	209	247	58.0	59.4	68.2	70.2	71.1	0	0	1.13

[a]According to Table 16, the temperature of the flue gas should not exceed 170 ˚C

[b]According to Table 16, the maximum volumetric flow of the flue gas in Nm^3/s is 80 and thus the values in Table 26 are checked after transferring them to units of Nm^3/s

Figure 22 shows the fuel reduction as a percentage of the fuel flow for the standalone unit during the different part-load operations. It can be seen that for a certain part load operation, as the bio-oil production is increased from 5 to 40 MW (as compared to the fuel consumption of the standalone CHP plant at the corresponding part load operation), the fuel percentage reduction increases.

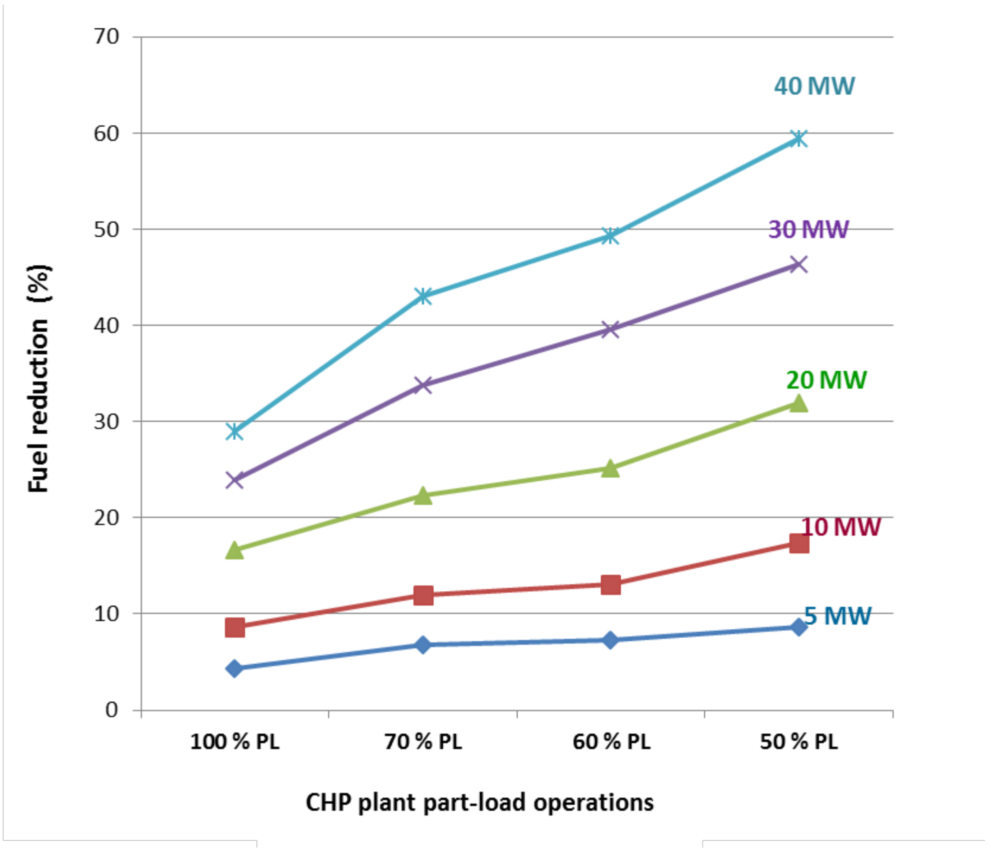

Figure 22 shows the results of the fuel saved for all of the scenarios considered

The choice of the reference case scenario was a function of the operational limitations observed from the simulation results. Theoretically, it was possible to integrate all the scenarios considered in this study. Given that the boiler can operate below the minimum nominal fuel capacity and that the flue gas condensing unit can accommodate higher temperatures of the incoming flue gas after the air preheating section of the CHP plant, it is still possible to consider that the integrated plant can be designed for capacities above 20 MW. As per the results for the 100% PL integrated with 30 MW indicated, for higher part load capacities of the CHP plant (above 70%), there is a possibility that high outlet temperature of the flue gas after the air preheating section can occur as well as higher need for additional quench/cooling water are encountered. The reason for the demand of additional water can be attributed to the fact that as the bio-oil production is increased more pyrolysis vapor needs to be handled in the vapor quenching and product cooling process. The single most influencing component in the pyrolysis vapors is the water vapor that mainly originates from the steam used in the pyrolysis reactor.

From the results of the different scenarios considered, it is possible to see that there is a fuel saving route introduced in the integrated plant owing to the additional flue gas and the non-condensable gas streams that are sent to the boiler. For instance, for the reference case scenario, the fuel flow is 7.5 kg/s and this compared to the corresponding standalone CHP plant's fuel flow (i.e. 9.7 kg/s) has shown a fuel reduction of about 22 %.

5.3 SUMMARY OF CRITICAL PARAMETERS OBSERVED FROM THE SIMULATION RESULT

For the Bio-oil capacities beyond 20 MW (LHV), it is observed that the following parameters are limiting factors for the integration.

For 100 % PL operation, the flue gas temperature after air preheating process exceeds (reaches 177.4 °C) the design temperature in Table 16. For part load operations 70% and lower, the main limiting factors for the integration of the CHP plant with a higher capacity bio-oil production ($\geq$30 MW) is the need for extra water for the vapor quenching process and the minimum design fuel flow (7 kg/s) to the CHP plant. For part load operation of 50 % , integration with 20 MW still results in a higher flue gas temperature after air preheating (179°C) and the need for additional water is 1.125 kg/s. The fuel flow for the scenario where the 50% PL is integrated with 40 MW, the mass flow of the fuel needs to be reduced down to 2.8 kg/s in order to achieve the same boiler thermal effect as the stand alone CHP unit operating at 50% PL. For full load operations of the boiler, the flue gas flow is observed to be limiting factor.

5.4 RESULTS OF ECONOMIC ANALYSIS

Table 27 summarizes the economic analysis result. It can be seen that the total investment cost based on the reference scenario results is 276 Million SEK. The total operating cost is estimated to be 98.4 Million SEK. The unit production of the bio-oil is estimated to be 4.7 SEK/kg or expressed in MWh produced bio-oil term it is 752.1 SEK/MWh.

Table 27 Summary of the results of the economic analysis

Investment	**MSEK**
Direct capital cost	177.6
Indirect capital costs	85.3
Working capital	13.1
Total project investment cost	**276**

Fixed operating costs	**MSEK/yr**
Maintenance	4.3
Labour cost*	4.2
Laboratory costs	0.8
Supervision	0.8
Plant overheads	2.1
Capital charges	8.5
Insurance	0.9
Tax	1.7
Total Fixed operating costs	**23.4**

Variable operating costs	**MSEK/yr**
Feed stock	70.5
Catalyst	6.5
Water	2.2
Total variable operating costs	79

Total operating costs:	102.5
Bio-oil production cost (SEK/kg)	4.7
Bio-oil production cost (SEK/MWh)	752.1

***Labour cost**	***Salary (MSEK/month)***
Plant manager (1)	*45000*
Shift leader (1)	*31000*
Administration (1)	*25000*
Lab expert (1)	*27000*
Maintenance head (1)	*35000*
Shift operators(2)	*64000*
Annual Labour cost including salary supplement	***4222200***

5.4.1 Sensitivity analysis results

In this section, the sensitivity analysis discussed in section 4.2 results is summarized in charts. Figure 23 shows the variation of the bio-oil production cost as the percentage value of the contingency. The bio-oil production cost increased from 752.1 to 772 SEK/MWh as the contingency is varied from 3% to 10%.

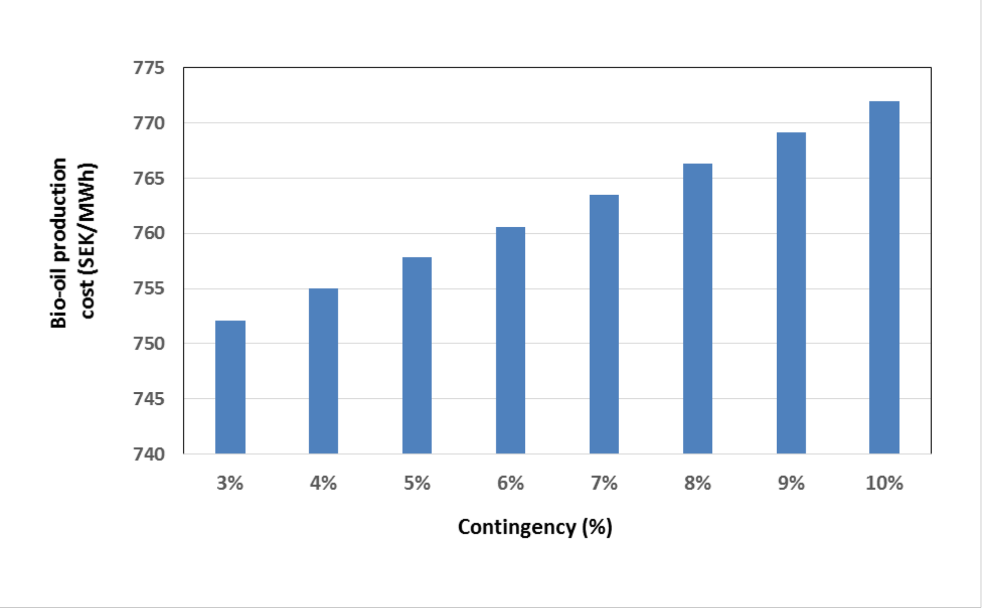

Figure 23 Sensitivity of the bio-oil production cost as the percentage value of contingency is varied from 3 to 10

Figure 24 shows the sensitivity analysis result when the feed stock price is increased from 600 SEK/t to 1000 SEK/t. For every 100 SEK/t price increment, the bio-oil production cost increases by 67 SEK/MWh.

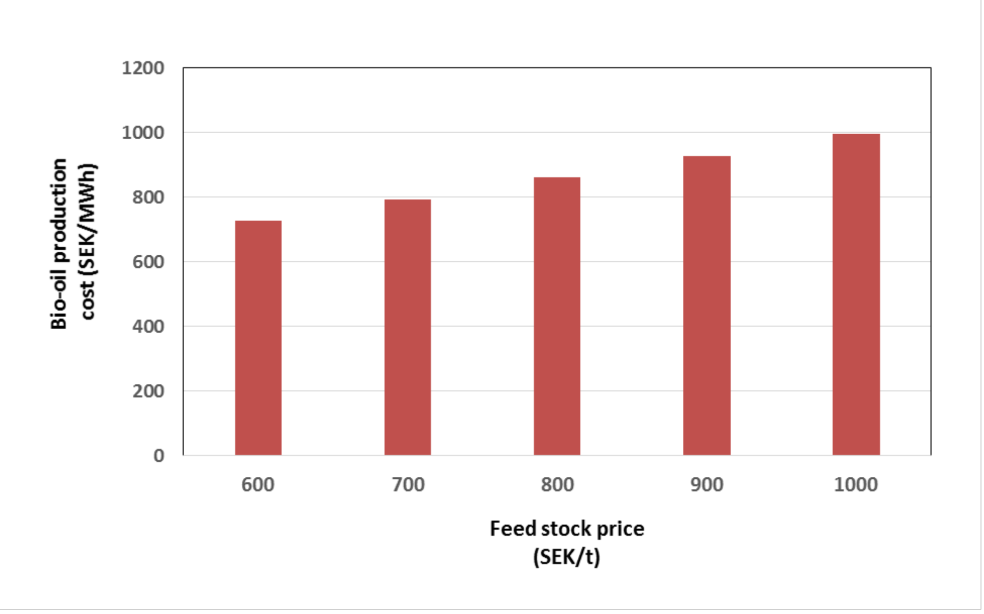

Figure 24 Sensitivity of the bio-oil production cost as the feed stock price is varied from 600 to 1000 SEK/t

Figure 25 shows the sensitivity of the bio-oil production cost as the catalyst replacement rate is varied from 0.2 to 1 %/h. As can be seen from the results, for 0.2%/h increment of the catalyst replacement rate, the bio-oil production cost tends to increase only slightly.

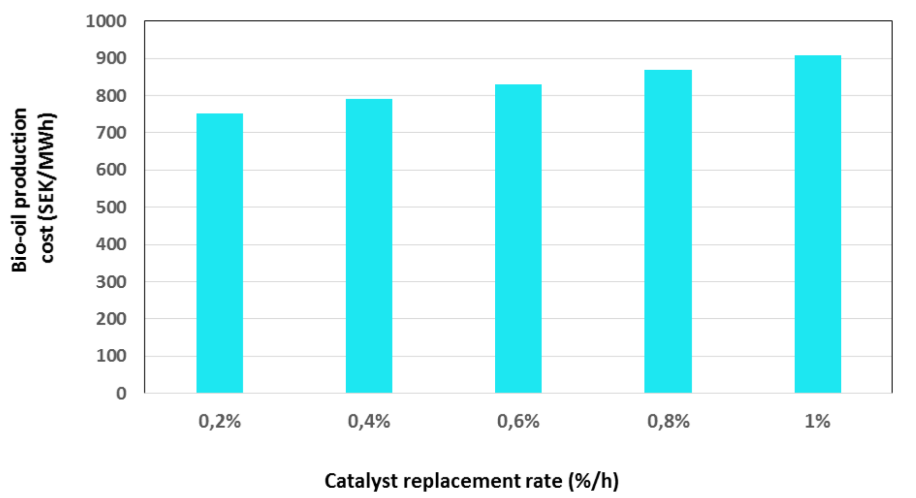

Figure 25 Sensitivity of the bio-oil production cost as the catalyst replacement rate is varied from 0.2% to 1%

5.5 OVERALL DISCUSSION

In this section, an overall discussion is made by highlighting some issues of interest that reflect the initial project objectives.

Determination of economically optimal cogeneration of electricity, heat and bio-oil as a function of seasonality.

What has been of interest in this study is the maximization of the bio-oil to the point where no limitations are observed while at the same time being able to run the CHP plant year round at different part loads. Based on observations made on the simulation results obtained and identification of the critical parameters for integration, the 20 MW bio-oil capacity combined with 70% part load operation of the CHP plant is chosen. The simulation result for the integrated plant of the 20 MW bio-oil capacity for the four CHP part load operations (i.e., 100%,70%,60% and 50%) has shown that it is possible to integrate for all the scenarios. The only critical parameter observed is the minimum fuel flow to the boiler, where for the integrated case 20MW-50%, there is a need to lower below this minimum flow. There is an interest from Övik Energi to be able to utilize the boilers underutilized capacity during the months April-September where the district heat need is lower. In the case where Övik Energi is interested in operating the bio-oil plant during winter season, it is still possible to operate upto 20 MW bio-oil production where the fuel flow to the boiler needs to be decreased during higher CHP part load operations inorder to accommodate the fluegas and the non-condensable gases from the pyrolysis process. However, it is recommended that during the winter season, the choice of whether to operate with 20 MW bio-oil or lower capacity, needs to be decided based on the preferences of Övik Energi. Based on the simulation results, operation of the bio-oil plant below 10 MW is recommended during winter as the increase in the

CHP part load operation (case of winter season) combined with increased bio-oil capacity will require decreasing the fuel flow to the boiler and buying more expensive feedstock to the pyrolysis process. On the other hand, as the limitations discussed in this report are assessed only in theoretical terms and are not tested practically, for the summer season, there is a room for the possibility of operating the bio-oil plant with higher capacities beyond the 20 MW. Here it should be noted that higher bio-oil plant capacity means handling more waste water, bio-oil sales related logistics (like distribution, transportation, etc.), and increased demand of quench water. As all these factors define what the optimum integrated plant scenario is, the 20 MW-70% PL integrated plant scenario selected in this study may not be the optimum scenario for Övik Energi. The waste water separation process needs to be thoroughly investigated in the future.

Clarification of technical details before a realistic integration of the pyrolysis process

The technical details for both the pyrolysis and CHP plants is supported by the data gathered for both plants, several discussions during meetings, field study outcomes, information obtained through email correspondences and literature review. Relevant technical details are available in sections 1.3 and 1.4. These are then used for conceptualizing the integrated scheme.

Development of a technical system scenario for the integrated plant

This is discussed in section 1.5 by shown the schematic diagram and indicating the integration points between the stand alone units. Generally, the pyrolysis plant is a heat-sink in the integrated scheme. The integration points considered are, the district heat and drying section, quench water to pyrolysis and back to CHP plant, flue gas and non-condensable gases from pyrolysis plant to CHP plant, feed water for steam generation and use in the pyrolyzer. As mentioned in the methodology part of this report, there are 5 bio-oil capacity plants and 4 part-load operations of the CHP plant considered which led to 20 scenarios.

Optimization of operating parameters to determine the optimal cogeneration of electricity, heating and bio-oil annually.

As mentioned earlier, the choice of the reference case scenario is determined based on the observation of the limiting factors from the simulation results (refer to section 5.2). Comparison of some of the selected scenarios including the reference case scenario with the stand alone CHP unit is illustrated in Figure 26. Comparison of some of the actual average operation parameters for the CHP standalone unit discussed in section 1.4 with some scenarios from Table 25, the theoretical operation profile of the integrated scheme is seen.

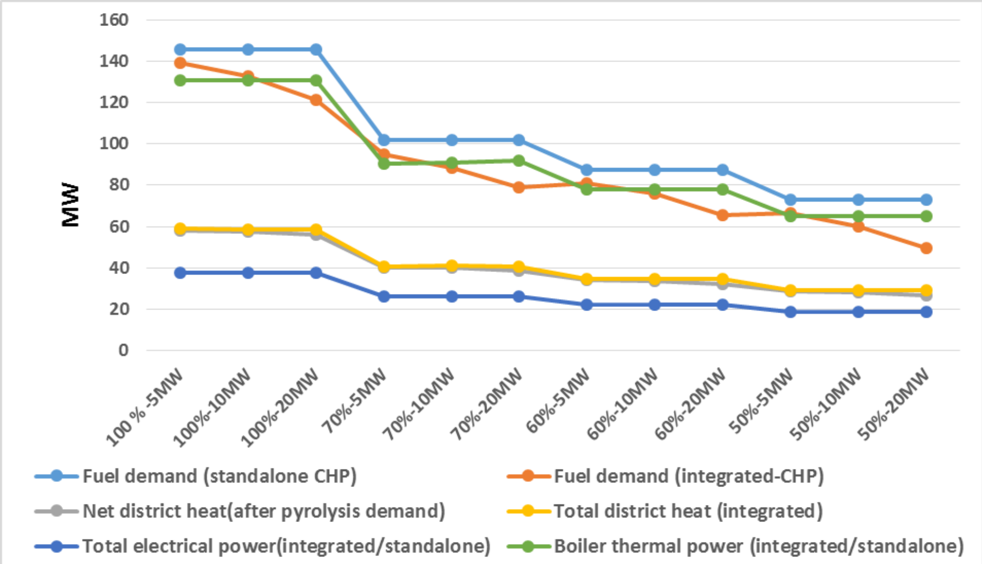

Figure 26 Comparison of stand-alone and integrated scenarios

The curves in Figure 26 show a maximum bio-oil production capacity of 20 MW and a minimum of 5 MW for 12 scenarios and the pattern followed by these values is (boiler thermal power, electrical power output) of the standalone CHP plant is inline with the seasonal variation shown in section 1.4. The district heat need for the pyrolysis unit is small amount however; it decreases the net district heat for the existing district heat customers. The fuel for the integrated scenario is lower than for the stand alone case as shown in the figure. The practicality of operation of the pyrolysis plant for different partload operations need to be further investigated. The main equipment considered for the pyrolysis unit among others include: CFB pyrolysis reactor, BFB catalyst regenerator, belt-dryer as it can make use of low temperature heat source and hammer mill.

5.6 PROJECT DISSEMINATION

In addition to what is reported in this document, the knowledge dissemination will further continue through publications, seminars and conferences.

6 Conclusion and recommendations

In this work, a conceptual process of integrated an existing CHP plant and catalytic fast pyrolysis of biomass with production of heat, power and biooil-CHOP is proposed. A process model is developed basing on ASPEN Plus. Using the developed models, different technical system scenarios for the integrated plant have been evaluated. A simple economic analysis of the proposed system together with sensitivity has been performed.

Results have indicated that it is definitely possible to integrate the existing CHP plant with a pyrolysis unit for heat, power and bio-oil production. Throughout the integration process, the main interest was to maximize the bio-oil production capacity as much as possible while at the same time being able to run the CHP plant year round at different part loads. Based on observations made on the simulation results obtained and identification of the critical parameters for integration, the 20 MW bio-oil capacity combined with 70% part load operation of the CHP plant is chosen. However, the reference case scenario is optimum only theoretically and Övik Energi can have another optimum bio-oil capacity.

Year round operation of the pyrolysis plant with different combination of the bio-oil plant and part load operation of the CHP plant is also subject to the interest of Övik Energy and the decision is defined by the identified critical parameters and how these can be handled in practice. Based on observations made on the simulation results obtained and identification of the critical parameters for integration, the 20 MW bio-oil capacity combined with 70% part load operation of the CHP plant is chosen. The CHP plant can choose to operate below 10 MW bio-oil capacity for winter season and at 20 MW bio-oil capacity for the summer season. It is worth to point out that the design capacity should be investigated carefully due to the technical limitation of the existing CHP plant. The developed process model using Aspen Plus has enabled to investigate the possibility of integration and also has provided simulation results for different scenarios that helped to choose the optimum operation scenario. The main technical conclusions from this modelling study for the specific cases are:

- The underutilized boiler capacity of the CHP plant can be made use of during low production seasons as well as during winter at an optimum bio-oil production capacity of 20 MW.
- The integration process has its limitations due to the capacities of the facilities in the existing CHP plant. These facilities include the size of flue gas passage, capacity of fresh water supply, waste water separation and treatment etc.
- For the existing plant, the 20 MW bio-oil capacity integrated with the part load operations 60-100 % will enable the plant to run during the winter and part of the summer season if the case of 20 MW-50% PL is seen as a hindrance for integration. On the other hand, if the case of 20 MW-50% PL is seen as a minor problem, the plant will be able to maintain the existing operation hours per year.
- For higher capacities ≥30MW the critical parameters stated in the results section, have put a limit to the integration concept, however if the influence factors is minimized by further investing in small retrofit activities like in the flue gas condensing section and the need for additional water is also compensated by the added benefits from the integration, then it might be possible to consider higher bio-oil production integrated plant.

- The bio-oil production cost and selling price are subject to different factors and the estimated production cost (4.7 SEK/kg or 752.1 SEK/MWh) is only indicative.
- For full lad operation the limiting factor for integration is observed to be the flue gas flow after the air preheater.
- The bio-oil production cost is sensitive to the feed stock cost. Since a commercial scale integrated plant using catalytic steam fast pyrolysis is not available for comparison, the catalyst replacement rate was taken from literature and the sensitivity analysis result shows that the bio-oil production cost is influenced by the catalyst replacement rate.
- Due to the integration process, it was possible to reduce the fuel flow to the boiler and the percentage reduction in comparison to the fuel consumption of the standalone unit increased as the production capacity of the pyrolysis unit is increased.

7 Future work

The following points can be considered for future work:

- The simulation in this study focused only on the mass and heat balance aspects and the best results for the integration process can be obtained if 'design oriented' simulation technique is adopted. This means incorporating the design parameters of the actual equipment of the CHP plant under consideration into the simulation input parameters. Though this needs ample time, it will result in a model which can predict the 'close to realistic' behavior of the integrated plant.
- The moist air from the dryer section has varying amounts of heat (depending on the temperature of the district heat and thus the preheated air temperature) that can be recovered. Similarly, the additional water returned from vapor quenching and cooling sections of the pyrolysis plant has utilizable amount of heat for instance in the drying section itself. Such ideas need to be further investigated.
- The vapor quenching section of the pyrolysis unit is simulated by setting the condensation temperature of the pyrolysis vapors in two condensation stages. It would be beneficial to further analyze the quenching process by varying these two temperature values.

Finally, the work in this study will be compiled in an article form that can be used to produce a journal or conference paper.

8 References

[1] A. Hornung, Transformation of Biomass: Theory to Practice (ed A. Hornung), 2014, John Wiley & Sons, Ltd, Chichester, UK. doi: 10.1002/9781118693643.ch4

[2] P. Basu, Biomass gasification and pyrolysis: Practical Design, 2010, doi:10.1016/B978-0-12-374988-8.00003-9. ch3

[3] B. Robert C., ed. Wiley Series in Renewable Resource : Thermochemical Processing of Biomass : Conversion into Fuels, Chemicals and Power. Hoboken, NJ, USA: John Wiley & Sons, 2011. ProQuest ebrary. Web. November 2015.

[4] D. Radlein, A. Quignard. A short historical review of fast pyrolysis of biomass.

Oil and Gas Science and Technology, Institut Fran_cais du P_etrole (2013) 68 (4), pp.765-783. Available at: https://hal-ifp.archives-ouvertes.fr/file/index/docid/909065/filename/A9RD5D8.pdf. Accessed: February 2015.

[5] G. Benjaminsson, J. Benjaminsson, N. Bengtsson, Gasefuels AB. Decentraliserad produktion av pyrolysolja för transport till storskaliga kraftvärmeverk och förgasningsanläggningar. Gasefuels AB (2013). Available at: http://gasefuels.se/media/rapporter/Decentraliserad%20produktion%20av%20pyrolysolja%20f%C3%B6r%20transport%20till%20storskaliga%20kraftv%C3%A4rmeverk%20och%20f%C3%B6rgasningsanl%C3%A4ggningar.pdf . Accessed: February 2015.

[6] BTG-BTL, Commercial scale plants. Available at: http://www.btg-btl.com. Accessed: February 2015.

[7] Empyro: Implementation of a commercial scale fast pyrolysis plant in the Netherlands. Available at: http://www.researchgate.net/publication/280305765_Empyro_Implementation_of_a_commercial_scale_fast_pyrolysis_plant_in_the_Netherlands. Accessed November, 2015.

[8] Ensyn, Key RTP facilities. Available at: http://www.ensyn.com/technology/key-rtp-facilities. Accessed November 2015.

[9] BioPAD, Fortum Jeonssu- Value adding by producing bio oil from wood. Available at: http://www.biopad.eu/wp-content/uploads/Case-study-of-Fortum-in-Joensuu.pdf. Accessed: October,2015.

[10] M. Ringer, V. Putsche, and J. Scahill, Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis (2006), NREL. Available at: http://www.nrel.gov/docs/fy07osti/37779.pdf. Accessed: January 2015.

[11] S. Boust, M Green, S. Machi, Fluidized Catalytic Cracking to Convert Biomass to Fuels , 2015 , University of Pennsylvania, Department of Chemical & Biomolecular Engineering. Available at: http://repository.upenn.edu/cbe_sdr/72. Accessed: August 2015.

[12] GTI (Gas Technology Institute) IH2 GTI Available at: http://www.gastechnology.org/news/Pages/New-IH2-Advanced-Biofuels-Plant-

Broadens-Options-for-Converting-Biomass-into-Transportation-Fuels.aspx. Accessed: November 2015.

[13] E. Kantarelis , Catalytic Steam Pyrolysis of Biomass For Production of Liquid Feed stock,Doctoral thesis (2014). Royal Institute of Technology, Material Science and Engineering. Available at: https://www.diva-portal.org/smash/get/diva2:703293/FULLTEXT01.pdf. Accessed: January 2015.

TECHNICAL AND ECONOMICAL POTENTIAL FOR COMBINED HEAT, POWER AND BIO-OIL PRODUCTION IN POWER PLANTS-CHPO

Projektet har undersökt ekonomiska och tekniska möjligheter med att integrera en bio-oljeproduktion i ett biobränslebaserat kraftvärmeverk. Biooljan produceras genom en katalytisk snabbpyrolysprocess. Syftet är att producera värme, el och även bio-olja för att bättre kunna utnyttja kapaciteten hos biobränslebaserade kraftvärmeverk. Rapporten visar att en samtidig produktion är möjlig och redovisar begränsningar, förutsättningar och ekonomi för en integrerad produktion av bioolja.