KME

CONSORTIUM MATERIALS TECHNOLOGY for demonstration and development of thermal energy processes

Efficient Power Generation from Renewable Fuels

Reference Power Plant Project

Per-Axel Nilsson, Lennart Larsson, Erik Skog

KME-601

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Preface

The project has been performed within the framework of the fifth stage of the material technology research programme KME.

KME, Consortium Materials technology for demonstration and development of thermal Energy processes, was established 1997 on the initiative of the Swedish Energy Agency. In the consortium, the Swedish Energy Agency, seven industrial companies and 18 energy companies participate. The programme stage has been financed with 60.2 % by participating industrial companies and with 39.8 % by Swedish Energy Agency. Elforsk manages the consortium.

The programme shall contribute to increasing knowledge to forward the development of thermal energy processes for various energy applications through improved expertise, refined methods and new tools. The programme shall through material technology and process technology developments contribute to making electricity production using thermal processes with renewable fuel more effective. This is achieved by

- Forward the industrial development of thermal processes through strengthen collaboration between industry, academy and institutes.
- Build new knowledge and strengthen existing knowledge base at academy and institutes
- Coordinate on going activities within academy, institutes and industry

KME's activities are characterised by long-term industry relevant research and constitutes an important part of the effort to promote the development of new energy technology with the aim to create an economic, environmentally friendly and sustainable energy system.

Abstract

The project goal to increase the electrical efficiency of 3-4% units can be achieved with renewable fuels. Profitability is possible with pure forest fuels for plants of the 100 MW_e size. The efficiency increase is somewhat lower for Swedish conditions. For renewable fuels with 75% recycled wood it's profitable for the plant size from 25 MW_e and above. For installations with condensing operating profitability is very good.

Sammanfattning

I KME-programmet finns en målsättning att demonstrera i en fullstor anläggning hög elverkningsgrad med förnyelsebara bränslen. Projektet KME-601 har studerat hur anläggningar skulle kunna byggas för att uppfylla projektmålet på 3-4 % enheters verkningsgradsökning på elproduktionen.

Anläggningar med ångdata upp till 600 °C finns idag i drift med fossila bränslen. Förnyelsebara bränslen innehåller ämnen (K, Na) som kan orsaka kraftig korrosion på överhettare. Införandet av koldioxidskatt i Sverige på värmeproduktion med fossila bränslen 1991 genererade ombyggnader och nybyggnation av anläggningar till förnyelsebara bränslen. Stora skador på överhettare initierade forskning och utveckling inom området och utvecklingen mot högre ångdata stannade upp för de förnyelsebara bränslena. Idag bedöms kunskapen tillräcklig för att närma sig de ångdata som fossileldade anläggningar uppnått.

Två bränslemixar har används; Virgin (skogsbränsle) och Wide (75 % retur trä och 25 % skogsbränsle) samt tre olika storlekar på anläggningar; 100, 50 och 25 MW_e. Vid förändring av ångdata har mängden producerad värme hållits konstant.

Olika anläggningskoncepten inklusive basfall med ”normala” ångdata har utvärderats med processberäkningar i ThermoFlex. Därefter har ett antal koncept valts ut där panna- samt turbinlösningar har konstruerats, utvärderats och kostnadsberäknats. Risker har bedömts och hanterats med olika konstruktion- eller systemlösningar för att möta dessa. Driftkostnader har beräknats inkluderande förändringar som de valda ångdata kan orsaka.

För bränslet ”Virgin” och kraftvärmeproduktion kan upp till 3,6 % ökning i elverkningsgrad uppnås med ångdata på 175/46 bar och 600/600 °C. Lönsamheten samt begränsningar i dellast gör det mindre intressant för kraftvärmeproduktion, för kondensdrift och större anläggningar dock mycket mer intressant. Mer troligt för kraftvärme är en enkel ångcykel med 175 bar och 600 °C som uppnår 2,3 % och har acceptabla driftegenskaper. Lönsamheten är bättre än basfallet för den större anläggningen men lägre för de mindre.

För bränslet ”Wide” uppnås även en ökning upp till 3,8 % med ångdata på 160/44 bar och 560/560 °C i både kraftvärmeproduktion och kondensdrift, för en enkel ångcykel på 160 bar och 560 °C ca 2,8 %. Lönsamheten är för ”Wide” bättre även för de mindre anläggningsstorlekarna.

Projektets målsättning med en ökning av elverkningsgraden på 3-4 % enheter kan uppnås med förnyelsebara bränslen. Lönsamheten för rena skogsbränslen finns för anläggningar på 100 MW_e med något lägre verkningsgradsökning för svenska förhållanden. För förnyelsebara bränslen med 75 % returträ finns lönsamhet för anläggningar från 25 MW_e och uppåt. För anläggningar med kondensdrift är lönsamheten mycket god. Förslag till utvecklingsaktiviteter har lämnats till KME-programmet och lett till uppstart av nya projekt.

Lönsamheten för de avancerade koncept med högre verkningsgrad är naturligtvis beroende av flera faktorer, där totala elpriser, inkl elcertifikat eller feed-in tariffer, samt bränsleprisers utveckling är speciellt viktiga. Nämnda

lönsamhet gäller för redovisade förutsättningar för Sverige med faktorer som naturligtvis kommer att variera i tid och för olika marknader. Denna extra ”gröna” investering ger en väsentligt ökad produktion av förnybar el baserat på ett begränsat värmeunderlag för kraftvärmefallet eller baserat på en given bränslemängd för kondensfallet. Hur denna värderas och vilket avkastningskrav som ställs på denna extra investering kan variera för olika intressenter.

Nyckelord:

Kraftvärmeproduktion, Förnyelsebara bränslen, hög elverkningsgrad, 600 °C ångtemperatur

Summary

The KME program has a goal to demonstrate high electrical efficiency with renewable fuels in a full-scale plant. The project KME -601 has studied how plants could be built to meet the project goal of 3-4 %-unit efficiency increase of electricity production.

Plants with steam data up to 600 °C are currently in operation with fossil fuels. Renewable fuels contain species (K, Na) that can cause excessive corrosion of the superheater tubes. The introduction of carbon dioxide tax in Sweden on district heat production with fossil fuels in 1991, generated rebuilt and construction of new plants for renewable fuels. Severe damage on superheater tubes occurred and initiated research and development in the area. The trend towards higher steam data then stalled for the renewable fuels. Today sufficient knowledge to mitigate the corrosion and approach steam data as for fossil-fired plants is possible.

Two fuel mixes has been used in the project; Virgin (forest residues) and Wide (75 % recycled wood and 25% Virgin) and three different plant sizes; 100, 50 and 25 MW_e. The heat production has been kept constant when calculating the plant performance for varies steam data.

Different plant concepts including a base case with "normal" steam data were evaluated with process calculations in Thermoflex. A number of concepts where selected for design and cost calculations. Risks has been assessed and dealt with different design or system solutions. Operating costs have been calculated including changes that the selected steam data could cause.

For "Virgin" fuel up to 3.6 % increase in electric efficiency can be achieved with steam data of 175/46 bar and 600/600 °C in cogeneration. Profitability and constraints in partial load makes it less interesting. For condensing operation and larger plant sizes reheat is more interesting. A simple steam cycle with 175 bar and 600 °C, which achieves 2.3% and have acceptable operating characteristics is more likely for CHP application. Profitability is better than the base case for the larger plant, but lower for the smaller ones.

The "Wide" fuel plant achieves an increase of up to 3.8 % with steam data at 160/44 bar and 560/560 °C in both cogeneration and condensing operation. For a simple steam cycle at 160 bar and 560 °C, about 2.8 % is achieved. Profitability for the "Wide" fuel is better even for the smaller plant sizes.

The project goal to increase the electrical efficiency of 3-4% units can be achieved with renewable fuels. Profitability with current Swedish conditions is possible with pure forest fuels for plants of the 100 MW_e size. The efficiency increase is somewhat lower for Swedish conditions. For renewable fuels with 75% recycled wood it's profitable for the plant size from 25 MW_e and above. For installations with condensing operating profitability is very good. Proposal for development activities have been provided to the KME program and the generation of new projects.

The profitability for the advanced concepts with high efficiency is off course dependent on several factors, where the development of total electricity prices, including green certificates or feed-in tariffs, and fuel prices are of special importance. The mentioned profitability is valid for presented

conditions in Sweden, comprising factors that will vary in time and for different markets. This “green” investment will give an significant increase in the production of renewable electricity, based on a limited heat sink for the CHP case, or based on a limited biomass fuel volume for the condensing case. How this will be evaluated and which profitability requirements that will be valid can vary between different stakeholders.

Keywords:

Cogeneration, Renewable fuels, high electrical efficiency, 600 °C steam temperature

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1 Introduction

1.1 Background

KME is a consortium with material technology development as a base to make thermal energy processes more effective. KME 2010-2013 is the fifth phase of the programme that was established in 1997. The programme is divided into two main programme areas; Material technology, Base programme and Programme area “More Effective Power Production” (EPP). The main focus for the sub programme More Effective Power Production is to elaborate a reference power plant concept (RPP) with in-creased power efficiency to be demonstrated in a full-scale pilot plant in year 2017-2018.

The first project KME-601 within the EPP Programme area was formed to technically and economically analyse different RPP concepts that would be of interest for the stakeholders.

In 1991 a carbon dioxide tax for fossil fuels used for heat production was introduced in Sweden. Most of the new built plant was then designed for biomass and many old plants was converted to biomass fuels. Several of these plants suffered from high temperature corrosion on the super heaters. Two new research programs were then initiated, the High Temperature Corrosion centre (HTC) at Chalmers in 1996 and KME in 1997. Together with Värmeforsk they started R&D activities in order to understand and mitigate the corrosion.

It has been found that the higher content of alkali metals and the lower content of sulphur in combination with chloride in renewable fuels play a major roll in the corrosion process. Condensation of alkali chlorides on the superheater tubes is the major cause of the corrosion. Test with probes and design changes of super heater with increased superheater temperatures above the dew temperature for alkali chlorides have shown a decreased corrosion rate.

The corrosion can now be mitigated with a combination of fuel mixtures, selection of superheater materials, additives and new boiler designs and it is possible to built power plants with steam data as used in fossil fired plants.

Large fossil fired plants operate today with high electric efficiency in the range of 42-45 % in condense mode. The steam data is up to 600-620 °C and 300 bar. The possibility to use high pressures is very much dependent of the plant size and especially the volume flow and boundary losses in the turbine. Reported problem for some of the super critical power plants is internal oxidation of the super heater causing oxide spallation during start and stops.

1.2 Goal

The goal for the KME-601 project is to create and evaluate high efficient, and competitive, model concepts - Reference Power Plant(s) “RPP”. The RPP model concept(s) aim to be realised in demonstration project(s) and will be moving target(s) that will be elaborated along with new findings and results from projects within the programme.

The project object is also to identify and evaluate supporting R&D projects in line with KME Program and required for a later demonstration.

1.3 Main activities

Main activities for KME-601:

- Overall project planning and time schedules for the demonstration project(s)
- Coordination – meetings, information transfer between project partners, reports, definition common framework for calculations
- Analyse and elaborate the results from the pre-study "Efficient power generation from renewable fuels – initial phase" as a base for further work.
- Put together economic input data such as investment costs and economic input data for further assessments in an economic assessment model.
- Heat and mass balance calculations for different Reference Power Plant (RPP) designs.
    - Define input data / assumptions
    - Collect data for boiler and steam turbine from Metso and Siemens and other sources and projects
    - Assist in techno-economic optimisation (e.g. steam data reheat, process configuration and data, integrated fuel drying, etc.)
- Assessments of project proposals on behalf of the Steering committee, evaluating in which extent the proposals are in line with RPP targets.
- Collect functional and operational data for possible demos and sites from energy companies
- Assessment of proposed new data, concepts, features, and configurations from on going parallel projects
- Put together the input from all project partners (technical descriptions, heat and mass balance calculations, cost calculations) for each RPP into a final report
- Based on results for the RPPs, identify critical areas and define project proposals for other parts of KME (e.g., material testing, demonstrations in existing plants)
- Assist in finding and defining basis for external financing, such as EU funding
- Final result of the project => Define concept(s) for demo plant and possible sites

1.4 Participating parties in KME 601

Participating companies in KME 601:

E.ON Climate & Renewables (UK)

E.ON Värme AB

Fortum Värme AB

Göteborgs Energi AB

Kraftringen AB

Metso Power AB

Metso Power OY

Mälarenergi AB

Siemens Industrial Turbomachinery AB

Skellefteå Kraft AB

Svensk Fjärrvärme (Swedish District Heating Association)

Söderenergi AB

Vattenfall AB

Växjö Energi AB

Öresundskraft AB

1.5 Project organisation

The project works have been done by representatives from the larger member companies in the project, see Table 1. The work was coordinated by a smaller group consisting of persons marked with an asterisk in Table 1.

Table 1; Working group participants

Project responsibility	Company	
Project manager	Erik Skog AB	Erik Skog *
Boiler system	Metso Power AB Metso Power OY	Jan Olofsson * Mikko Lethiniemi * Tero Luomaharju Asko Rantee Terhi Tallqvist Hanna Kinnunen Kari Mäkelä Sonja Enestam Johanna Tuiremo Ari Kokko
Steam Turbine system	Siemens	Jari Nyqvist * Oscar Mazur * Arne Karlsson Patrik Bengtsson
Fuel, operation costs/conditions & materials	Vattenfall E.ON Värme E.ON C&R	Maria Jonsson * Pamela Hendersen Christer Forsberg Raziyeh Khodayari * Mats Åbjörnsson * Khamun Ward *
Process analysis & Economical assessments	Pöyry Vattenfall	Per-Axel Nilsson * Lennart Larsson Martin Petersen Clas-Göran Andersson
KME	Elforsk	Lars Wrangensten * Bertil Wahlund *

The working has been reporting to the EPP steering committee with representatives from each main party within the consortium.

The project has been totally financed within the KME program. The costs was covered without contribution from the Swedish Energy Agency, see Table 2. The reason was that industrial persons did al the work done in the project.

Table 2; Project financing in kSEK.

Company	In kind	Cash	Total
Siemens	400		400
Metso	300	100	400
Vattenfall	400	300	700
E.ON Värme	150	100	250
E.ON C&R	300		300
Fortum	0	250	250
Kraftringen	0	100	100
Svensk Fjärrvärme		500	500
Göteborgs Energi		300	300
Mälarenergi		200	200
Skellefteå Kraft		200	200
Växjö Energi		200	200
Öresunds Kraft		200	200
Söderenergi		100	100
Total from Industry	1 550	2 550	4 100
From KME		0	
Total	1 550	2 550	4 100

1.6 Time schedule

1.6.1 Main time schedule for the EPP program

A goal for the KME program was to demonstrate a high efficient CHP plant to be commissioned around 2017-2018, see Figure 1. The KME 601 project, which was included in R&D activities, had both a short and a long-term focus. The short-term focus was related to the demonstration project(s) and required tests for realizing the demonstration(s). The RPP project also assisted in finding concepts that could be demonstrated. If a commissioning should take place 2017, a host for the demonstration plant should be selected by the end of 2013. The KME 601 project should assist the possible host with the bases for making this decision. Risk mitigation for the demonstration plant project is one important area that shall be addressed within the RPP project.

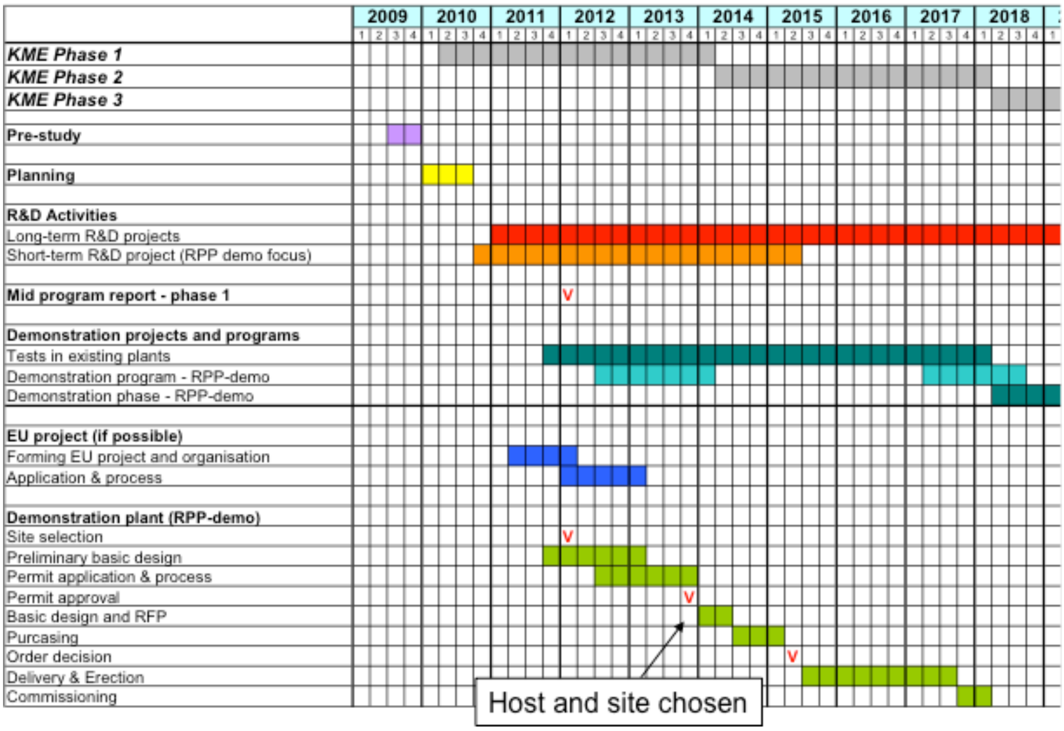


Figure 1; Work plan

2 Conditions and requirements

The project group have selected typical general conditions and requirements for different fuel specifications and CHP sizes. A size range from 25 up to 100 MW_e has been selected.

2.1 Fuel specification

Fuel specification is the most important factor for designing the CHP plant, and a limitation for advanced steam data. Moisture, ash, chlorides, alkali and other metals such as Pb, Zn, and Al are critical compounds, see Table 3.

Alkaline chlorides are critical for high temperature corrosion in super heaters. Pb content that is significant for waste wood is forming PbCl2, which is especially critical for “mid-temperature” corrosion in furnace panel walls and in back-pass tubes. Content of Zn forming $ZnCl_2$ can is critical for low temperature corrosion in the cold end of the boiler.

The content of the critical compounds is varying a lot in waste wood, depending on both source and between different countries. This will also change over time. Hereby maximum values have to be defined and in practice controlled by monitoring and mixture between waste wood and virgin wood.

Table 3; Fuel specifications for virgin and wide range biomass fuels

		"Virgin"		"Wide"	
		Average	Max.	Average	Max.
Forestry residues chips	% LHV	100		25	
Recovered waste wood chips	% LHV	0		75	
LHV (incl. moisture & ash)	MJ/kg a.r.	9,1	11,7	12,3	14,2
Moisture	mass-%	45,0	55,0	29,7	37,3
Ash	mass-% DS	3,1	4,5	3,6	8,1
C	mass-% DS	50,1	50,7	49,2	50,0
H	mass-% DS	6,1	6,4	6,0	6,2
O	mass-% DS	40,1	40,5	39,8	40,9
S	mass-% DS	0,05	0,11	0,06	0,12
N	mass-% DS	0,58	0,77	1,50	2,09
Cl	mass-% DS	0,03	0,04	0,12	0,15
Pb	mg/kg DS	4	N/A	158	266
Zn	mg/kg DS	100	N/A	116	278
K	mg/kg DS	2000	3000	1201	1785
Na	mg/kg DS	300	300	707	1026

Two typical alternatives have been studied. A **virgin biomass** fuel specification based on forestry residues (GROT) and a second alternative representing a **wide range** fuel specification, based on 75% demolition wood and 25% forestry residues.

These specifications are essential for the design of the boiler. The basic specifications for virgin wood and waste proposed by Vattenfall have hereby been thoroughly discussed within the working and steering group before decided.

2.2 Operation

Operational conditions such as operation time, part-load operation, condensing or re-cooling operation modes, district heating connection and temperatures are of great importance for the optimisation of the plant and the possibility to use enhanced steam data or other efficiency boosting measures see example in Figure 2.

The basic analyses have been carried out for combined heat and power (CHP) applications, but also condensing plants have been considered.

CHP plants are in general designed and optimized for a heat generation system; in this case the focus is a district heating system. The heat production in a district heating system consists of several different production units for base, mid and peak capacity. Even if every system is unique, a typical system is used for setting the operation conditions for the studied CHP concepts. In Figure 3 below a load curve and correspondent heat duration diagram show a usual situation where waste heat or a waste-to-energy plant, with low variable operation cost, occupies the bottom of the base load in the diagram, and typical operating space above (after waste heat) for a biomass CHP plant. Possible production will be dependent on the heat capacity, minimum operation load and availability.

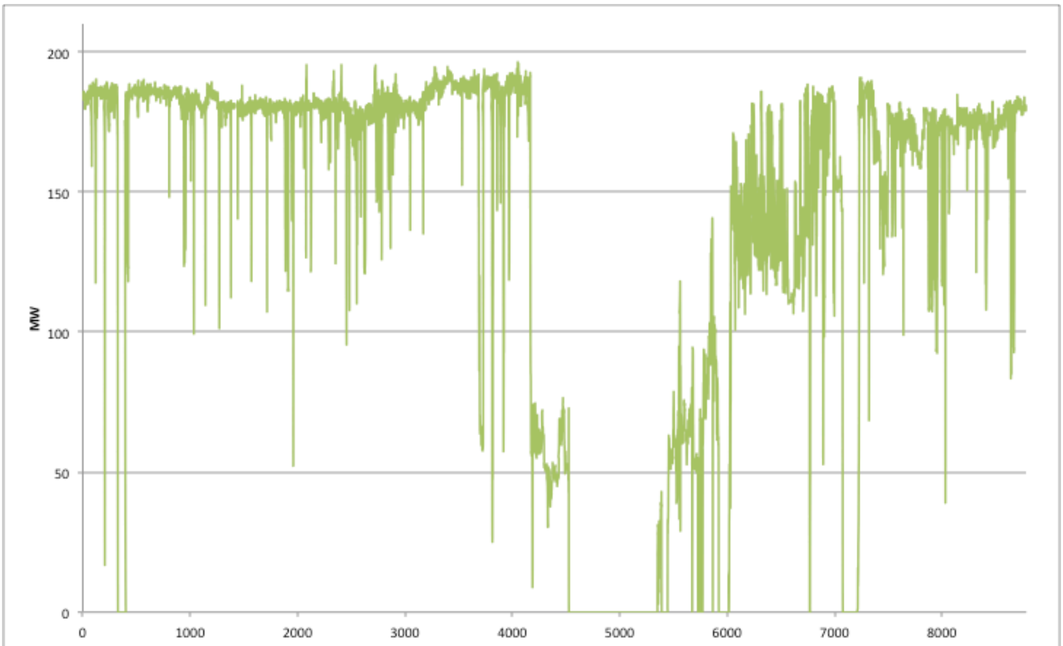
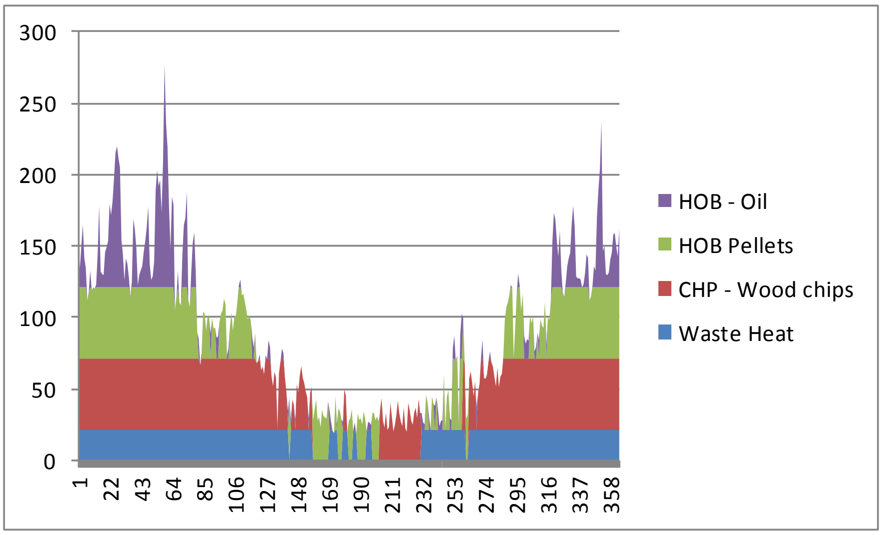


Figure 2; Thermal Power for P5 at Mälarenergi 2011

In the system shown in Figure 3 the CHP plant operation time would be about 6800 h and the equivalent full load duration about 6000 h per year, based on a minimum load of 35 %.



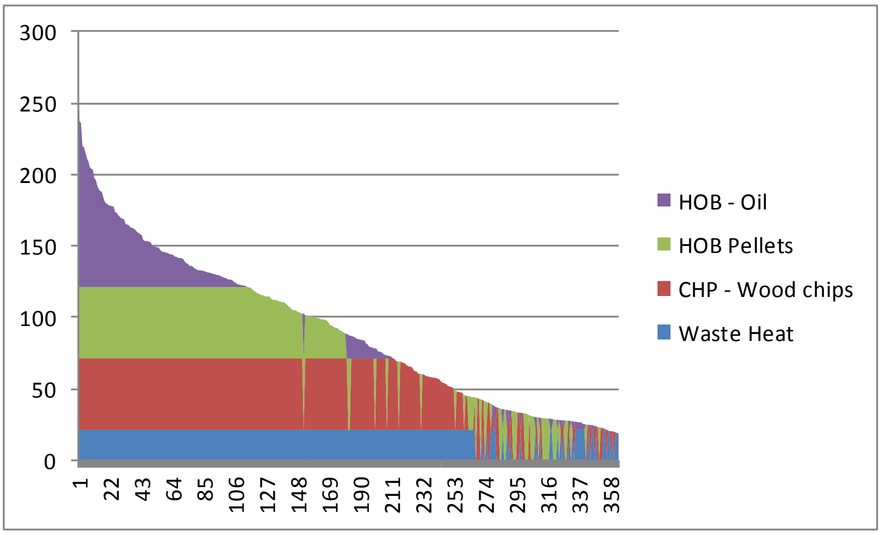


Figure 3; load curve and correspondent heat duration diagram (MW vs. operation days)

General data for analyses:

- Operation mode
  - CHP – back-pressure mode
  - Condensing mode (large plants)
- Equivalent full load operation time
  - Back-pressure mode 5000-7000 h/a

    - Condensing mode >7000 h/a
- Flue gas condenser (FGC) not included in base case
- District heating temperatures
    - Design supply temperature 90 °C
    - Design return temperature 45 °C
- Condensing operation mode: condensing pressure
    - See water condenser 0,03 bar (see water inlet 5 °C)
    - Air cooled condenser 0,07 bar (air inlet 15 °C)

2.3 RPP alternatives

Efficiency can be improved by several means. Some of the main measures for increasing efficiency are listed below (from ref 1):

- Steam temperature and pressure
- Turbine isentropic efficiencies (in different parts), tightening/leakage steam, handling moisture in last stages, mechanical and generator losses
- Process configuration (Reheat, no of pre-heaters and heat condenser stages, etc.)
- District heating return and supply temperature
- Boiler efficiency (flue gas temperature / material choices / flue gas cleaning / auxiliary power requirements)
- Reduction of auxiliary power (pumps, fans, pressure drop water and flue gas side, fuel preparation, auxiliary systems)
- Maintenance (optimisation / status controlled maintenance)
- Improved dynamics and control
- Improved part load efficiency (control, design)

Many of these improvements could be done for both existing and new plants with conventional steam data. In KME 601 the focus has been to improve the steam process with enhanced steam and feed water data with or without reheat, in order to achieve a significant efficiency increase.

Plant capacity range has been selected based on different interest among the stakeholders of the project, i.e. district heating system owners and energy companies of different sizes. General RPP alternatives so far are summarised in table below.

	Capacity	Fuel mix	
		Virgin	Wide
Small	"25" MW_e	SV	SW
Medium	"50" MW_e	MV	MW
Large	"100" MW_e	LV	-

The studied RPP concepts are named by the presented prefix followed by a number combination stating the version, for example "LV1.0.3".

For each size and fuel mix a "benchmark" version have been defined. The benchmark stands in this case for conventional steam data and performance. The numbering of the benchmark concepts starts with a zero, for example benchmark for 100 MW_e Virgin is named "LV0.1".

The selection of RPP concepts that have been studied are to begin with based on what is technical and practical possible, in order to achieve a major increase of the efficiency. Findings from the pre-study "Efficient Power Generation from Renewable Fuels" (ref 1) have been considered.

CHP concepts with virgin fuels have been studied for all sizes, while for wide fuel range only for medium and small sizes. When studying different CHP concepts for a certain capacity range, the heat output is kept constant. This means that the boiler capacity have to be increased for a concept with a higher electricity efficiency and power output.

Some condensing cases have been studied for $\geq$100 MW_e class plants based on virgin fuels only. In these cases the fuel input is kept constant.

Based on functional and economically assessment the most interesting concepts could be sorted out.

2.3.1 Benchmark or reference steam data

For virgin fuels common steam data for mid-size plants built in Sweden the last 10-15 years is 140 bar, 540 ºC, even if the more advanced configurations (reheat) and steam data have been available, see Table 4.For larger plants higher steam data can be offered today. One example is the Fortum Värtan plant to commissioned 2016 at Värtan with a boiler capacity of 330 MW and steam data of 140 bar and 560 °C.

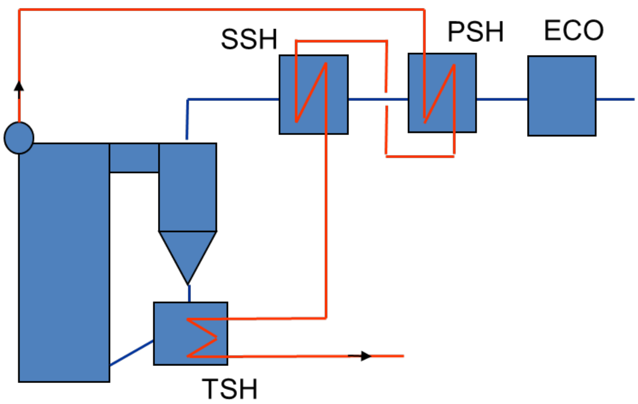
Table 4; Biomass fuelled CHP plants

	Comm.	Boiler	Fuel	Thermal	Electric	Eff. Gross	Steam		F.W.	HPFW
				MW,th	MW	calculated	bar,g	C	C	no.
Virgin biomass fuels										
Västerås	2001	CFB	wood chips, peat, coal	157	58	*33%*	170	540/540	240	3
Eskilstuna	2000	CFB	bark, sawdust, wood chips	110	39	32%	140	540		
Östersund	2002	CFB	forest residues, shavings	125	45	32%	140	540		
Skellefteå	1996	CFB	forest residues	98	34	31%	140	540	230	2
Ö-vik	2008	BFB	bark, chips, sawdust, peat 15%	130	40	28%	140	540	210	2
Kalmar	2009	BFB	forest residues	90	31	31%	140	540	210	2
Växjö	1996	CFB	forest residues, peat 10%	104	38	33%	140	540	230	2
Östersund	2002	CFB	forest residues, sawdust	125	45	32%				
Lycksele	2001	CFB	forest residues	46,5	14,2	27%	87	520		
Enköping	1994	Vibro	forest residues, pellets	80	24	27%	100	540	200	2
Brista	1996	CFB	forest residues	122	44	32%	140	540	230	2
Örebro	2012	BFB	forest residues	70	24,2	31%	140	540	210	2
Växjö	2014	BFB	forest residues	105	38	33%	140	540		
Recycled wood, RDF, Agro										
Jordbro	2010	BFB	recycled wood (RT) 100%, agro	63	20	29%	81	470		
Blackburn Meadows (UK)	2014	BFB	recycled wood (RT)	88	30	31%	85	487		
Igelsta	2009	CFB	wood chips, RT 70 %, REF 25 %	240	85	32%	90	540	210	2
Maxau -Mill (D) (back-press.)	2010	CFB	wood, mill sludge, REF, coal	155	41	24%	95	520		
Delfzijl (NL) (cond)	2013	CFB	recycled wood (RT) 100%	127	49	35%	90	520		
Munksund	2002	CFB	bark, sawdust, cardboard	96	25	23%	60	480		
Falun	2006	BFB	wood chips, bark, sawdust, RT	31	8,7	25%	70	500		
Fynsverket (DK)	2009	Vibro	straw 100%	106	34,5	29%	110	540		

For the wider band of fuel mixtures with recycled wood and/or agro fuels, the picture is not that clear. The specific fuel mix, boiler technology and measures taken for preventing fouling and corrosion problems have to be considered. It is however evident that the pressure is lower in all plants built for this more difficult fuels in order to prevent furnace corrosion. Temperature is also lower, at least for all BFB boilers in order to reduce high temperature corrosion. CFB have the possibility to put the final super heater in the loop seal and can hereby reduce risk for high temperature corrosion.

2.3.2 Virgin biomass

Benchmark steam data for virgin fuels has been defined as 140 bar and 540 °C, which can be achieved with both BFB and CFB boiler technology. The studied benchmark concept is a CFB boiler with final superheating in loop seal.



The first target for RPP has been 190 bar and 600 °C with or without reheat. For large size CHP and virgin fuels Metso will propose CFB drum boilers with natural circulation for steam data max 176 bar and 570 °C, with reheat. For higher pressure than 175 bar, forced circulation will be required.

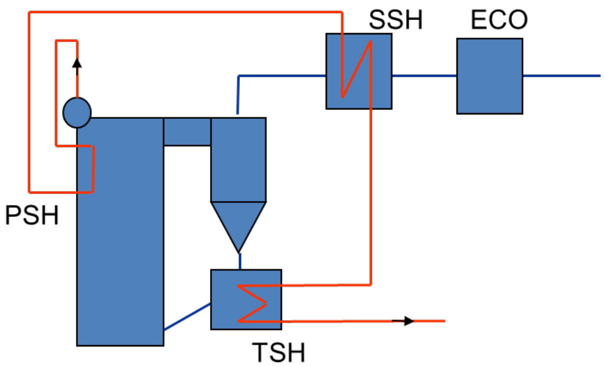
For the smaller capacity of about 25 MW_e the benchmark boiler technology is assumed to be a BFB boiler, whereas the advanced concepts are all based on CFB technology.

Siemens can commercially offer steam turbine concepts for the large size plant with steam data up to 175 bar and 570 °C, with a 1 or 2 turbine solution.

For the small size, 25 MW_e CHP, the pressure has to be reduced due to losses in the high-pressure section of the steam turbine (short turbine blades). A 2-casing turbine solution will be required in this case where the HP turbine with a high speed is connected via a gear. For this size a limit of max 175 bar and 570 °C would be possible to offer according to Siemens. The steam data limits for available turbines of this size will probably, especially for pressure, be lower for several other suppliers.

2.3.3 Wide fuel mix

Benchmark for wide fuel mix would according to Metso be 90 bar and 500 °C for a CFB boiler. The main reason for the reduced pressure is as mentioned the "mid temperature" corrosion driven by heavy metals such as lead chlorides condensing on evaporation tubes, where the metal temperature is about 350-400 °C, due (saturation temperature and temperature diff to metal to be considered).



In order to achieve a major efficiency increase Metso proposes to enhance the pressure significantly. The target steam data has in this case been 160 bar and 560 °C, with or without reheat. This means that measures have to be taken in order to prevent mid-temp corrosion, further described in chapter 4.

All concepts, both benchmark and advanced, and all sizes are assumed to be based on CFB technology and on Metso's new CYMIC design for waste wood.

3 Process analysis

3.1 General

An initial study Elforsk 2483 (ref 2) was performed in order to identify and list relevant problem areas and research needs to be studied and solved in the planned new research programme in order to reach the goal with higher electrical efficiency. Preliminary targets for advanced CHP plants; "Reference Power Plants" (RPP) were studied for virgin fuels.

The main purposes for the process analysis in KME 601 are to further define the target RPPs for both virgin fuels and for wide range fuels. Process calculation results have been used for selecting the RPP options to be further analysed in the economic assessment and for defining the interface data for the boiler design studies.

Steam data for the different options have been decided within the KME 601 working group. The steam cycle layouts have made in cooperation between Siemens and Pöyry/Vattenfall. Siemens have made selected process calculations of the steam-water process only and Pöyry/Vattenfall has made "total" heat balance calculations including both steam-water process and boiler. Input for the boiler configurations have been received by Metso.

The major parts of the simulations have been done with the software Thermoflex, a well-known steady state tool from Thermoflow Inc. for modelling and simulation of power plant systems. It contains standard power plant components and has robust solver for quick convergence. The input data for the steam turbine cycle, e.g. isentropic efficiency, gland steam flows are mainly based on data from Siemens and the Siemens Heat Balances. Boiler input data are mainly based on data received from Metso.

The processes are not fully optimised in this study. The process layout, number of preheaters, extraction points, feed water temperatures, heat transfer areas, are chosen based on what is reasonable from an economical and functional perspective. The main goal is to find the potential of each step. However, the differences in efficiency compared to a fully optimised steam cycle should not be significant.

As a general approach, as for the design and economic studies, the process analysis has focused on the larger options based on the assumption that there are more viable possibilities for the larger sizes, and what is not of interest for the larger sizes will probably not be of interest for the smaller sizes.

As basic condition for the CHP concepts, the heat output is kept constant for RPP cases (in the same capacity range). This means that the boiler capacity have to be increased for a concept with a higher electricity efficiency and power output. For the condensing cases fuel input is kept constant.

The process analysis has been made in following steps:

1. Definition of base Benchmark references cases for each sizes and fuel mixes
2. Definition of process configurations and targeted steam data
3. Obtain preliminary solutions for steam turbine system and boiler system presented by the Suppliers within the consortium to be input for heat balance analysis
4. Heat balance and performance analysis including integration between boiler and steam turbine system, for the defined process cases to be used for elaboration of the most technical economic RPP

3.2 Simulation conditions

In the appendix "PM – KME601 Heat balance calculations", calculation conditions as well as results from all valid heat balance calculations are presented. A summary of important calculation conditions:

- District heating return/supply temperature 45/90 ºC, 2 heat condensers aimed at equal heat duties
- Condensing cooling water temperatures 5/15 ºC or 15/30 ºC depending on type of cooling source
- Flue gas condenser is not included in the basic design
- CFB boiler combustion technique as a base for all calculations

- Steam and flue gas heated air preheating
- Bag house filter flue gas cleaning (fly ash)

- The efficiencies of the steam turbines and gland leakage flow are generally based on Siemens heat balance data
- All fans are assumed to have a design point isentropic efficiency of 80 % and a mechanical efficiency of 99 %
- All pumps are assumed to have an isentropic efficiency of 85 %.
- The efficiency of the motors is calculated by Thermoflex, typically around 95 %.
- The efficiency of the generator and gear is also estimated by Thermoflex to be around 98.4 %.
- Pressure drop in different parts of air and flue gas path as well as in steam line is presented in attachment 1.

Table 5; General outline of boiler and air and flue gas path

Boiler system	Data input
Air system	The primary air is 40 % of the total air
Air temperature inlet FD fan	35 °C
Furnace	Furnace temperature 870 °C Excess air 24 %
Steam circuit	Boiler blow down 0.25 %
Flue gas temperature inlet ID fan	150 °C

The convective heating surfaces have been divided into three super heaters for all cases, with temperature control before the second and third super heater. Table 6; General outline for the convective heating surfaces shows the basic assumptions for the convective heating surfaces. In addition, it is assumed that approximately 5 % of the heat release in the super heaters is transferred to the panel walls.

In addition to the convective super heaters there is an embedded final super heater placed in the loop seal (cyclone leg).

There is one economiser section placed in the final draft in front of the main air preheater.

Table 6; General outline for the convective heating surfaces

Minimum pinch		Configuration	Attemperation/Sub cooling
SH 4		embedded	15 °C Attemperation at inlet
SH 3	10 °C	Counter flow	1 % Attemperation at inlet
SH 2	10 °C	Counter flow	1 % Attemperation at inlet
SH 1	10 °C	Counter flow	
Eco 1	10 °C	Counter flow	>10 °C Sub cooling at exit

The air preheater is a rotary air preheater, except for 190 bar live steam and cases below 100 MW_e where a tubular convective air preheater has been considered.

The lowest acceptable metal temperature that can be tolerated to avoid low temperature corrosion is considered to be 100 °C at a moisture content in the flue gas between approximately 20-25%. At an exit flue gas temperature of about 150 °C, it is considered necessary to rise the air temperature, with a steam fed air-preheater, to above 60 °C before it enters the flue gas air preheater

Feed water preheaters and DH condenser input for TTD (Terminal Temperature Difference), DCA (Drain Cooler Approach) and residual superheat temperature are presented in ref 2.

The auxiliary power consumption for the plant, based on the electrical consumption, has been calculated in the Thermoflex simulations. This includes all the major power consuming components; for example, feed water pump, FD and ID fan. In addition to the major components, it is assumed that there are miscellaneous consumptions as follows:

- Miscellaneous minor uses 2 % of gross power output, mainly fuel handling corresponding to about 7,4 kWh/ton fuel

3.3 Virgin fuels

A starting point for the process analysis for virgin fuels was the most enhanced steam data identified in the initial study, called RPP enhanced: 190 bar/600/600°C. According to chapter 2.3.2 this is also the first target for RPP with or without reheat.

Different defined technical steps from benchmark to the most advanced target have been studied for the virgin biomass fuelled 100 MW_e size CHP process.

The first step down was to reduce the admission pressure down to 175 bar. This enables a drum boiler with natural circulation, avoiding pumps for forced circulation. This also enables a 2-casing steam turbine instead of 3-casing which reduces Capex significantly.

Other steps and reasons for these are further described in chapter 4. The different steps are summarized in Table 7; Steam data steps studied for virgin fuels.

Table 7; Steam data steps studied for virgin fuels

Step	Pressure (°C)	Temp (bar)	RH Temp (bar)	Comment
Initial advanced target	190	600	600	Forced circulation, full steam temp to 80%
Advanced with target temp - RH	175	600	600	Circ. pumps not required
Advanced - RH	175	585	585	Flue gas circ. not required + improved operation range
Enhanced - RH	175	570	570	Commercial steam turbine temp data
Reheat and conventianal data	140	540	540	Conv. steam data
Target temp - No reheat	175	600		Smaller loop seal s.h. => less excess air and NOx
Avanced - No reheat	175	585		Improved operation flexibility without RH
Enhanced - No reheat	175	570		Commercial steam turbine temp data
Benchmark	140	540		Commercial proven for virgin biomass

Process layout and feed water temperature have been chosen for each case. Considerations have been taken to flue gas temperature (max 150 °C), margins and based on experience reasonable heat transfer surfaces (see ref 2).

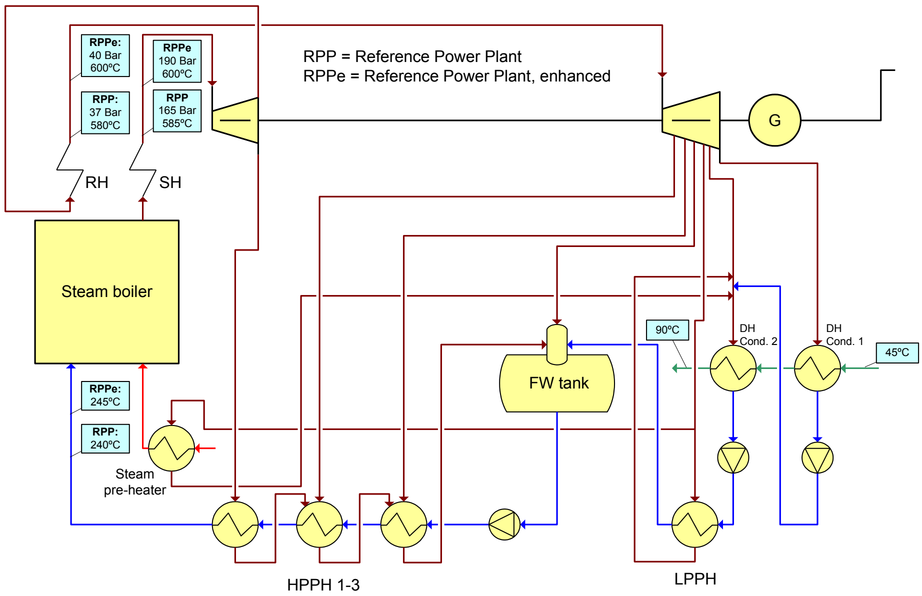


Figure 4; Schematic process for targeted advanced plant for virgin fuels

In the reheat options for CHP, considerations have to be taken to part load performance. Hereby the RH pressure have been increase compared to the ideal for full load, in order to avoid too steam high temperatures at last stages of the steam turbine.

Feed water temperature have an significant impact on the efficiency. An extra HP feed water heater increasing the temperature about 30-40C could result in extra 0,5-1%-points efficiency. This will however have an impact on Capex and on heat surfaces in boiler and/or flue gas temperature.

Even if a high feed water temperature (about 280 °C) would be preferred thermodynamic the recommendation is max 256 °C, based on a rough total evaluation of both Capex and efficiency (including flue gas temperature), also considering technical limitations. By allowing somewhat higher flue gas temperature the air preheater surface and pressure drop can be reduced. This is especially important for smaller units where rotating air preheater will probably not be feasible.

Calculations have also been done for the most promising options for 50 MW_e and 25 MW_e. For the 25 MW_e size reheat is not examined and the temperature is limited to 570 °C, correspondent to available steam turbines from Siemens. The commercial available steam turbines from other suppliers above benchmark steam data (140 bar, 540 °C) are limited for this size. Pressures above 160-170 bar increases border losses due to short turbine blades.

3.4 Wide range fuels

Based on the expected market for wide range fuel CHP plants the 100 MW_e was ruled out for this fuel mix. The first calculation was made for an intermediate 75 MW_e size. The largest size for wide fuel range was however later changed to 50 MW_e, after a decision that this was a more interesting CHP size for the stakeholders.

Metso proposed the target for the wide fuel range. According to chapter 2.3.3 the target was defined to 160 bar and 560 °C, with and without reheat.

The steam data for the process is proven for virgin fuels but is very advanced for the actual waste wood share. Apart from the no reheat option no other steps have been studied for the wide fuel range between the advanced and the conventional steam data. The reason for this is that major challenge in this case is the mid-temperature corrosion risk, which occurs already at steam pressure above 100 bar, and the mitigation measures will be more or less the same (see chapter 4).

3.5 Heat balance calculations

A large number of heat balance calculations have been made in order to investigate the potential and different steps of advanced steam data. The calculations have been for defining input and interface data to the boiler and steam turbine design studies, as well as a tool for checking different steps, such as changing, admission steam data, feed water chain and temperature, RH steam data, air preheating, etc. for both design and economic evaluation.

The models are based on input from both Siemens and Metso. The boiler calculation model is made based on Metsos presented principle design, heat surface distribution and interface data. Due to confidentiality reasons Metso have made internal boiler calculations for the design study. Detailed data such as heat surface areas, losses and temperature distribution has not been available for the working group. Hereby approximations have been required for the process analyses, with an expected accuracy that is good enough for the aim of this analysis.

Further conditions and results are presented in ref 2.

I Figure 5 and Figure 6 some of the calculation result are shown for the 100 MW_e size CHP plants for virgin fuels.

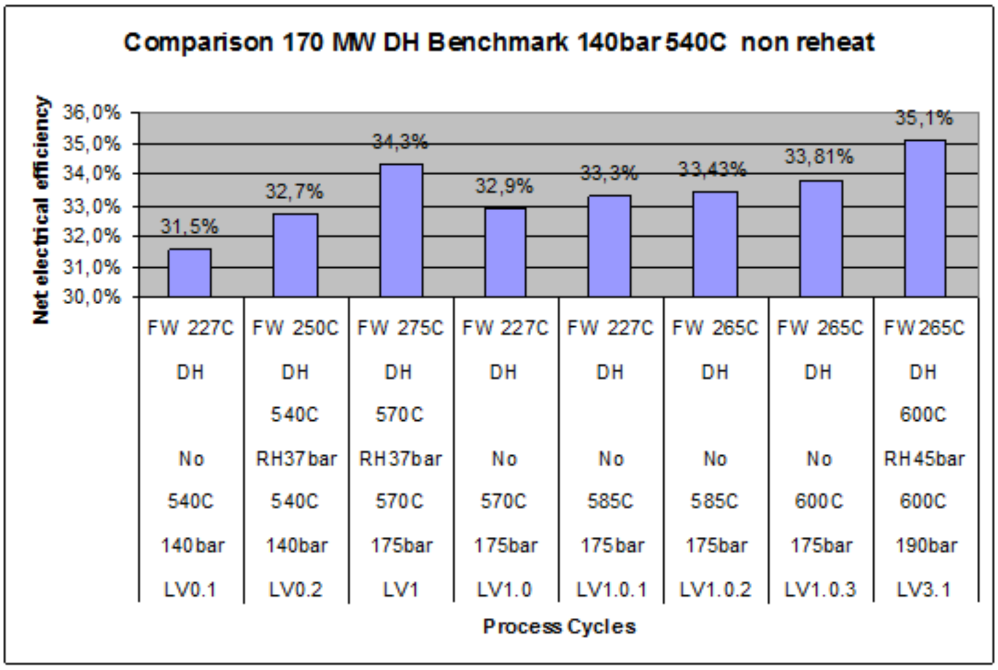


Figure 5; CHP 100 MW_e virgin fuels – Comparison of different steam data

The improvement from benchmark to the most advanced process with 190 bar and 600/600 °C (reheat) is about 3,6 %.

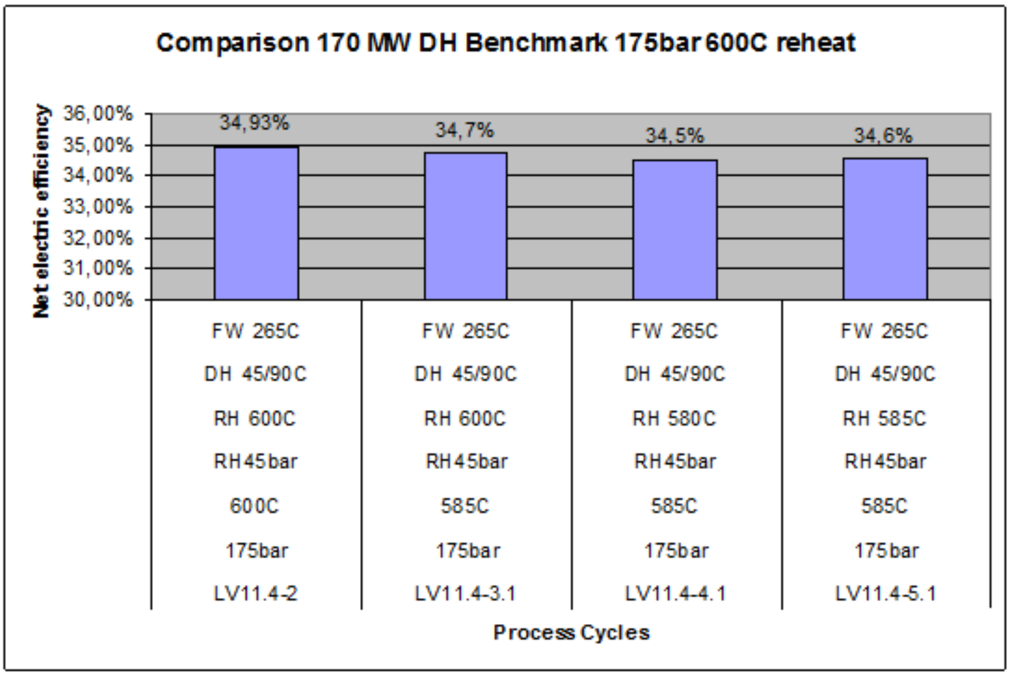


Figure 6; CHP 100 MW_e virgin fuels – Impact from RH temperature

By reducing the pressure down to 175 bar the boiler circulation pumps could be avoided, which was recommended by Metso, for availability and cost reasons.

A sensitivity analysis was made for reducing the admission and reheat temperature. By reducing temperatures from 600/600 °C to 585/585 °C the efficiency loss is approximately 0,3 %-units. The gain is reduced super heater area and physically volume required for loop seal final super heaters. This improves the operating range and margins, less flue gas recirculation requirement, and more proven materials can be used, according to the design study.

The 175 bar 585/585 °C process were selected as the most promising reheat concept and 175 bar 600 °C without reheat for virgin fuels. The gain compared with benchmark in these cases is 3,1 % and 2,3 %-units.

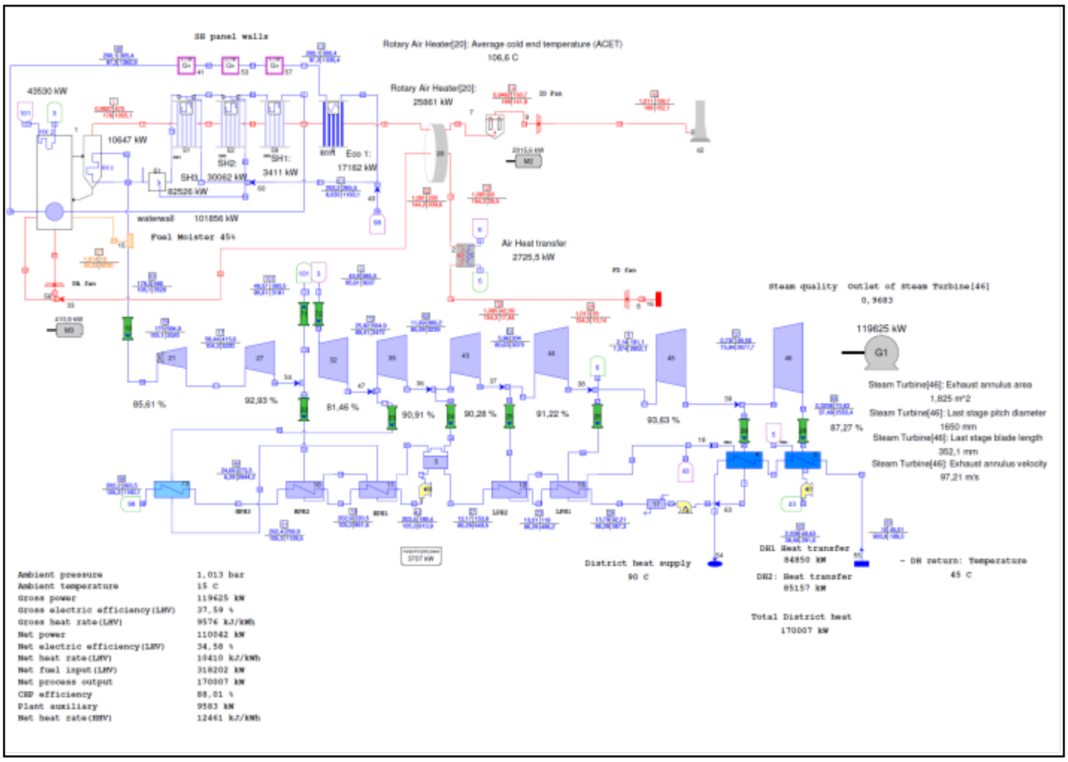


Figure 7; Virgin fuels 100 MW$_e$ class – 175 bar, 585/585 °C – Thermoflex

For the large virgin fuelled plant calculations have been performed for condensing applications. I addition to the CHP calculations some supercritical processes was performed for the condensing case. The improvement compared to the selected benchmark is however in the range (+3,4 to 3,6 %) as in the CHP case.

The performance in the condensing cases is dependent on the cooling water conditions and condensing pressure. As presented in the Figure 8 the difference between cooling water 15/30 °C (condenser 38 °C, 0,07 bar) and 5/15 °C (condenser 24 °C, 0,03 bar) will mean about 1,9 %-units difference.

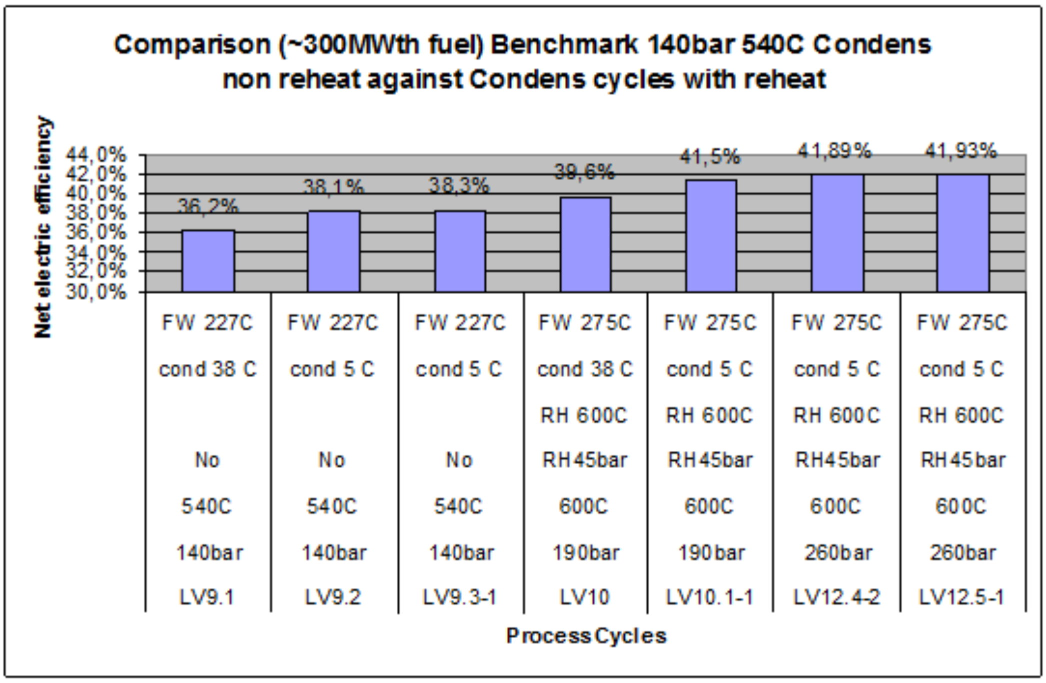


Figure 8; Condensing plant 100-150 MW$_e$ – Impact of different steam data

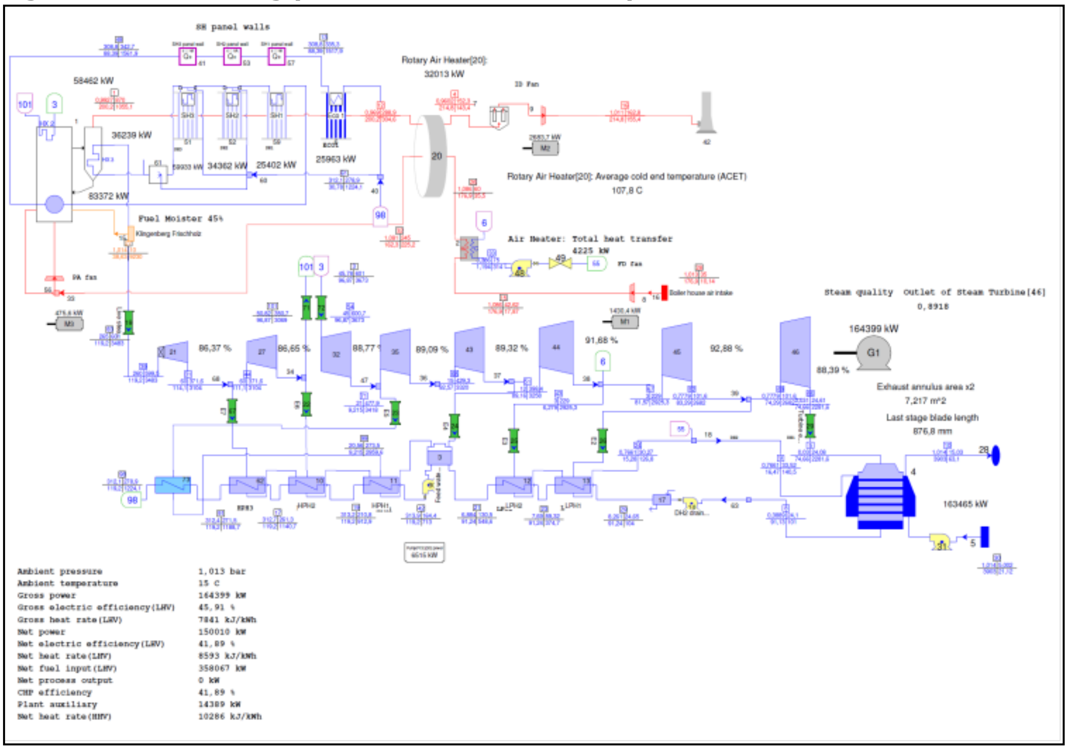


Figure 9; Condensing plant, virgin fuels 150 MW$_e$ - supercritical 260 bar 600/600 °C

For the wide fuel range cases the challenge has not been to create an advanced steam process but to design a boiler for very advanced steam data.

For the heat balance calculation the Thermoflex boiler model has been modified based on the presented Metso CFB design with a second evaporator in the back-pass. This approximation have not been calibrated with Metsos own models, but should be sufficient when comparing the benchmark and the advanced plants, which both are based on the mentioned design.

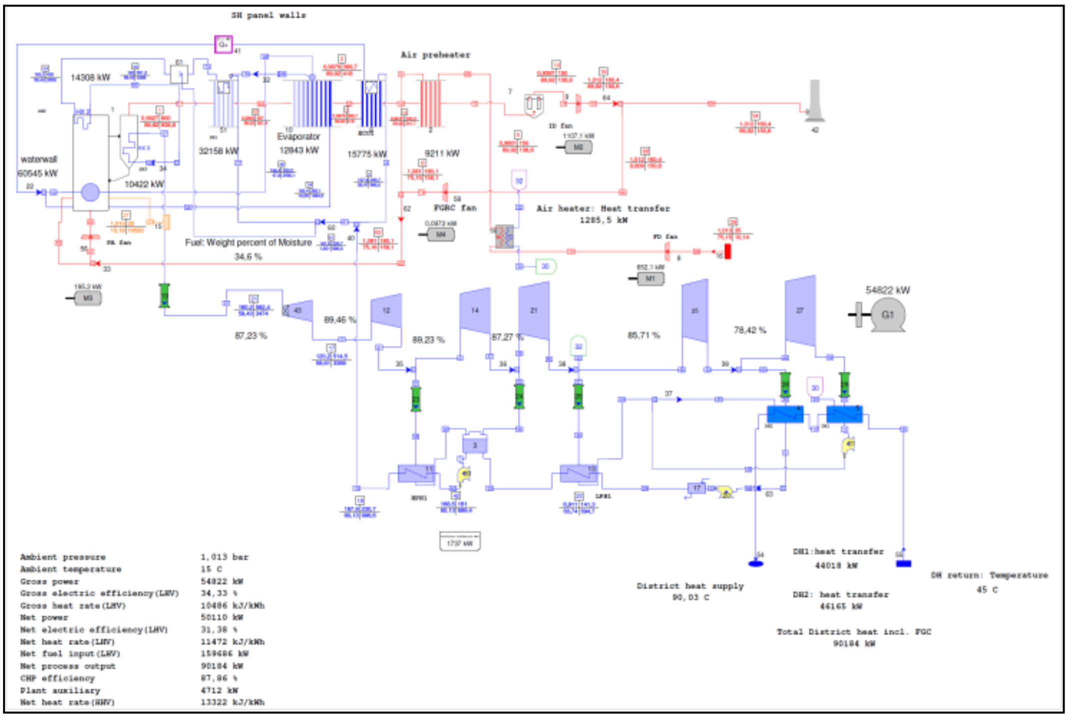


Figure 10; CHP 50 MW$_e$ wide fuel – 160 bar, 560 °C

The results from the heat balance calculations shows that there is a potential of increasing the electrical efficiency with about 3,8 %-units for an option with reheat and a potential of 2,8 % for an option without reheat.

3.6 Conclusions & summary

3.6.1 Virgin fuels

Based on the process analysis with input from the design study, see chapter 4, these are main findings.

- Reheat will improve efficiency by about 1,2 %-units
- Improvement potential is about the same for CHP with or without flue gas condenser and even condenser conditions (cooling & district heating temperatures), due to the fact that the change is connected to the top of the cycle.

- Improvement potential compared to benchmark for most advance cycle for both CHP and condensing process, i.e. 190 bar 600/600 °C is about 3,6 %-units. This steam data would probably be of main interest for condensing plants.
- Main advanced steam data options for CHP based on technical assessment for virgin fuels:
  - 175 bar, 585/585 °C: +3,1 %
  - 175 bar, 600 °C +2,3 %
- About the same improvements for 100 MW_e and 50 MW_e
- Reheat has not been investigated for 25 MW_e (not regarded economic viable). Poor improvement, about +1,3 %-unit without reheat, due to lower temperature and higher relative losses.
- Flue gas condenser will decrease electricity efficiency by about 0,3-0,6 %-units. About the same impact for benchmark as for advanced.
- Efficiency more sensitive to supply temperature than return temperature (impact from FGC). A decrease of supply temperature from 90 to 80 °C will increase the efficiency with about 0,9 %-units.
- Reheat pressure would ideally be about 37 bar have been increased to 45 bar in order to avoid high temperatures in steam turbine last stages at low loads. The loss is 0,1-0,2 %-points.

Table 8; Results for selected options for virgin fuels 100, 50 and 25 MW_e

VIRGIN BIOMASS FUELS		Reference 0			Advanced 1			Advanced 2		
		100 MWe	50 MWe	25 MWe	100 MWe	50 MWe	25 MWe	100 MWe	50 MWe	25 MWe
		LV0.1	MV0	SV0	LV1.0-3	MV5	SV1	LV11.4-2	MV4	
Steam temp		540	540	540	600	600	570	585/585	585/585	n.a.
Steam pressure		140	140	140	175	175	175	175/46	175/46	
Installed capacity										
	Electricity gross	102,1	49,6	25,8	114,6	55,4	27,8	119,6	57,2	
	Electricity net	94,2	45,4	23,7	105,3	50,7	25,3	110	52,7	
	Heat	170	85	45	170	85	45	170	85	
	Boiler output	272,1	134,6	71	284,6	140,4	73	289,6	142,2	
Fuel input		298,6	148,9	78,5	311,6	155,2	80,6	318,2	155,9	
Gross efficiency		34,2%	33,3%	32,9%	36,8%	35,7%	34,5%	37,6%	36,7%	
Net efficiency		31,6%	30,5%	30,1%	33,8%	32,7%	31,4%	34,6%	33,8%	
Boiler efficiency		91,1%	90,4%	90,2%	91,3%	90,5%	90,4%	91,0%	91,2%	
Fuel efficiency		88,5%	87,6%	87,4%	88,4%	87,4%	87,3%	88,0%	88,3%	

3.6.2 Wide range fuels

Wide range fuels have as mentioned earlier only been analysed for 50 and 25 MW_e. A summary of the findings for this fuel mix:

- Reheat will improve efficiency by about 1 %-units
- Improvement for main advanced steam data options for both CHP and condensing mode, based on wide range fuels:
  - 160 bar, 560 °C +2,8 %

- 160 bar, 560/560 °C: +3,8 %

- About the same improvements for 50 MW_e and 25 MW_e for 160 bar, 560 °C (no reheat) => Very high potential for the smallest size compared to virgin fuels.

Table 9; Results for selected options for wide range fuels 50 and 25 MW_e

WIDE RANGE BIOMASS FUELS		Reference 0			Advanced 1			Advanced 2		
		100 MWe	50 MWe	25 MWe	100 MWe	50 MWe	25 MWe	100 MWe	50 MWe	25 MWe
		n.a	MW0.2	SW0	n.a.	MW1.2.2	SW1	n.a.	MW6.2.3	n.a.
Steam temp			500	500		560	560		560/560	
Steam pressure			90	90		160	160		160/44	
Installed capacity										
	Electricity gross		46,9	24,9		54,7	29,8		59,1	
	Electricity net		43,2	22,8		50	26,9		54,1	
	Heat		90	50		90	50		90	
	Boiler output		136,9	75		144,7	80		149,1	
Gross efficiency			31,3%	30,3%		34,6%	33,9%		35,6%	
Net efficiency			28,8%	27,8%		31,6%	30,6%		32,6%	
Fuel input			150,0	82,2		158,2	88,0		166,1	
Boiler efficiency			91,3%	91,1%		91,5%	90,7%		89,8%	
Fuel efficiency			88,8%	88,6%		88,5%	87,4%		86,8%	

4 Design studies

4.1 General

Design studies have been performed for:

- Virgin 100 MW_e class
  - Benchmark 140, 540 °C (conventional data)
  - Advanced 175-190 bar, 585-600 °C with and without RH
- Wide 50 MW_e class
  - Benchmark 90 bar, 500 °C
  - Advanced 140-160 bar, 540-560 °C

Main focus has been to analyse differences between benchmark and advanced concepts, as regarding design, materials, localisation of heat transfer surfaces and Capex. Also Opex differences connected to the proposed designs have been studied.

The main design studies for Virgin 100 MW_e was carried out 2011-12, while the design studies for wide range fuels were performed 2012-13.

The design studies made by Metso and Siemens where performed by in-house personnel, design principles and tools. In order to maintain required confidentiality the results have in some extent been presented as a "black box". Some information have been received by the working group but cannot be presented because it´s of strictly confidential.

In the following chapters the information available for the working group is presented.

4.2 Boiler for Virgin fuels

4.2.1 Benchmark

Benchmark for virgin fuels is 140 bar, 540 °C. For 100 MW_e size the CFB solution is a natural choice, while for 50 and especially 25 MW_e BFB could become a competitive option. The design study has however focused on the 100 MW_e size.

Metso has presented following main data for the virgin fuel benchmark plant:

Main concept

- Main steam 140 bar, 540 °C, 112 kg/s
- Feed water: 227 °C
- Steam capacity 275 MW_{th}
- Fuel capacity 298 MW_{fu}

- Boiler type CFB

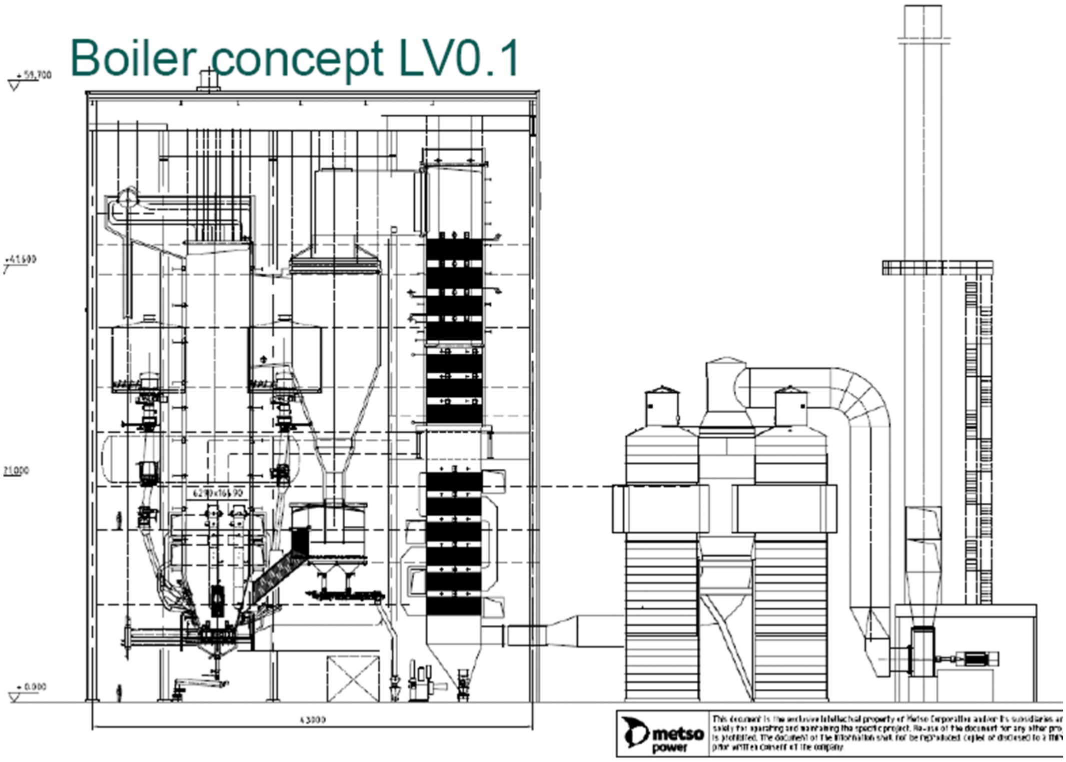


Figure 11; Benchmark design for 100 MW_e, virgin fuels 140 bar, 540 °C

System overview

- Natural circulation
- Furnace walls, walls of cyclones + loop seals (2 pcs)

- Final super heaters:
    - located in loop seals
- Emissions:
    - Ammonia injection for NO_x control
    - Bag house for particulate capture

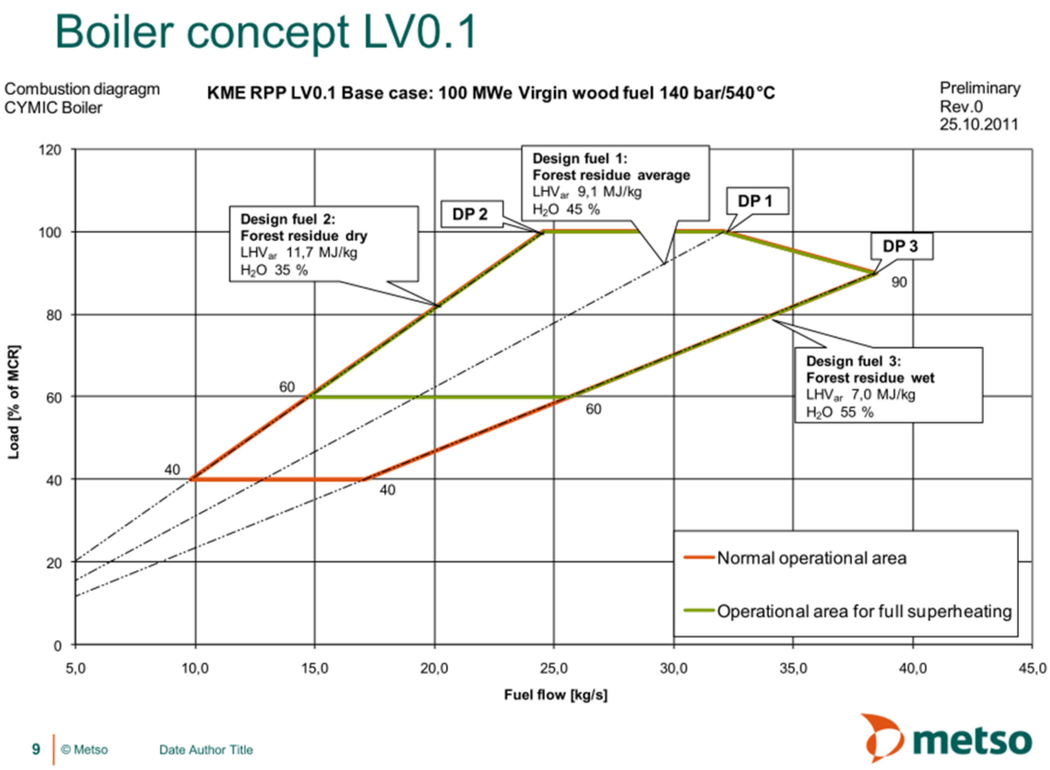


Figure 12; Firing diagram for 100 MW_e, virgin biomass, 140 bar, 540C

Process data (load=100%, fuel w=45%)

- Boiler efficiency 90,9 %
- Flue gas exit 152 °C, 165 kg/s
- LP steam to air preheating 1,3 kg/s
- Feed water tank operating p & T 6,2 bar(a), 160 °C

4.2.2 Advanced RPP

The design study started with the defined first target, a CFB boiler 190 bar and 600 °C with or without reheat. Even higher pressure would be a step into the grey zone between sub- and supercritical data, and in that case it is recommended to go all the way to super-critical and a once-through boiler for high pressures such as 240-260 bar.

According to Metso a once-through boiler (OTU) the investment cost will in the same range as a drum boiler. The high pressure would not lead to any significant increase of the furnace corrosion risk. It would however not be realistic to scale down this technology to 50 and 25 MW_e, due to high boiler costs but even more limitations for the steam turbine solution.

The compromise 190 bar would require forced circulation, which early was ruled out due to availability reasons. At 175 bar, drum boilers with natural circulation can be used. This was chosen for the design study.

The boiler for the RPP concept LV11 for CHP virgin fuels is described below:

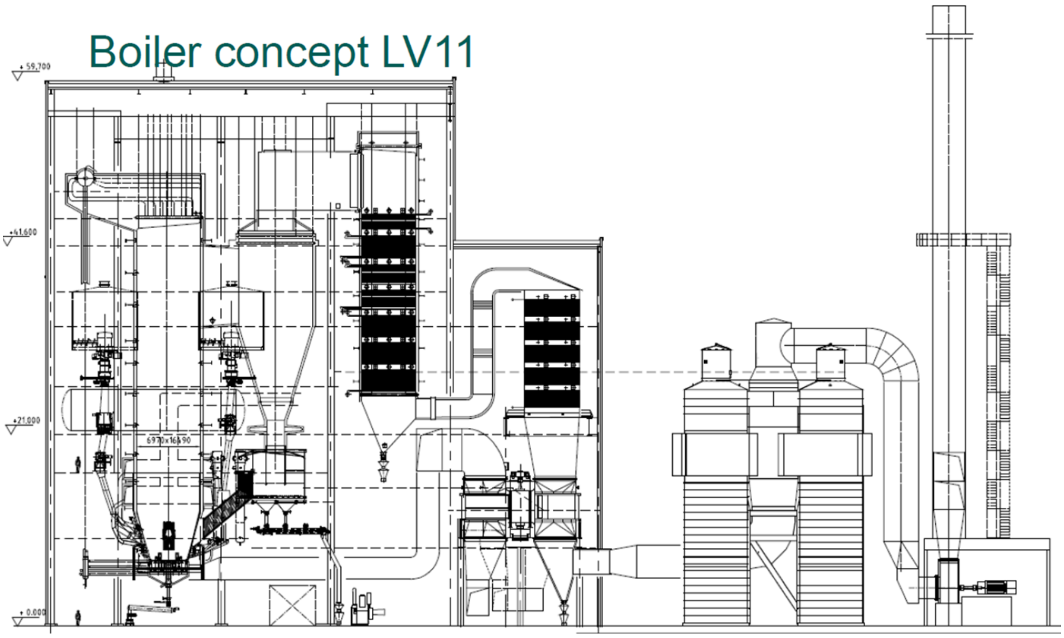


Figure 13 Advanced design for 100 MW_e, virgin fuels 175 bar, 600/600C

Main concept

- Main steam
    - 175 / 47 bar
    - 600 / 600 °C
    - 103 / 92 kg/s
- Feed water: 264 °C
- Steam capacity 291 MW_{th}
- Fuel capacity 315 MW_{fu}
- Boiler type CFB

System overview

- Natural circulation
- Final HP and RH Super heaters:
    - located in loop seals
- Air preheating
    - Regenerative (rotary) flue gas air preheater

- Emissions:
    - Ammonia injection for NOx control
    - Bag house for particulate capture
- Other added systems compared to base case
    - Recirculation gas system for furnace temperature control
    - Sulphur injection to flue gas for corrosion control

Process data (load=100%, fuel w=45%)

- Boiler efficiency 91,4 %
- Flue gas exit 137 °C, 175 (185) kg/s
- LP steam to air preheating 0,5 kg/s
- Feed water tank operating p & T 12,3 bar(a), 189 °C

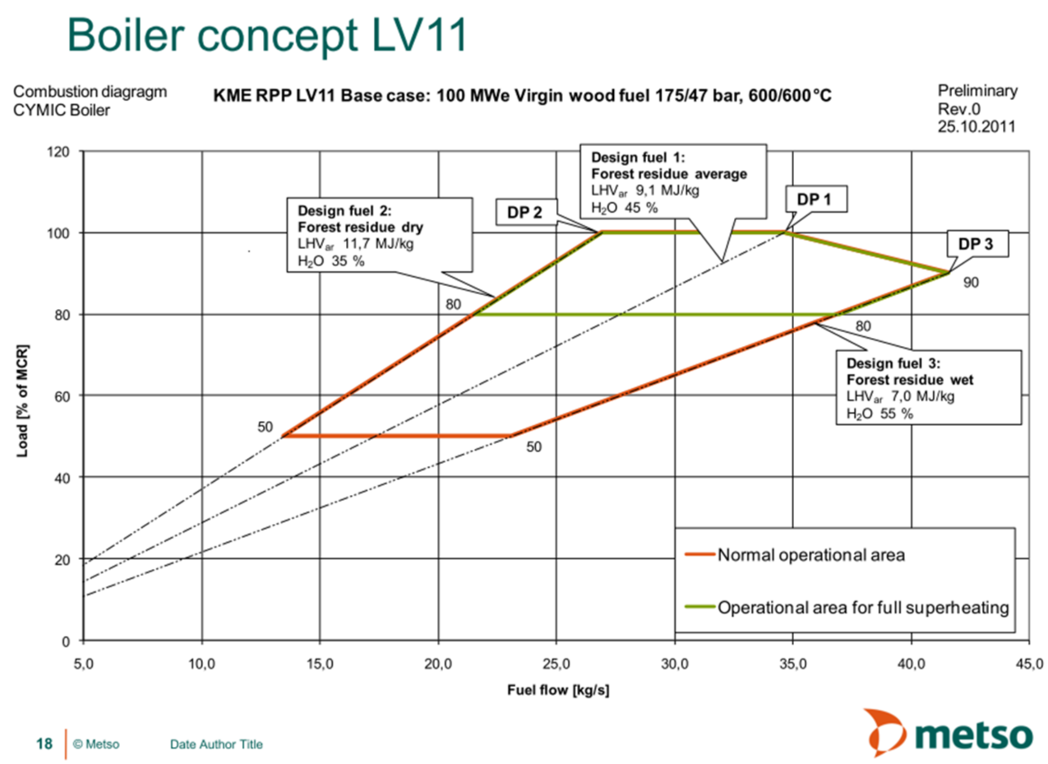


Figure 14; Firing diagram advanced RPP Virgin fuels 100 MW_e, 175 bar 600/600C

4.2.3 Technical challenges, uncertainties

The conclusions from the study, points out that the LV11 concept looks technically feasible with some drawbacks and/or question marks concerning sulphur additives for mitigating the high temperature corrosion risk in back pass, the sulphur additives impact on emissions, material to be used for 600/600 °C.

Reheat and high temperature results in large heat transfer area required in the loop seal, which will be a design challenge. Margins for steam control by attemperators will decrease at these high temperatures, as well as the sensitivity for decreased circulation at part load.

As could be seen in presented fire diagram, see Figure 14, the operation range will be reduced for LV11 compared to benchmark. Full superheating can be maintained down to 80 % load, compared to 60 % for benchmark. Minimum load is about 50 % with the LV11 compared to < 40 % for benchmark. This is especially a drawback for the CHP but not for the condensing option.

Material strength for metal temperature up to 700 °C in the final super heater (TSH) in loop seal going for 600 °C steam temperature is not jet proven and demonstrated in a real environment.

For virgin wood, austenitic stainless steels (like TP 347H FG) experience similar fireside corrosion rates as with coal firing. Austenitic will exhibit large amounts of internal corrosion under the oxide scales (shall be included in the corrosion data. Austenitic stainless steels like TP 347H FG, HR3C and AC66 are suitable for use as super heaters in flue gas for 600 °C with virgin biomass.

For super heaters in the loop seal, materials with higher strengths than HR3C are available. For example SAVE 25 (Sumitomo) or NF 709(Nippon).

Metsos design is based on maximum corrosion rate of 0,1 mm/year. If the allowed limit would be 0,25 mm/year instead of 0,1 mm, would probably allow some higher material temperatures (corrosion accelerates above a certain temperature).

Proposed materials:

- Secondary HP super heater 2 (convective, in second pass)
    - SA-213TP310HCbN, but still too high corrosion rate or excessive amount of sulphur to be added (needs extensive flue gas cleaning equipment?)
    - => needs more detailed studies for corrosion rate, sulphur amount, flue gas cleaning equipment and operating cost
- Primary reheater 2 SA213TP310HCbN (HR3C) for corrosion risk in revised counter flow construction. (also smaller wall thickness than if X10)
    - Tertiary HP super heater a and b (sand super heaters in loop seal
        - SA-213TP310HCbN (HR3C) or equal:
        - Poor strength with this high temperature; high wall thickness
        - => needs more detailed strength calculations if to be applied

- Secondary RH super heater A&B (sand super heater in loop seal, two packages)
    - SA-213TP310HCbN or equal/better could be applied: =>needs more detailed strength calculations anyway if to be applied
- Headers and connection pipes where steam at 600 °C (unheated pipes)
    - X10CrMoVNb9-1 or X10CrMoVNb9-2
    - Material & cost needs to be identified

Findings & challenges

- For LV11 with 600/600 °C there is no heat or physical space available in sand loop superheating to get the same operation range as in LV0.1
    - Superheating at HP and RH steam drops more rapidly with lower loads if the steam exit temperature is this high
    - Generally, less margin to different boiler limitations and less possibilities to compensate any deviations if the boiler is designed for very challenging targets
- Air preheating optimization depends on required feed water temperature, plant size, desired flue gas temperature and other preheating requirements. For the 100 MW_e size and virgin fuel both rotary or tubular air preheater could be chosen. Generally the high feed water temperatures >265 °C together with 100MW_e promotes the use of rotary preheaters. Indirect solutions with a separate flue gas cooling & air preheating water circuit with a potential to decrease flue gas temperature is an interesting option that could be evaluated separately from this project.
- Tertiary HP super heater 600 °C in loop seal needs more detailed strength calculations for final design. New material and high tube wall thickness have to be analysed further.
- Flue gas recirculation will be required for the operating ranges >90 % load and at drier fuels with 35-40 % moisture.

Metso normally design for 15 years lifetime for super heaters. However when difficult fuels are used, shorter lifetime should be acceptable if this is economic viable. This opens up for other material choices. Based on a discussion in the working group and with material expertise and experience. Normal replacement frequency of 8 years should be an acceptable value. This is especially of interest for the sand loop-seal final HP super heater for 600 °C steam, where creep strength could be critical for new materials.

The results from this investigation:

- Based on the drawbacks, especially for the CHP applications, Metso proposed to investigate lower admission and reheat temperatures. Also the feed water temperature was investigated.

- Based on process analysis and design study, 175 bar 585/585 °C looks promising
    - This solves some material uncertainties. Conventional materials can be used. Final super heater in loop seal can be done of SA213TP310HCbN, tube available and bending/manufacturing is practically doable. Novel materials can be utilized if they appear to be cheaper / more practical.
    - Interconnecting pipes can be done of X10CrMoVNb9-1
    - Improves operation range. Less SH & RH heat surfaces needed for 80-100 % full superheating range or slightly wider operating range with the original surfaces. Still full superheating range is limited, compared to benchmark.
    - Price reductions compared to 600/600 °C concept -3 MEUR
    - The efficiency loss would be small, about -0,3 %-units
- Since the reheat adds much efficiency but is both an expensive feature and reduce flexibility at high design steam temperature, RPP concepts without reheat was investigated. Results from studying LV 1.0.2 (175 bar 585C):
    - Better operation flexibility
    - More heat available in hot loop and in back pass for superheating, more design alternatives
    - Less superheating surface needed
    - At constant heat output fuel & flue gas capacity is reduces by -2.5 % => furnace and back pass cross section decreased
    - Feed water and main steam flow +14 % => bigger feed water pumps and main steam pipe
    - Price reductions compared to 585/585 °C concept -8 MEUR
    - Significant efficiency reduction vs. 585/585 °C concept -1,2 %
- An interesting compromise was proposed by keeping the flexibility without reheat but maintaining the original steam temperature at 600 °C. Results from studying and LV1.0.3 (175 bar 600 °C):
    - Efficiency increased by +0,4%-units compared to 585 °C (-0,8 % compared to 585/585 °C)
    - Main steam flow decreased slightly, but fuel capacity increased slightly
    - More flue gas available to superheat less steam
    - Main changes and challenges are related to materials
        - SA213TP310HCbN (HR3C or equal) strength in loop seal super heater with steam 600 °C is on the edge. Headers and main steam pipe at steam 600 °C must be one step better than normal X10CrMoVNb9-1. Suggested material

X10CrMoVNb9-2. Price impact and other consequences not checked, just estimated.

- Steam temp also in PSH2 slightly higher -> slightly higher corrosion risk: corrosion allowance added (increase wall thickness or upgrade material from 7CrMo to X10)
- Estimated price addition vs. 585 °C concept about +1.5 MEUR

- Additive amounts in LV concepts
  - Injection amounts are expressed as sulphur (S) elements. Injection either as sulphur granulates to furnace or as solution (liquid) before super heaters
  - Estimated injection amounts are derived mainly from fuel S and Cl amounts in fuel composition. Actual injection amounts shall be based on online flue gas measurements at super heaters.

100 % forestry residues specification for KME-601		NEW PROPOSAL (2012-08-23)		
		Average	*Min.*	*Max.*
S	mass-% DS	0,05	0,02	0,11
Cl	mass-% DS	0,03	0,02	0,04

  - 585/585 °C concept:
    - With average fuel composition: no need for S injection.
    - With average S and Max Cl: small amount, needed.
  - 585 °C concept - Slightly lower figures than 585/585 (-10 %)
- Remaining uncertainties
  - Amount of additive and other O&M cost in flue gas cleaning
  - The expected / targeted lifetime of SSH2.
  - Price and availability of valves and instruments for steam 600 °C.

4.2.4 Summary of studied RPP concepts & Capex steps estimations for boiler system

The design study for CHP and virgin fuels 100 MW_e have comprised steam data steps from LV0.1 (benchmark) up to LV11 (175 bar 600/600 °C). The steam data steps are connected to performance and cost steps. In **Fel! Hittar inte referenskälla.** the water/steam temperature profiles are summarized:

Metso have made Capex calculations for the boiler "package", comprising the total boiler system including auxiliary system and in short what is included in the boiler building. The scope is described in attachment 3 see Table 1.

Table 10; Summary table for studied virgin fuel concepts

Concept	Temp °C	Pressure bar	Steam flow kg/s	Fw temp °C	Fuel capacity MWf	Power gross MWe	Boiler price MEUR	Remarks
LV0.1	540	140	112	227	299	102	96	Checked Oct-2012
LV1.0-2	585	175	120	262	310	113	111	Checked Oct-2012
LV1.0-3	600	175	118,5	262	312	115	112,5 *	Checked Oct-2012
LV11.4-2	585/585	175/46	105/96	265	318	120	119	Checked Oct-2012
LV11	600/600	175/46	103/92	264	320	121	121,5 *	Checked Oct-2012

For LV1.0-3 and LV11 there is still an uncertainty about the extra cost for the final super heater design in the loop seal with a new material.

Due to the adopted strategy to keep the heat output constant the boiler capacity will increase for the more advanced concepts. This means that a part of the Capex increase is an upscale of the boiler. For these virgin fuel concepts the up scaling part is roughly 20 % and the extra cost share for the advanced design will then be about 80 % of the total difference compared to benchmark.

The design study has been done for the 100 MWe-class CHP. Boiler Capex for selected advanced concepts for 50 MWe and 25 MWe capacities have been derived from these results.

Table 9; Boiler Capex for different capacities

Boiler - Virgin fuels															
	100 MW					50 MW					25 MW				
	Boiler	Steam data			Capex	Boiler	Steam data			Capex	Boiler	Steam data			Capex
	MWth				MEUR	MWth				MEUR	MWth				MEUR
Reference 0	272,1	140/540	LV0.1	CFB	96,0	134,6	140/540	MV0	CFB	66,5	70,8	140/540	SV0	BFB	40,5
Advanced 1	284,6	175/600	LV1.0-4	CFB	112,5	140,4	175/600	MV5	CFB	78,0	72,8	175/570	SV1	CFB	54,0
Advanced 2	289,6	175/585/586	LV11.4-2	CFB	119,0	142,2	175/585/586	MV4	CFB	82,0		n.a		CFB	

4.2.5 Opex

By changing the steam parameters and the design for more advanced concepts the operation and maintenance expenditure "Opex" will also change. In the initial economic assessments the Opex was assumed by rough estimations. After realizing that the Opex is one of the more important parameters a more detailed analysis has been performed. This has been made in cooperation with the KME 609 project, where also risks and Opex in fall-back options have been studied for a demonstration plant.

Focus has been on the difference in variable Opex comprising consumables and residues, replacement of wearing parts and superheaters, as well as general variable maintenance.

There are however still significant uncertainties, which are handled, in the economic assessment. Lifetime and cost for replacing the final superheater, where the material is not finally decided and there is a lack of experience are two important uncertainties.

- *Consumables*: A small increase in dosage of Sulphur additive. This dosage is to decrease high-temperature corrosion of the secondary superheater.
- *Residues*: Based on the cost for disposal of fly- and heavy ash. No change when increasing the steam data
- *Replacement (Re-investment)*: Increases with advanced steam data. The change is estimated by an increased cost for upgrading material of heat transfer surfaces.
- *Additional variable maintenance*: The base assumption is that this cost corresponds to 1 % of the investment for virgin fuel case. Due to higher investment for the advanced case this cost will increase. This cost includes different increased maintenance costs for the plant not related to cost for replacement:
    - Higher corrosion rate in primary super heaters, last eco, cyclone and loop seal walls:
    - Maintenance cost for higher amount of refractory
    - Repair and replacement cost of valves and instruments for higher pressure and temperature
    - Maintenance and replacement cost for sulphur system
    - Stock value of spare parts (final super heater, feed water pump)

Based on the analysis the variable Opex will increase about 1,4 SEK/MWh fuel, see Figure 15 (wide fuel case is described in chapter 4.3.4.). This is used as a nominal value for the difference in variable Opex between benchmark and advanced concepts. A sensitivity analysis is presented in the financial assessment in chapter 6.

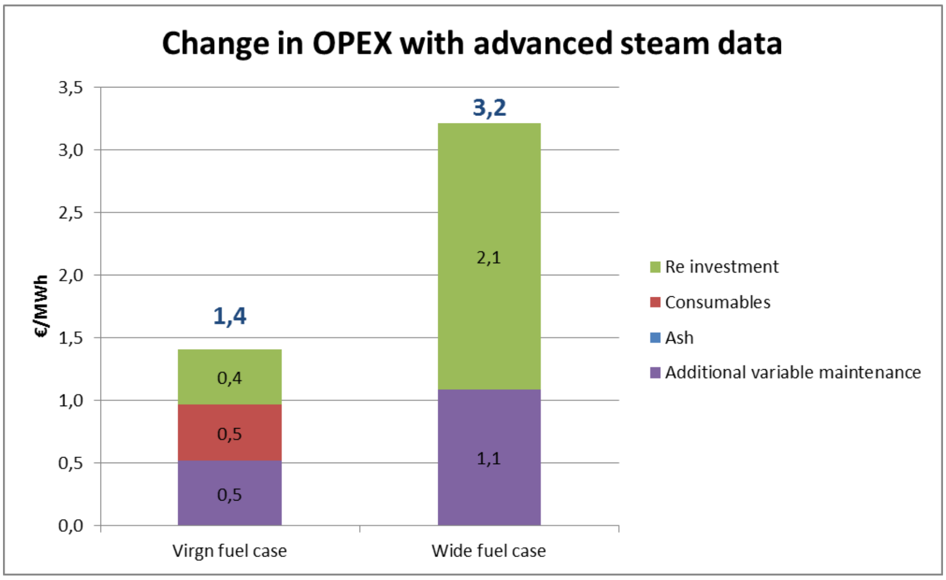


Figure 15; Change in OPEX for virgin and wide fuel when going from reference steam data to advanced seam data.

4.3 Boiler for Wide range fuels

Benchmark for wide range fuels is 90 bar, 500 °C. For 50 MW_e size a CFB solution is chosen.

Wide fuel range calls for more and other challenges than for only virgin fuels. As earlier described, the wide fuel range is for this study defined as 75 % waste wood (recycled wood) and 25 % virgin wood. The main problem areas are described by Metso in Figure 16 below:

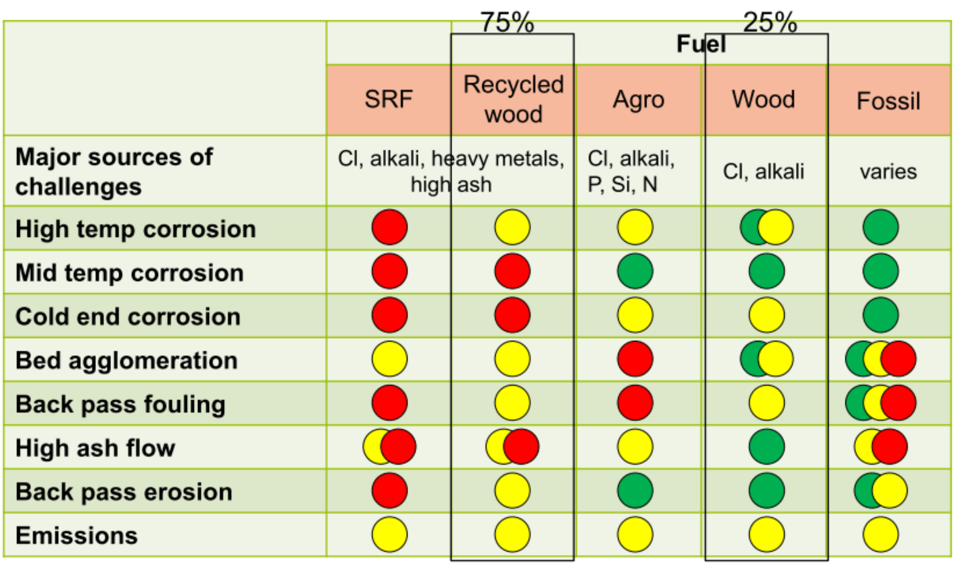


Figure 16; Major challenges for different fuels

There are several challenges for boilers designed for waste wood. There are high risks for fouling and erosion in the back pass and the cold end (air preheater, ducts) as well as high temperature corrosion.

The main challenges for recycled wood are "mid temperature corrosion" (metal temperature, driven by heavy metals (mainly lead) and chlorine compounds.

Other metals like Zn are forming compounds causing the low temperature corrosion in cold end.

4.3.1 Benchmark

In the benchmark design the risks mentioned are considered and mitigated. Metso meets the (mid-temperature) corrosion problem caused by lead chlorides $PbCl_2$, in furnace by reducing pressure to a level in order to avoid the critical metal surface temperature for condensation of $PbCl_2$, which is the usual way.

The first plant with this design is to be commissioned in autumn 2013 in Netherlands (127 MW_{th}, 90 bar, 520 °C).

Figure 17; Benchmark design for wide fuel range CHP 50 MW_e

Based on initial corrosion risk evaluation Pb content in the fuel mix should not exceed 0,7 ppm or 40 mg/kg for a safe design. Metso has presented following main data for the wide range fuel benchmark plant:

Main concept

- Main steam 90 bar, 500 °C, 56 kg/s
- Feed water: 210 °C
- Steam capacity 139 MW_{th}
- Fuel capacity 150 MW_{fu}
- Boiler type CFB

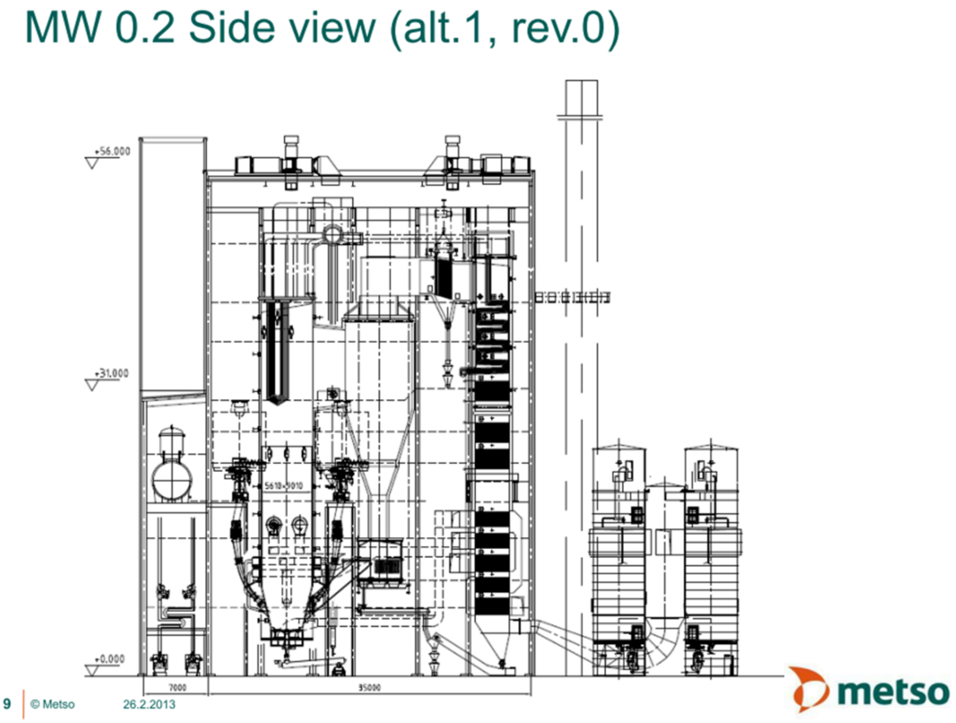


Figure 18; Benchmark design for 50 MW_e, wide range fuels 90 bar, 500 °C

System overview

   - Natural circulation
- Super heaters:
   - TSH packages, sand loop super heaters
- Air preheating
   - Tubular flue gas air preheater
- Emissions:
   - Ammonia injection for NOx control
   - Bag house for particulate capture
- Primary super heater in furnace: 16Mo3 or in sand-loop: 13CrMo4-5
- Secondary super heater: 16Mo3
- Tertiary super heater in sand loop: X7CrNiNb18-10
- Evaporator in furnace, back-pass packages, back-pass walls: P265GH

4.3.2 Advanced RPP for wide range fuels

The proposed RPP concepts for the wide fuel range are based on the benchmark design, with following changes in design process data:

- Steam pressure: 90 => 160 bar
- Steam temperature: 503 => 563 °C
- Feed water temperature: 211 => 231 °C
- Boiler thermal output: 137 => 145 °C

Levels of 540-560 °C were studied initially. Process analysis show that going from 540 to 560 °C will an extra 0,4-0,5 %-units, and will not give more risk than 540 °C.

The major challenge is the pressure, which is increased from 90 to 160 bar. This means that the evaporation temperature is about 346 °C and the metal temperature about 370-380 °C, which is within the critical temperature range for "mid-temp corrosion" driven by $PbCl_2$.

In the proposed concept Metso mitigates the mid-temp corrosion risk by:

1. Fully refractory covered furnace walls
2. Steam cooled back pass walls, cyclone, loop seal walls

Increased corrosion rate risk remains in back pass evaporator and in economizer (mid-temp corrosion). If higher corrosion rate is accepted this shall be met by easy replaceable tube bundles.

Main concepts

	No reheat	*Reheat*
• Main steam	160 bar	160/44 bar
	560 °C	560/560 °C
	59 kg/s	52/51 kg/s
• Feed water:	230 °C	230 °C
• Steam capacity	145 MW_{th}	149 MW_{th}
• Fuel capacity	158 MW_{fu}	166 MW_{fu}

4.3.3 Summary of studied RPP concepts & Capex estimations for boiler system

Target cases look technically feasible, but there are still corrosion challenges to be handled:

- Accept high corrosion rate; higher corrosion margins and increased replacement frequency
- Evaluate material and coating alternatives.
- Accept lower feedwater temperature

The reheat alternative looks promising (+3,8 % efficiency). There is heat enough available from flue gas to reheat steam.

The min load can be limited to 75 % due to corrosion risk at low temperature (850 °C, 2 s. can be reached down to 60% load). This is not feasible for a CHP application, where minimum load often is important. In this case 100% virgin wood have to be used below 75 %. The part load has to be further studied in terms of:

- Mid temp corrosion ($PbCl_2$) at part load (critical temperature window) for primary reheater and other sections
- Accurate feed water and reheat data at part load
- 850 °C, 2s operation range
- Steam temperature at part load

Metso have made Capex calculations for the boiler "package", comprising the total boiler system including auxiliary system and in short what is included in the boiler building. The scope is described in attachment 2.

Table 11; Summary table for studied concepts for wide range fuels

Case		MW0.2	MW1.2.2	MW6.2.3
Price	MEUR	70	77	82,5

The design study has been done for the 50 MWe-class CHP. Boiler Capex for selected advanced concepts for 25 MWe have been derived from these results.

Table 9; Boiler Capex for fifferent capacities

Boiler - Wide range fuels															
	100 MW					50 MW					25 MW				
	Boiler	Steam data			Capex	Boiler	Steam data			Capex	Boiler	Steam data			Capex
	MWth				MEUR	MWth				MEUR	MWth				MEUR
Reference 0		n.a.				136,9	90/500	MW0.2	CFB	70,0	74,9	90/500	SW0	CFB	48,5
Advanced 1		n.a.				144,7	160/560	MW1.2.2	CFB	77,0	79,9	160/560	SW1	CFB	53,4
Advanced 2		n.a.					160/560/560	MW6.2.3	CFB	82,5		n.a		CFB	

Due to the adopted strategy to keep the heat output constant the boiler capacity will increase for the more advanced concepts. This means that a part of the Capex increase is an upscale of the boiler. For these virgin fuel concepts the up scaling part is roughly 35-40 % and the extra cost share for the advanced design will then be about 60-65 % of the total difference compared to benchmark.

4.3.4 Opex

Opex estimates has been made in cooperation with the KME609 project, where also risks and Opex in fallback options have been studied for a demonstration plant.

Focus has been on the difference in variable Opex comprising consumables and residues, replacement of wearing parts and superheaters, as well as general variable maintenance.

For the advanced concept the big change is to prevent mid-temperature corrosion when increasing the steam pressure.

- *Consumables*: No increased dosage of sulphur additive. It is assumed that it is more feasible to have a decreased life time of the secondary super heater than increasing the sulphur dosage.
- *Residues*: Based on the cost for disposal of fly- and heavy ash. No change when increasing the steam data
- *Replacement (Re-investment)*: Increases with advanced steam data. The change is estimated by both a decreased life time and improved material. Parts that are affected are final super heater, furnace wall and evaporators.
- *Additional variable maintenance*: The base assumption is that this cost corresponds to 1,5 % of the investment for wide fuel case. Due to higher investment for the advanced case this cost will increase. This cost includes different increased maintenance costs for the plant not related to cost for replacement:
    - Higher corrosion rate in primary super heaters, last eco, cyclone and loop seal walls:
    - Maintenance cost for higher amount of refractory
    - Repair and replacement cost of valves and instruments for higher pressure and temperature
    - Maintenance and replacement cost for sulphur system
    - Stock value of spare parts (final super heater, feed water pump)

There are significant uncertainties for this concept that are further handled in the economic assessment. Based on the analysis the variable Opex will increase about 3,2 SEK/MWh fuel, see Figure 15. This is used as a nominal value for the difference in variable Opex between benchmark and advanced concepts. A sensitivity analysis is presented in the financial assessment in chapter 6.

4.4 Steam Turbine

Siemens have for selected RPP:s studied suitable steam turbine systems. Possible steam turbine solutions are based on existing modules and modifications.

4.4.1 Benchmark and advanced steam data

The steam data defined for benchmark for Virgin fuels and wide range fuels, are conventional steam data for CHP steam turbines today.

Siemens steam turbine types are:

- 100 MW_e Virgin fuels 140 bar, 540 °C: SST900DH
- 50 MW_e Virgin fuels 140 bar, 540 °C: SST 700DH

- 50 MW_e Wide fuel range 100 bar, 500 °C: SST900 (IP)

Siemens have experience from large steam turbines with high steam data. Commercially Siemens offer standard steam turbine concepts for "Industrial Steam Turbines" up to 250 MW_e with steam data up to 165 bar and 585 °C, with a 1 or 2 turbine solutions.

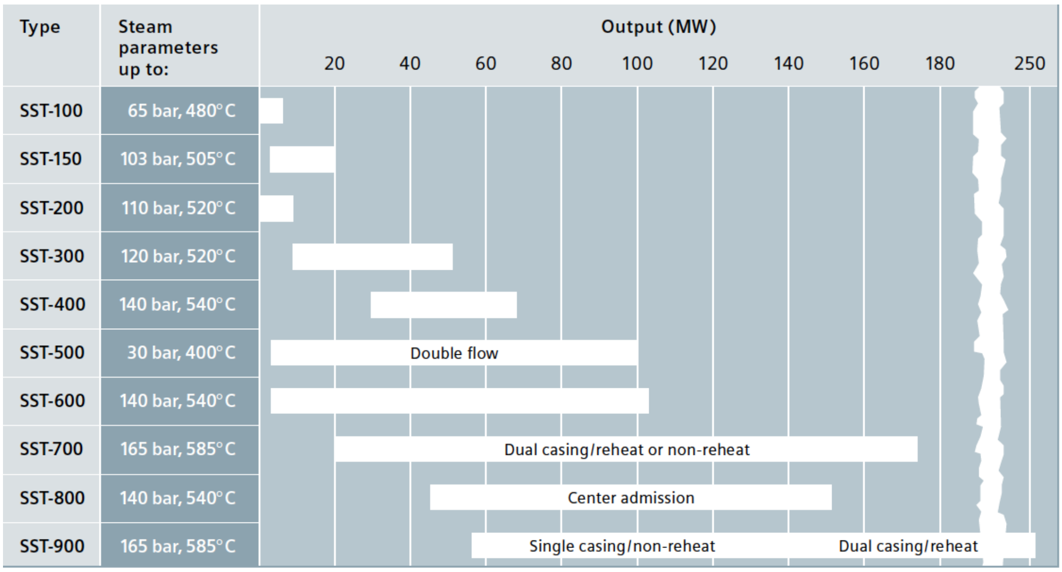


Figure 19; Siemens commercial range of steam turbines

Siemens could however offer 3-casing solutions for steam data 260 bar 620/620 °C for 250 MW_e size plants, developed for coal-fired plants.

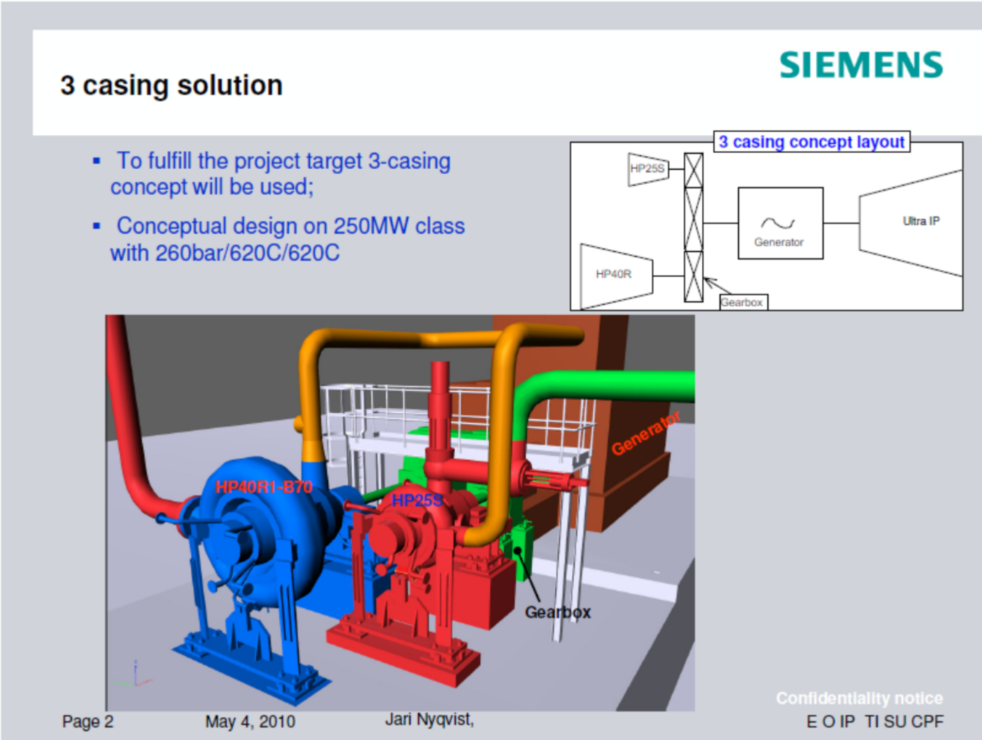


Figure 20; Steam turbine concept in 3-casing configuration

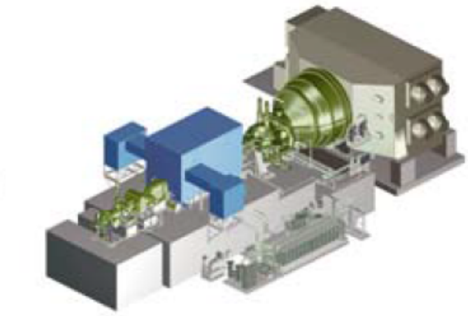
Pressures of 175 bar will be possible with the available steam turbine modules according to Siemens.

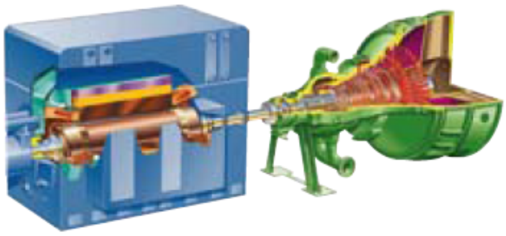
Siemens has put together a matrix showing different steam data and sizes with required configurations (1-, 2- or 3-casing turbine) and status for the actual concepts, see Table 12.

Table 12; Steam turbine solutions for different steam data (Siemens)

Steam data	Size								
	100MWe			50MWe			25MWe		
	No. Casings	Available today*	Comment	No. Casings	Available today*	Comment	No. Casings	Available today*	Comment
140/540	1	Y		1 or 2	Y		1 or 2	Y	
165/570	1 or 2	Y	1 casing solution in evaluation phase	1 or 2	Y	1 casing solution in evaluation phase	2	Y	
165/570/570	2	Y		2	Y		2	Y	
165/600/600	2	N	In progress	2	N		2	N	
175/570	1 or 2	Y	1 casing solution in evaluation phase	1 or 2	Y	1 casing solution in evaluation phase	2	Y	
175/570/570	2	Y		2	Y		2	Y	
175/600	2	N	In progress	2	N	In progress	2	N	
175/600/600	2	N	In progress	2	N	In progress	2	N	
190/600	3	N	In progress	3	N	In progress	3	N	
190/600/600	3	N	In progress	3	N	In progress	3	N	
190/620/620	3	N	In progress	3	N	In progress	3	N	

All advanced 100 MW_e size concepts will be based on SST900DH, while the 50 MW_e will be based on SST700DH and SST900DH, in single or reheat versions.





SST-700

up to 175 MW

The SST-700 is a dual-casing turbine consisting of a geared HP module and LP module. Used for power generation applications, especially in combined cycle and solar thermal power plants. Each module can be used independently or can be combined for the optimal configuration.

Technical data

- Power output up to 175 MW
- Inlet pressure (with reheat) up to 165 bar / 2,395 psi
- Inlet temperature (with reheat) up to 585°C / 1,085°F
- Reheat temperature up to 415°C / 780°F
- Rotational speed 3,000 – 13,200 rpm
- Controlled extraction up to 40 bar / 580 psi and up to 415°C / 780°F
- Bleed up to 7; up to 120 bar / 1,740 psi
- Exhaust pressure (back pressure) up to 40 bar / 580 psi
- Exhaust pressure (condensing) up to 0.6 bar / 8.5 psi
- Exhaust pressure (district heating) up to 3 bar / 45 psi
- Exhaust area 1.7 – 11 m^2 / 18.3 – 118 sq. ft.

SST-900

up to 250 MW

The SST-900 is a single-casing turbine for 2-pole generators for power generation and industry. SST-900 RH is a dual-casing turbine for reheat applications.

Technical data

- Power output up to 250 MW
- Inlet pressure (with reheat) up to 165 bar / 2,395 psi
- Inlet temperature (with reheat) up to 585°C / 1,085°F
- Reheat temperature up to 580°C / 1,075°F
- Rotational speed 3,000 – 3,600 rpm; HP up to 13,200 rpm (for reheat)
- Bleed up to 7; up to 60 bar / 870 psi
- Controlled extraction up to 55 bar / 800 psi and up to 480°C / 895°F
- Exhaust pressure (back pressure) up to 16 bar / 230 psi
- Exhaust pressure (condensing) up to 0.6 bar / 8.5 psi
- Exhaust pressure (district heating) up to 3 bar / 45 psi
- Exhaust area 1.7 – 11 m^2 / 18.3 – 118 sq. ft.

Figure 21; Steam turbine types for the RPP applications

There are in principle two possible reasons for going from 1-turbine to 2-turbine solution:

- Pressure will result in too high axial forces for one turbine.

- Pressure will result in too small blades with high boundary losses and require higher rotation speed via an extra gear.

With steam data 175/600/600 a 2-casing solution would be possible (upper limit). Pressure of 190 bar will at 100 MW_e require a 3-casing concept. The extra cost would be in the range of 10 % for 100 MW_e and maybe 15 % for the 50 MW.

The HP-turbine speed is expected to be:

- 7000 rpm for 100 MW_e
- 9000 rpm for 50 MW_e

Steam turbine for 175/585/585 will require a 2-casing solution for 50 MW_e size. For 100 MW_e size a 2-casing concept is available today but a 1-casing solution could be developed based on available technology. This would decrease the Capex by about 10 %.

For the wide fuel range solutions and 160/560 or 160/560/560 will require 2-casing solutions.

The options for 25 MW_e are more limited. High pressures lead to small turbine blades and thereby high boundary losses. Generally the live steam volume flow has to be in the range above 0,5-1 m^3/s in order to get reasonable design of the inlet blades of the turbine. The limit for commercial units is today about 165 bar, even with a high speed HP turbine. However 175 bar is assumed in the process analysis, based on earlier information. This also means that for both Virgin (165-175 bar, 570 °C) and Wide fuel range (160 bar, 560 °C) will require a 2-casing solution.

All the steam turbine concepts are based on available modules except for the 600 °C levels.

4.4.2 Opex

There are no significant extra Opex anticipated for the steam turbine in the advanced concepts. (Increased Capex will in the economy model lead to increased fix Opex, calculated as a fix Opex.)

4.4.3 Summary of studied RPP concepts & Capex for steam turbine

The steam data required for the advanced concepts will be feasible and available for all cases up to 575 °C.

Following challenges remain:

- Temperature of 600 °C in this size is not proven but will be based on existing modules and experience from big steam turbines.
- At temperatures at 600 °C there is a risk for steam side oxidation (spallation), which could cause some problems. This could be handled with by applying coating.

- Commercial smaller steam turbines have a limit at about 165 bar of technical reasons.
    - Uncertain how many other suppliers that have commercial steam turbines > 140 bar.
    - Uncertain how to reach the target of 175 bar.

Siemens have performed Capex calculations for the steam turbine "package", comprising the total 100 MW_e and 50 MW_e systems including ground/foundation and auxiliary system, and in short what is included in the ST building.

Table 13; Steam turbine Capex for 100 MW_e at different steam data for virgin fuels (excl. project costs, erection, commissioning)

Steam Turbine 100 MWe class		
Virgin fuels	MEUR	MEUR
		Diff
140 bar, 540C (1-casing)	29	
175 bar, 585C (2-casing)	33	4
175 bar, 585C (1-casing)	30	1
175 bar, 600C (2-casing)	33	4
175 bar, 585/585 C (2-casing)	34	5
175 bar, 600/600C (2-casing)	34	5

Table 14; Steam turbine Capex for 50 MW_e at different steam data for virgin fuels (excl. project costs, erection, commissioning)

Steam Turbine 50 MWe class		
Virgin fuels	MEUR	MEUR
		Diff
140 bar, 540C (2-casing)	22	
175 bar, 585C (2-casing)	23	1
175 bar, 600C (2-casing)	24	2
175 bar, 585/585 C (2-casing)	27	5
175 bar, 600/600C (2-casing)	27	5

Table 15; Steam turbine Capex for 50 MW_e at different steam data for wide fuel range (excl. project costs, erection, commissioning)

Steam Turbine 50 MWe class		
Wide range fuels	MEUR	MEUR
		Diff
100 bar, 500C (1-casing)	21	
160 bar, 560C (2-casing)	23	1
160 bar, 560/560C (2-casing)	24	2

Since Siemens Sweden is responsible for steam turbines down to 50 MW_e, more rough estimations have been done by Siemens Sweden for 25 MW_e class steam turbines. These are presented in the financial assessments chapter 6.

5 Real cases and risks

A goal for project has been to study some real project cases (virgin or wide fuel specification) in addition to the defined general cases. Many of the stakeholders in the KME programme have plans for new CHP plants. One reason is the termination of old green certificate contracts.

Even if no decision would be taken in this phase for letting this project emerge into a possible demonstration project, this could be of interest for both a potential host as well as for other stakeholders. Comprehensive cost and risk analyses have to be made before is possible to make a decision by the stakeholder to act as a host for a high efficient demonstration plant.

Time schedule, capacity, fuel mix should be more or less in line with goals for the RPP demonstration. The following companies has announced their interest to be a possible host:

- Falun CHP - 20 MW_e
- Vattenfall - Uppsala CHP 50 MW_e
- E.ON. - Antwerp 100-200 MW_e condensing plant

Further assessment of possible real cases has to be studied in the beginning of a next phase of the project.

During the projects initial face meetings where held with the project manager, Falun and Elforsk. Falun was the possible host that was first to realize their plans to build a new power plant. After discussions with lawyers we where recommended not to continue these discussions due to the risk to violate the Public Procurement Act. The reason was that Siemens and Metso participated in the project and would have first hand information ahead of their competitors.

If a demonstration plant were to be built there would be an initial risk for the first plant since some of the technology in the boiler is not yet demonstrated. For the turbine and the other systems the technology has been proven in coal fired plants, although in quite large plants. These risks has been handled together with the KME 609 project and reported by them. In the KME 601 a more mature technology have assumed and not the first built. The technical risks for the increased steam data have been mitigated with various design solutions.

In order to improve the possibility to build the first demonstration plant the plant owner could need technical and financial support. One model that has been discussed is to finance the risks or the cost for a possible fall back solution. Also to finance an evaluation and R&D project coupled to the plants first years of operation. The plant owner, plant suppliers, other utilities and government agencies could jointly finance this.

There are several risks during the procurement face that has not been answered. How should an inquiry be formulated allowing different suppliers to bid for a system in a high performance plant including fall back solutions?

Especially if the cost for a fall back solution should be financed by another group of companies and agencies. Since bidding companies can offer different fall back solutions and included costs. It is a difficult task is to arrange an agreement to finance the fall back solution and an evaluation and R&D project within the time frame for valid quotations?

6 Financial assessment

6.1 Approach

The basic question is if it is profitable to construct an advanced plant instead of a plant using standard technology, named as "Base plant" in the following text.

The performance of an advanced plant will be compared to a corresponding Base plant. The result will be given as financial performance for the difference between the advanced alternative and the reference plant.

The second question is if the results differ depending on the capacity of the plants.

In order to address this question the analyses are performed for two different capacity levels, one around 100 MWe and one around 50 MWe. Calculations are also done for 25 MWe based on scaling and more uncertain basis. For both levels the heat output is fixed to the level reached by the Base plant and then the electric capacity is varied. This mean that the more **advanced concepts will require a larger boiler capacity, which will result in a Capex increase compared to benchmark which is a mixture of capacity increase and of a more advanced design**.

Based on the design and process study together with preliminary economic assessments the most promising advanced concepts have been selected for the final financial assessment. The Advanced concepts for at least the larger sizes are studied for both without and with reheat.

- Advanced 1 – High steam data
- Advanced 2 – High steam data with reheat

6.2 Calculations models

First the Cash flow for a new Base plant is set up. Then the same is calculated for the alternatives. Based on these cash flows the differences in financial performance between the base plant and each one of the advanced alternatives are calculated in terms of:

- Key Performance Indicators (NPV, IRR and payback) for the differences between the Base plant and the alternatives
- The financial influence on the company's result (Financing needs, positive influence on result, etc)

The incomes consist of sales from:

- Heat = heat production x heat price
- Electricity =electricity generation x electricity price
- Green certificates = electricity generation x green certificate price
- Reduction in network connection cost

Heat capacity is the same for the base plant and the advanced alternatives. However there might be differences in the availability between Base and the alternatives and therefore the income from heat can differ between the alternatives too. Therefore we need a heat price forecast to calculate the income from heat sales. This price is then estimated to a level that makes the base case profitable (NPV=0) for the actual size and assumed operating conditions.

The costs consist of:

- Fuel cost
- Cost of auxiliary power including tax and the cost of obligatory green certificates
- Other variable Operation and Maintenance cost (Opex)
- Fixed Operation and Maintenance

Other Variable Opex - excluding fuel (expressed in SEK/MWh fuel or electricity)

- Consumables (bed material, chemicals, additives, water, etc)
- Maintenance and revisions incl hired personnel, spare parts, wearing parts, material
- Reinvestments such as replacement of larger wearing parts such as fuel prep system, super heaters, refractory, etc.
- Handling, transport of rest products as ash, metal scrap from fuel handling, sludge from FGC, products from water cleaning system, etc

Fix Opex (expressed in SEK/kW, MSEK/a or % of Capex)

- Personnel (major part)
- Insurance
- Fix fees for, water, electricity, sewage
- Fix fees & contracts for maintenance works, wearing & spare parts
- Environmental and other inspections
- Guarding services, cleaning

6.3 Technical and Financial Conditions

6.3.1 General

The result from the financial analysis is of course very dependent on the actual conditions valid in a specific market with typical operational conditions and price scenarios. The assessment is focused on the Swedish market conditions for CHP.

Some of the most important conditions are discussed in the following sections:

The ***biomass fuels*** that included in fuel mix are virgin wood chips from forestry ("Skogsflis") and waste wood or recycled wood ("Returträ") such as demolition wood, etc. Swedish energy agency presents statistics for the price development for these fuels, according to Figure 22. Biomass prices have increased up to 2010 and after there is a stabilization and a small decrease.

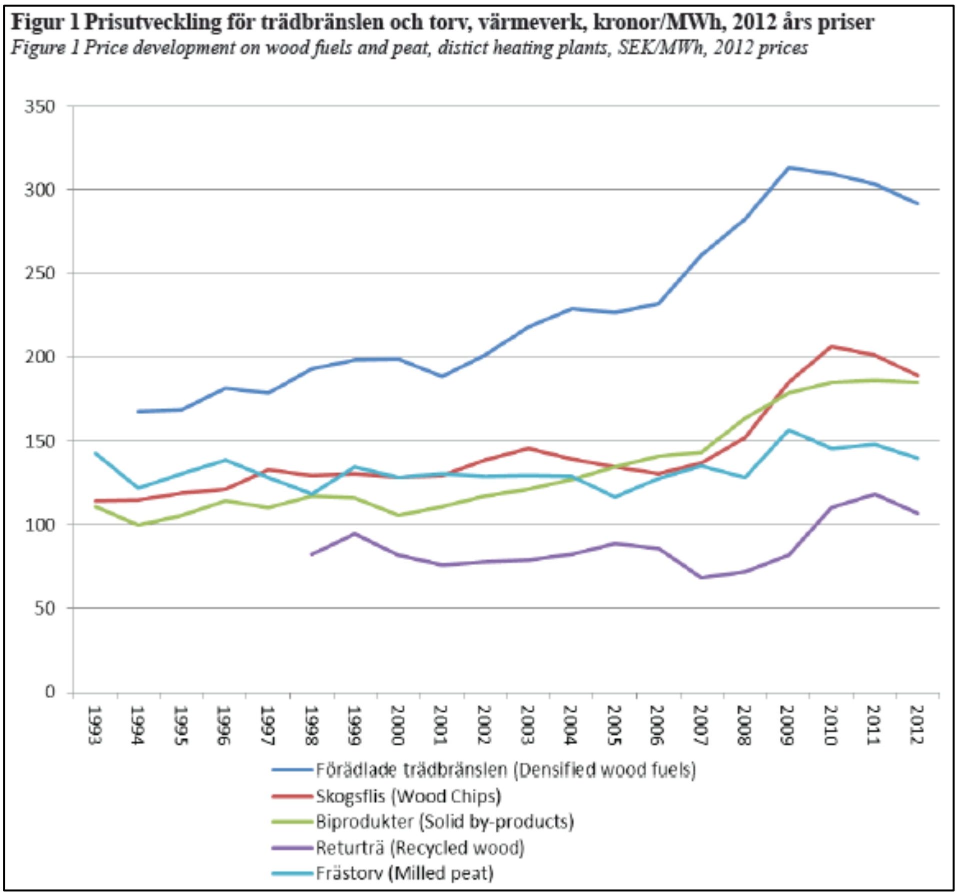


Figure 22; Price development for different types of biomass fuels in Sweden

One of the most important factors is the ***electricity price***. There are official scenarios presented by Svensk Energi based on the spot price futures from NordPools at 38-42 EUR/MWh up to 2020, see Figure 23.

Grid fee have been calculated from the Swedish E.ON.-tariff "N130L", based on reduced purchased electricity from the 130V-nätet.

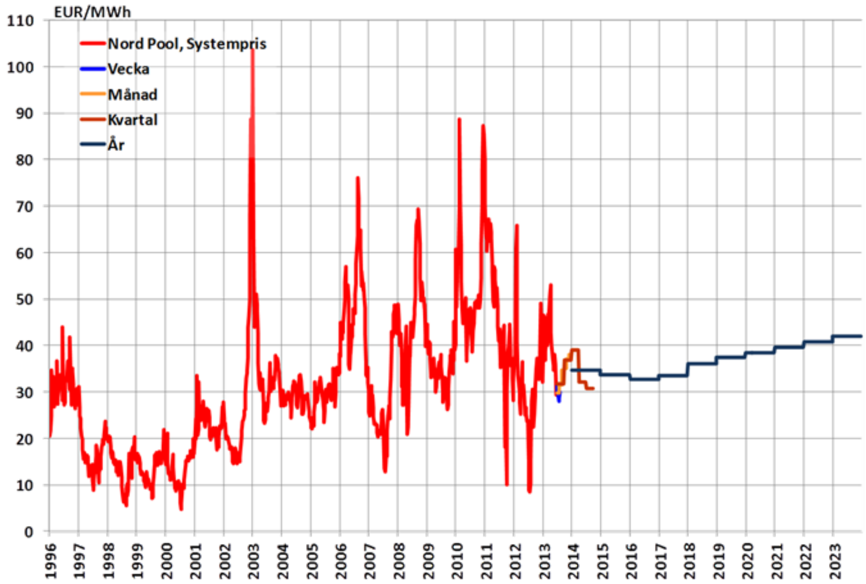


Figure 23; Nord Pool electricity price outlook

One factor that has a big impact on the future electricity price is the development of the carbon dioxide allowance market, EU-ETS.

In the current situation there is a big surplus of allowances. In Figure 24 a diagram from Svensk Energi show the price collapse of the allowance price:

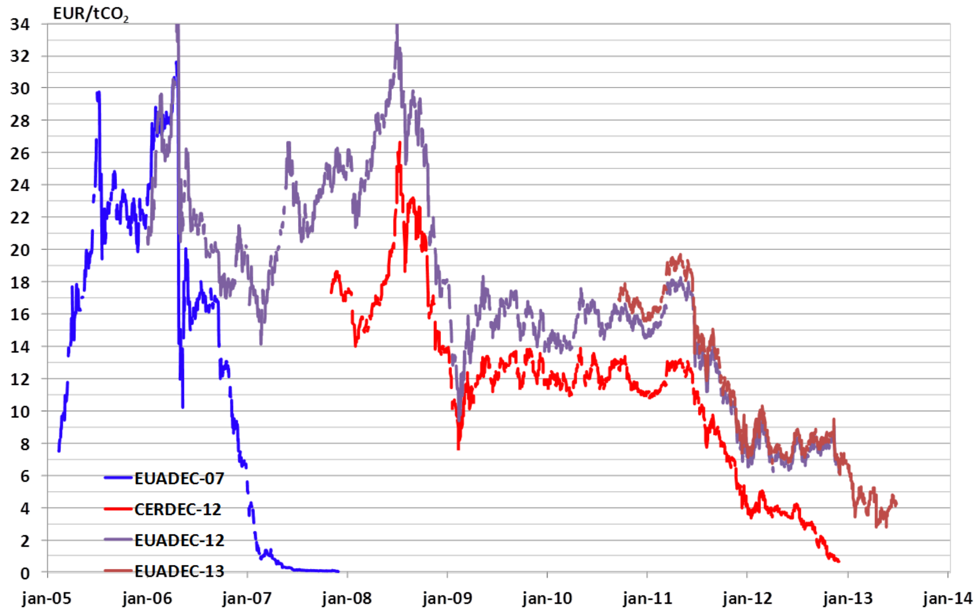


Figure 24; Price collapse of the allowance price

Based on the same source a rule of thumb is that the electricity price on the Nord Pool market would increase by about 8 öre/kWh based on an increase of the allowance price of 10 EUR/ton.

The Swedish green certificate system (Elcertifikatsystemet) will be valid at least up to 2035. The green certificates will be contracted for the actual plant for 15 years. The price is set by a designated market place (for Sweden and Norway) but will also be dependent on the actual required quota for the consumers. The price is expected to fall in later part of period. In Figure 25 the development of the green certificate price is shown since 2009.

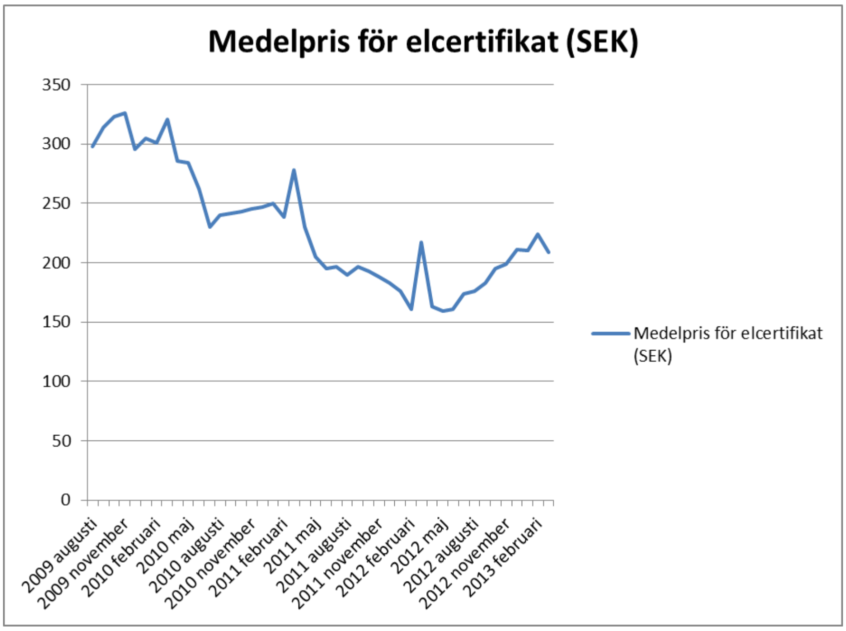


Figure 25; The development of the green certificate

These important factors for the economic assessments have been discussed and approved as basic values within the steering group. The prices have been assumed to constant in real terms during the studied period.

In Table 16 the general assumptions used in this project are given.

Table 16: General assumptions

Component	Value	Unit
Electricity price	400	SEK/MWh
Marginal Network price	20	SEK/MWh
Electricity tax	290	SEK/MWh
Green certificate price	200	SEK/MWh
Proportion of aux power to be taxed	20%	
Obligation to procure green cert	14%	
Exchange rate	9	SEK/EURO
Virgin biomass fuel	210	SEK/MWh
RT fuel	120	SEK/MWh
Mixed fuel (25% Virgin / 75% RT)	142,5	SEK/MWh
Real discount rate	6%	
Plant life time	25	years
Plant availability	96%	
Plant minimum production capacity	35%	

6.3.2 Plant Specific Technical and Financial data

In Table 17 and Table 18 the main technical and financial data for the Base plants and for the advanced alternatives all using either virgin biomass or wide fuel mix are given.

Table 17: Plant specific Technical and Financial data for Virgin Biomass plants

Plant		100 Mwe - Virgin Biomass Fuel			50 MWe - Virgin Biomass Fuel			25 MWe - Virgin Biomass Fuel	
		Base plant	**Adv 1**	**Adv 2**	**Base plant**	**Adv 1**	**Adv 2**	**Base plant**	**Adv 1**
		LV0.1	LV1.0-3	LV11.4-2	MV0	MV5	MV4	SV0	SV1
Steam temp		540	600	585/585	540	600	585/585	540	570
Steam pressure		140	175	175/46	140	175	175/46	140	175
Installed capacity									
	Electricity gross	102,1	114,6	119,6	49,6	55,4	57,2	25,8	27,8
	Electricity net	94,2	105,3	110	45,4	50,7	52,7	23,7	25,3
	Heat	170	170	170	85	85	85	45	45
	Fuel input	298,6	311,6	318,2	148,9	155,2	155,9	78,5	80,6
	Net efficiency	31,6%	33,8%	34,6%	30,5%	32,7%	33,8%	30,1%	31,4%
Investment (MEUR)									
	Boiler	96,0	112,5	119,0	66,5	78,0	82,0	40,5	54,0
	Steam Turbine	29,0	30,0	34,0	22,0	24,0	27,0	20,0	20,5
	Steam Turbine indirect [1)]	13,0	13,0	13,0	10,6	10,6	10,6	8,6	8,6
	Fuel	40,0	41,2	41,8	28,3	29,2	29,2	19,4	19,7
	Civil, I&C, El, BOP & Indirect	92,0	92,0	92,0	56,6	56,6	56,6	34,9	34,9
	Sum	**270,0**	**288,7**	**299,8**	**184,0**	**198,3**	**205,4**	**123,3**	**137,6**
O&M and Sales prices (SEK/MWh)									
	Fix	1,5%	1,5%	1,5%	1,5%	1,5%	1,5%	1,5%	1,5%
	Variable (SEK/MWh,fuel)	28	29,4	29,4	28	29,4	29,4	28	29,4
	Fuel price	210	210	210	210	210	210	210	210
	Electricity price	400	400	400	400	400	400	400	400
	Marginal Network price	20	20	20	20	20	20	20	20
	Electricity tax	290	290	290	290	290	290	290	290
	Green certificate price	200	200	200	200	200	200	200	200

1) Adm, erection, comissioning (Siemens)

Table 18: Plant specific Technical and Financial data for wide fuel mix plants

Plant		50 Mwe - Wide Fuel Mix			25 Mwe - Wide Fuel Mix	
		Base plant	Adv 1	Adv 2	Base plant	Adv 1
		MW0.2	MW1.2.2	MW6.2.3	SW0	SW1
Steam temp		500	560	560/560	500	560
Steam pressure		90	160	160/44	90	160
Installed capacity						
	Electricity gross	46,9	54,7	59,1	24,9	29,8
	Electricity net	43,2	50	54,1	22,8	26,9
	Heat	90	90	90	50	50
	Net efficiency	28,8%	31,6%	32,6%	27,8%	30,6%
	Fuel input	150	158,2	166,1	82	88
Investment (MEUR)						
	Boiler	70,0	78,0	83,5	48,5	53,4
	Steam Turbine	21,0	22,0	24,0	20,0	20,5
	Steam Turbine indirect*	10,6	10,6	10,6	8,6	8,6
	Fuel	29,5	30,6	31,6	20,1	21,1
	Civil, I&C, El, BOP & Indirect	56,6	56,6	56,6	34,9	34,9
	Total	**187,6**	**197,8**	**206,3**	**132,1**	**139,1**
O&M and Sales prices (SEK/MWh)						
	Fix	1,5%	1,5%	1,5%	1,5%	1,5%
	Variable (SEK/MWh,fuel)	50	53,21	53,21	50	53,21
	Fuel price	142,5	142,5	142,5	142,5	142,5
	Electricity price	400	400	400	400	400
	Marginal Network price	20	20	20	20	20
	Electricity tax	290	290	290	290	290
	Green certificate price	200	200	200	200	200

1) Adm, erection, comissioning (Siemens)

6.3.3 Operational conditions

Usually a CHP operates as a base load unit with an annual maintenance period of around 4 weeks in the summer. The remaining time of the year (around 8000 hours) the unit will be available for heat and power generation. However the total annual generation will be influenced by the heat demand, which usually is rather low during the off heating season, and the plants capability to operate at these low demand levels.

When the heat production falls below the maximum capacity of the plant, the electricity generation will be reduced with an even higher proportion than the heat. This is taken into consideration when the annual electricity generation is calculated by simulation of the daily heat production and the coincident electricity generation. These simulations are performed using a demand curve from the Stockholm region.

In the simulations the plant has been assumed to be operating as a base load unit and the annual energy demand has been adapted to a level that gives the wanted utilisation time. The analyses have been made for utilisation times of 5000, 6000 and 7000 hours (equals to utilisation factors of 57%, 68% and 80%).

6.4 Base Result

6.4.1 Annual Heat and Electricity production together with Fuel and Power consumption

In Table 19 and Table 20 the annual production of heat and electricity is given together with the annual consumption of fuel and power.

Table 19: Production and consumption in MWh for plants using Virgin Biomass Fuel

Plant	100 Mwe - Virgin Biomass Fuel			50 MWe - Virgin Biomass Fuel			25 MWe - Virgin Biomass Fuel	
	Base plant	Adv 1	Adv 2	Base plant	Adv 1	Adv 2	Base plant	Adv 1
	LV0.1	LV1.0-3	LV11.4-2	MV0	MV5	MV4	SV0	SV1
Utilisation time (hours)	5000	**5 000**	**5 000**	**5 000**	**5 000**	**5 000**	**5 000**	**5 000**
Heat production	850 000	850 000	850 000	425 000	425 000	425 000	224 990	224 990
Electricity generation gross	501 099	562 448	586 988	243 433	271 899	280 733	126 703	136 401
Fuel consumption	1 483 094	1 547 041	1 579 107	739 417	770 054	782 409	389 904	399 769
Auxillary power consumption	38 773	45 644	47 116	20 613	23 067	22 304	10 611	12 191
Total efficieny	91,1%	91,3%	91,0%	90,4%	90,5%	90,2%	90,2%	90,4%
Utilisation time (hours)	6000	**6 000**	**6 000**	**6 000**	**6 000**	**6 000**	**6 000**	**6 000**
Heat production	1 020 000	1 020 000	1 020 000	510 000	510 000	510 000	269 988	269 988
Electricity generation gross	604 799	678 844	708 462	293 811	328 167	338 830	152 924	164 629
Fuel consumption	1 783 534	1 860 728	1 899 409	889 171	926 152	941 053	468 860	481 837
Auxillary power consumption	46 796	55 089	56 867	24 879	27 841	26 919	12 807	14 714
Total efficieny	91,1%	91,3%	91,0%	90,4%	90,5%	90,2%	90,2%	90,2%
Utilisation time (hours)	7000	**7 000**	**7 000**	**7 000**	**7 000**	**7 000**	**7 000**	**7 000**
Heat production	1 190 000	1 190 000	1 190 000	595 000	595 000	595 000	314 986	314 986
Electricity generation gross	708 214	794 920	829 602	344 049	384 281	396 766	179 072	192 779
Fuel consumption	2 085 950	2 181 231	2 219 343	1 041 074	1 085 677	1 099 519	547 736	562 932
Auxillary power consumption	54 798	64 509	66 590	29 133	32 601	31 522	14 997	17 230
Total efficieny	91,0%	91,0%	91,0%	90,2%	90,2%	90,2%	90,2%	90,2%
Reduced part load efficiency taken into consideration								

Table 20: Production and consumption in MWh for plants using Wide Fuel mix

Plant	50 Mwe - Wide Fuel Mix			25 Mwe - Wide Fuel Mix	
	Base plant	Adv 1	Adv 2	Base plant	Adv 1
	MW0.2	MW1.2.2	MW6.2.3	SW0	SW1
Utilisation time (hours)	**5 000**	**5 000**	**5 000**	**5 000**	**5 000**
Heat production	450 000	450 000	450 000	250 000	250 000
Electricity generation gross	230 182	268 463	290 058	122 060	146 354
Fuel consumption	744 996	785 206	824 118	408 408	436 995
Auxillary power consumption	18 159	23 067	24 540	10 061	14 216
Total efficiency	91,3%	91,5%	89,8%	91,1%	90,7%
Utilisation time (hours)	**6 000**	**6 000**	**6 000**	**6 000**	**6 000**
Heat production	540 000	540 000	540 000	300 000	300 000
Electricity generation gross	277 817	324 021	350 085	147 320	176 642
Fuel consumption	895 747	944 285	991 186	491 021	525 515
Auxillary power consumption	21 917	27 841	29 618	12 143	17 158
Total efficiency	91,3%	91,5%	89,8%	91,1%	90,7%
Utilisation time (hours)	**7 000**	**7 000**	**7 000**	**7 000**	**7 000**
Heat production	630 000	630 000	630 000	350 000	350 000
Electricity generation gross	325 321	379 425	409 946	172 510	206 846
Fuel consumption	1 063 831	1 124 082	1 158 069	576 086	613 942
Auxillary power consumption	25 665	32 601	34 682	14 220	20 091
Total efficiency	89,8%	89,8%	89,8%	90,7%	90,7%
Reduced part load efficiency taken into consideration					

6.4.2 Comparison

In Figure 26, the accumulated cash flow for the 50 MW Wide fuel mix alternatives with an utilisation time of 6000 hours is compared. The differences are rather small.

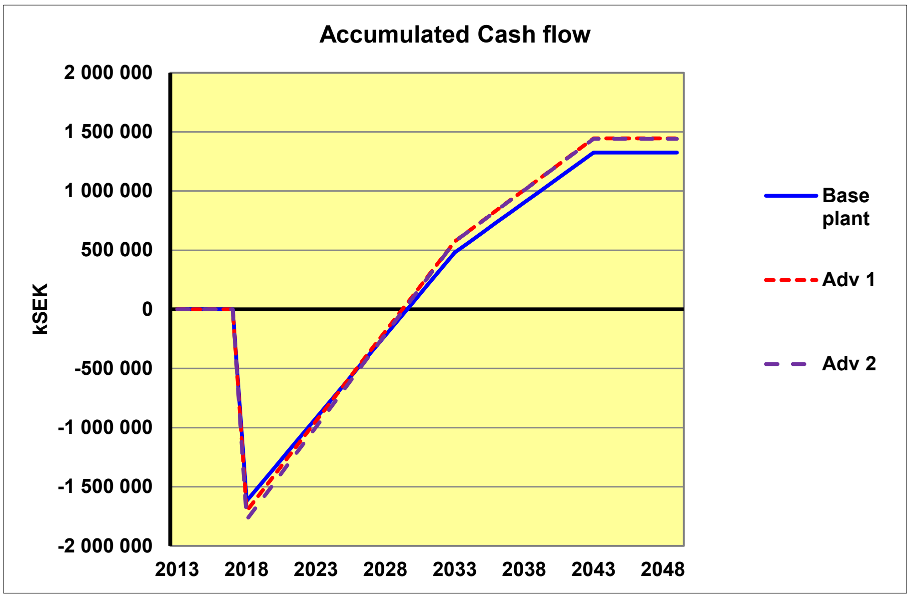


Figure 26: Cash Flow for 50 MW Wide fuel based plants

In order to make it easier to compare a huge number of alternatives, the cash flow can be recalculated to a number of KPI:s as Net Present Value (NPV), Internal Rate of Return (IRR) and payback time. The financial performance, in terms of these KPIs, is given in Table 21 and Table 23 for all of the alternatives using the same fuel.

Table 21: Financial performance for Virgin Biomass Fuel based plants

Plant		100 Mwe - Virgin Biomass Fuel			50 MWe - Virgin Biomass Fuel			25 MWe - Virgin	
		Base plant	Adv 1	Adv 2	Base plant	Adv 1	Adv 2	Base plant	Adv 1
		LV0.1	LV1.0-3	LV11.4-2	MV0	MV5	MV4	SV0	SV1
Utilisation time	**hours**	**5000**	**5000**	**5000**	**5000**	**5000**	**5000**	**5000**	**5000**
Heat price	SEK/MWh	358,2	358,2	358,2	461,8	461,8	461,8	558,5	558,5
Net present value	KSEK	0	-11 501	-56 246	0	-65 425	-108 749	0	-130 219
Internal rate of return	%	6,0%	5,9%	5,7%	6,0%	5,6%	5,3%	6,0%	4,7%
Pay back	years	12	12	12	12	13	13	12	14
Financial performance for "Extra" investment									
Net present value	KSEK		-11 501	-56 246		-65 425	-108 749		-130 219
Internal rate of return	%		5,0%	2,7%		-	-		-
Pay back	years		11	13		32	32		32
Utilisation time	**hours**	**6000**	**6000**	**6000**	**6000**	**6000**	**6000**	**6000**	**6000**
Heat price	SEK/MWh	314,3	314,3	314,3	402,3	402,3	402,3	483,4	483,4
Net present value	KSEK	0	27 989	-1 135	0	-46 899	-83 324	0	-128 484
Internal rate of return	%	6,0%	6,1%	6,0%	6,0%	5,7%	5,4%	6,0%	4,7%
Pay back	years	12	11	11	12	12	12	12	14
Financial performance for "Extra" investment									
Net present value	KSEK		27 989	-1 135		-46 899	-83 324		-128 484
Internal rate of return	%		8,4%	5,9%		-	-1,2%		-
Pay back	years		9	11		25	Never		Never
Utilisation time	**hours**	**7000**	**7000**	**7000**	**7000**	**7000**	**7000**	**7000**	**7000**
Heat price	SEK/MWh	283,4	283,4	283,4	360,7	360,7	360,7	429,8	429,8
Net present value	KSEK	0	51 810	61 051	0	-32 592	-50 694	0	-123 945
Internal rate of return	%	6,0%	6,3%	6,3%	6,0%	5,8%	5,6%	6,0%	4,7%
Pay back	years	11	11	11	12	12	12	12	13
Financial performance for "Extra" investment									
Net present value	KSEK		51 810	61 051		-32 592	-50 694		-123 945
Internal rate of return	%		10,3%	9,2%		-	2,0%		-
Pay back	years		8	9		14	15		Never
Reduced part load efficiency taken into consideration									

Table 21 shows clearly that with the base conditions and 100 MW the advanced alternative Adv 1 is more profitable than the base plant as soon as the utilisation time goes above 5500 hours. For smaller alternatives the base plant is most profitable.

The table shows also that the operating conditions (utilisation time) are very important in order to provide the customers with heat at a competitive price (or to get a higher profit).

It is also of interest to study the profitability of the "extra investment" required for the advanced concepts. Table 22 show that it would be very profitable to make an extra "green" investment for Advanced 1 at 6000 and 7000 h utilisation time.

Table 22; Financial performance for "Extra Investment" for Advanced plants

Plant		100 MWe - Virgin Biomass Fuel		50 MWe - Virgin Biomass Fuel		25 MWe - Virgin
		Adv 1	Adv 2	Adv 1	Adv 2	Adv 1
		LV1.0-3	LV11.4-2	MV5	MV4	SV1
Utilisation time	**hours**	**5000**	**5000**	**5000**	**5000**	**5000**
Internal rate of return	%	5,0%	2,7%	-	-	-
Pay back	years	11	13	32	32	32
Utilisation time	**hours**	**6000**	**6000**	**6000**	**6000**	**6000**
Internal rate of return	%	8,4%	5,9%	-	-1,2%	-
Pay back	years	9	11	25	Never	Never
Utilisation time	**hours**	**7000**	**7000**	**7000**	**7000**	**7000**
Internal rate of return	%	10,3%	9,2%	-	2,0%	-
Pay back	years	8	9	14	15	Never

For Wide range fuels the correspondent results are presented in **Table 23** and **Table** 24.

Table 23: Financial performance for Wide Fuel mix based plants

Plant		**50 Mwe - Wide Fuel Mix**			**25 Mwe - Wide Fuel Mix**	
		Base plant	**Adv 1**	**Adv 2**	**Base plant**	**Adv 1**
		MW0.2	MW1.2.2	MW6.2.3	SW0	SW1
Utilisation time	**hours**	**5000**	**5000**	**5000**	**5000**	**5000**
Heat price	SEK/MWh	384,4	384,4	384,4	484,0	484,0
Net present value	KSEK	0	13 270	-25 601	0	-10 605
Internal rate of return	%	6,0%	6,1%	5,8%	6,0%	5,9%
Pay back	years	12	12	12	12	12
Financial performance for "Extra" investment						
Net present value	KSEK		13 270	-25 601		-10 605
Internal rate of return	%		8,1%	3,6%		3,3%
Pay back	years		9	12		12
Utilisation time	**hours**	**6000**	**6000**	**6000**	**6000**	**6000**
Heat price	SEK/MWh	327,0	327,0	327,0	411,5	411,5
Net present value	KSEK	0	38 743	11 117	0	3 054
Internal rate of return	%	6,0%	6,3%	6,1%	6,0%	6,0%
Pay back	years	12	12	12	12	12
Financial performance for "Extra" investment						
Net present value	KSEK		38 743	11 117		3 054
Internal rate of return	%		11,7%	7,0%		6,7%
Pay back	years		8	10		10
Utilisation time	**hours**	**7000**	**7000**	**7000**	**7000**	**7000**
Heat price	SEK/MWh	291,4	291,4	291,4	361,2	361,2
Net present value	KSEK	0	54 534	92 403	0	23 135
Internal rate of return	%	6,0%	6,4%	6,6%	6,0%	6,2%
Pay back	years	12	11	11	12	12
Financial performance for "Extra" investment						
Net present value	KSEK		54 534	92 403		23 135
Internal rate of return	%		14,1%	13,2%		11,1%
Pay back	years		7	7		8
Reduced part load efficiency taken into consideration						

Table 23 shows clearly that for 50 MW and with the base conditions the Adv 1 alternative is always more profitable than the Base plant. Adv 2 50 MW and Adv 1 25 MW alternatives are also better than the Base plant as soon as the utilisation time is around 6000 hours or more.

This table also shows the importance of the operating conditions (utilisation time) for the possibilities to provide the customers with heat at a competitive price.

Table 24; Financial performance for "Extra Investment" for Advanced plants

Plant		50 MWe - Wide Fuel Mix		25 Mwe - Wide Fuel Mix
		Adv 1	Adv 2	Adv 1
		MW1.2.2	MW6.2.3	SW1
Utilisation time	**hours**	**5000**	**5000**	**5000**
Internal rate of return	%	8,1%	3,6%	3,3%
Pay back	years	9	12	12
Utilisation time	**hours**	**6000**	**6000**	**6000**
Internal rate of return	%	11,7%	7,0%	6,7%
Pay back	years	8	10	10
Utilisation time	**hours**	**7000**	**7000**	**7000**
Internal rate of return	%	14,1%	13,2%	11,1%
Pay back	years	7	7	8

A comparison between alternatives of the same size in two tables shows the importance of having low variable cost (=wide fuel mix) for the possibilities to provide customers with heat at competitive prices.

In order to show the influence on the financial outcome of different components Figure 27: Net present value (MSEK) per main cost/income component for 100 MW Virgin is prepared. It shows the net present value per main cost/income component. In Figure 28 the same is given for 50 MW wide fuel mix.

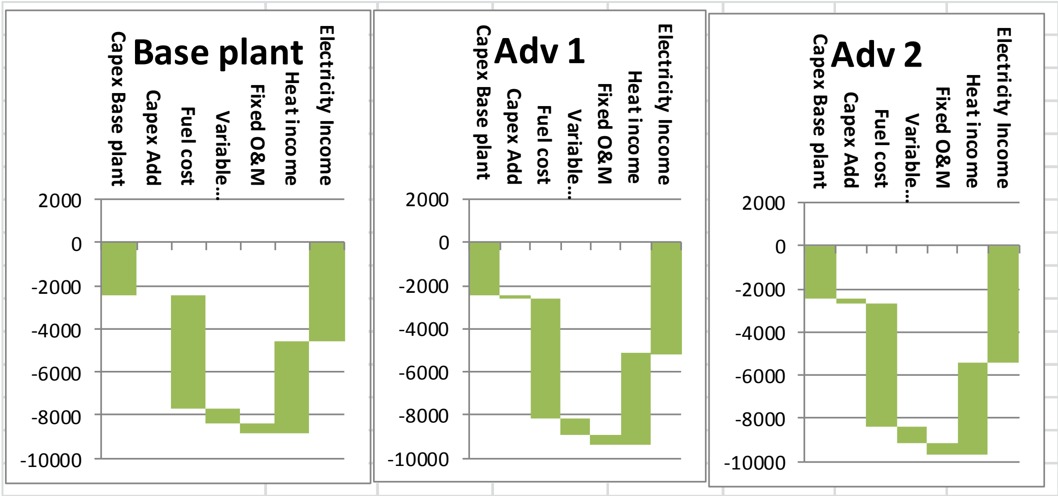


Figure 27: Net present value (MSEK) per main cost/income component for 100 MW Virgin

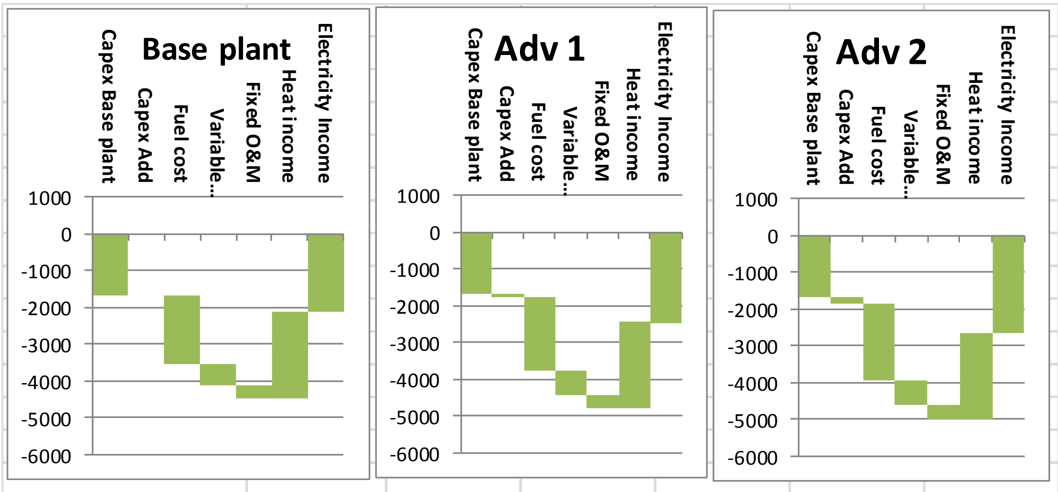


Figure 28: Net present value (MSEK) per main cost/income component for 50 MW Wide fuel mix

In Figure 27 and Figure 28 above it looks like they all end up at a total Net Present Value equal to 0. This is true for the Base plants because we have calculated the heat sales price so it should give that result for the project. For the advanced alternatives the figures in table 25 (Adv1 28 MSEK and Adv2 -1 MSEK) and 26 (Adv1 39 MSEK and Adv2 11 MSEK) shows that the total NPV is small compared to the NPV for the main components.

An interesting observation is that for a plant using Virgin fuel, the total NPV for fuel is roughly twice as big as the total CAPEX, while the total NPV for fuel for a plant using wide fuel mix is about the same as the total CAPEX for that plant. This indicates that the fuel price is extremely important for the long term financial outcome.

Another observation is that for both fuel mixtures the Variable OPEX increase is twice as big as the increase in CAPEX. This means that the focus should not be only on the differences in CAPEX between the Base plant and the advanced alternatives, it is as important to focus on the differences in Variable OPEX.

6.5 Uncertainties

6.5.1 Influence of changes in Capex, Fuel prices, Opex and Electricity prices

In Table 25 the influence of changes in Capex, Fuel cost, Opex and Electricity price on the Internal rate of return is given for the 100 MW/Virgin/6000 hours and for the 50 MW/Wide Fuel mix/6000 hour's alternatives.

Table 25: Influence of changes in basic assumptions

IRR (%)	Plant	100 MW, Virgin fuel, 6000 hours		
Component	**Variation**	**Base plant**	**Adv 1**	**Adv 2**
Base conditions		6,0%	6,1%	6,0%
Capex	+10%	4,5%	4,7%	4,5%
	-10%	7,7%	7,9%	7,7%
Fuel cost	+25%	-3,9%	-3,4%	-3,5%
	-25%	11,9%	11,9%	11,7%
Variable O&M	+25%	5,1%	5,2%	5,1%
	-25%	6,9%	7,0%	6,9%
Electricity price	+25%	9,7%	10,0%	9,9%
	-25%	1,4%	1,2%	1,0%

IRR (%)	Plant	50 MW, Wide fuel mix, 6000 hours		
Component	**Variation**	**Base plant**	**Adv 1**	**Adv 2**
Base conditions		6,0%	6,3%	6,1%
Capex	+10%	4,6%	4,9%	4,7%
	-10%	7,6%	7,9%	7,7%
Fuel cost	+25%	2,6%	2,9%	2,6%
	-25%	8,9%	9,2%	9,0%
Variable O&M	+25%	4,9%	5,1%	4,9%
	-25%	7,1%	7,4%	7,2%
Electricity price	+25%	8,3%	8,8%	8,8%
	-25%	3,4%	3,3%	3,0%

The figures in Table 25 show clearly that the advanced alternatives are as robust against changes in conditions as the Base plants. The most promising alternative seems to be the 50 MW Adv1 alternative, which have higher IRR than the Base plant, for all scenarios except when the electricity price decreases with 25% compared to the basic assumption. In that case IRR becomes 0,1% lower for Adv 1 than for Base plant.

6.5.2 Necessary Electricity price and Allowed levels for Fuel price and Opex

Another way to analyse the sensitivity is to calculate necessary or allowed levels for the main assumptions. In Table 26 such levels for Extra Capex, Variable Opex and for the Electricity price are given.

Table 26: Allowed extra Capex, allowed Variable Opex and Necessary Electricity price

Allowed extra capex (Adv-Base) to get the same IRR as for Base Plant			
Utilisation 6000 h	**Original estimate**	**Allowed value**	**Difference**
Plant	M€	M€	%
100 MW, Adv 1, Virgin	18,7	21,3	+14%
100 MW, Adv 2, Virgin	29,8	29,7	-0,3%
50 MW, Adv 1, Wide	10,1	13,7	+35%
50 MW, Adv 2, Wide	18,7	19,7	+5%
Allowed total variable O&M to get the same IRR as for Base Plant			
Utilisation 6000 h	**Original estimate**	**Allowed value**	**Difference**
Plant	SEK/MWh,fuel	SEK/MWh,fuel	%
100 MW, Adv 1, Virgin	29,4	30,5	+4%
100 MW, Adv 2, Virgin	29,4	29,36	+0,1%
50 MW, Adv 1, Wide	53,2	56,3	+5%
50 MW, Adv 2, Wide	53,2	54,1	+2%
Necessary Electricity price to get the same IRR as for Base Plant			
Utilisation 6000 h	**Original estimate**	**Necessary value**	**Difference**
Plant	SEK/MWh	SEK/MWh	%
100 MW, Adv 1, Virgin	400	368	-8,0%
100 MW, Adv 2, Virgin	400	401	+0,25%
50 MW, Adv 1, Wide	400	328	-18,0%
50 MW, Adv 2, Wide	400	388	-3,0%

The figures in Table 26 confirm the comments given about Table 25. 50 MW Adv 1 for Wide fuel mix allows reasonable negative changes compared to the qualified estimates used for investments, operational cost and for calculation of incomes and will still be more profitable than the Base plant.

6.6 Condensing plants

6.6.1 General

Above presented assessment has focused on the current Swedish conditions when assessing the competitiveness of high performance CHP plants. The stakeholders on the equipment supplier side, i.e. Metso and Siemens, are both working on a worldwide market. Stakeholders from the utility side, i.e. Vattenfall, E.ON., Fortum have all interests in other EU countries. It would hereby be of interest to assess both CHP and condensing plants in other EU countries where both electricity price and especially the RES supporting scheme differs from the Swedish conditions.

A broader assessment of the competitiveness in different EU countries has not been possible to perform in this phase of the Programme. In order to give an indication of the possible competitiveness of advanced biomass condensing plants of this kind compared to plants with conventional data, a more general assessment has been made for a 100 MWe class plant.

The calculation method is about the same as in the CHP case, but in this case the income is limited to the electricity sales including possible green certificates or feed-in tariffs.

In the condensing case the fuel feed capacity is assumed to be same for base case (bench-mark) and for the advanced alternative. An "total electricity price" (including green certificates or feed-in tariff) is calculated in order to be profitable (NPV=0) at the basic real rate of interest (6%), at the assumed operating conditions. This calculated total electrical price is then used as input for the advanced alternative in order to find out if this concept would be more profitable than the base case.

For the condensing plant only virgin fuels and the larger capacity class has been considered. In this case the base plant is based on the same boiler capacity and fuel feeding capacity as the CHP 100 MWe plant.

Further for the condensing plant maximum sub-critical steam data 190 bar, 600/600C (with reheat) is assumed for the advanced plant ("Advanced 2").This means supported boiler circulation. (This do not mean that this have to be the most profitable solution.)

6.6.2 Plant specific technical and financial data

In Table 27 the main technical and financial data for the Base plant and for the advanced alternative using virgin biomass.

Table 27; Technical and Financial input

Plant		100 MWe - Virgin bio	
		Base plant	**Adv 2**
		LV9.2	LV10.1.1
Steam temp		540	600/600
Steam pressure		140	190/45
Installed capacity			
	Electricity gross	119	130
	Electricity net	111	121
	Heat	0	0
	Fuel input	292,0	292,0
	Net efficiency	38,0%	41,4%
Investment (MEUR)			
	Boiler	94,3	113,7
	Steam Turbine	33,9	38,8
	Steam Turbine indirect [1)]	13,0	13,0
	Fuel	40,7	40,7
	Civil, I&C, El, BOP & Indirect	92,0	92,0
	Sum	**270,0**	**299,8**
O&M and Sales prices (SEK/MWh)			
	Fix	1,5%	1,5%
	Variable (SEK/MWh,fuel)	28	32
	Fuel price	210	210

1) Adm, erection, comissioning (Siemens)

Reduced part load efficiency taken into consideration

The investment is based on the assumption that the boiler capex will be the same as for CHP and based on recalculated capex for the steam turbine package for the condensing configuration.

The analyses have been made for utilisation times of 5000, 6000 and 7000 hours (equals to utilisation factors of 57%, 68% and 80%).

6.6.3 Results for condensing plant

In Table 28the annual production of electricity is given together with the annual consumption of fuel.

Table 28; Operational conditions and main output (MWh/a)

Plant	100 MWe - Virgin bio	
	Base plant	Adv 2
	LV9.2	LV10.1.1
Utilisation time (hours)	**5000**	**5 000**
Heat production	0	0
Electricity generation gross	595 000	650 000
Fuel consumption	1 460 000	1 460 000
Auxillary power consumption	40 000	45 000
Total efficieny	40,8%	44,5%
Utilisation time (hours)	**6000**	**6 000**
Heat production	0	0
Electricity generation gross	714 000	780 000
Fuel consumption	1 752 000	1 752 000
Auxillary power consumption	48 000	54 000
Total efficieny	40,8%	44,5%
Utilisation time (hours)	**7000**	**7 000**
Heat production	0	0
Electricity generation gross	833 000	910 000
Fuel consumption	2 044 000	2 044 000
Auxillary power consumption	56 000	63 000
Total efficieny	40,8%	44,5%
Reduced part load efficiency taken into consideration		

The annual production would hereby increase with more than 9% when the advanced alternative would be chosen.

Table 29 indicates clearly that advanced alternative Adv 2 is more profitable than the base plant for all utilisation time cases. Higher utilisation time will of course mean higher profitability.

Table 29; Main results from Financial assessment

Plant		100 MWe - Virgin bio	
		Base plant	Adv 2
		LV9.2	LV10.1.1
Utilisation time	**hours**	**5000**	**5000**
Electricity price	SEK/MWh	1021,4	1021,4
Net present value	KSEK	0	278 935
Internal rate of return	%	6,0%	7,1%
Pay back	years	13	12
Financial performance for "Extra" investment			
Net present value	KSEK		278 935
Internal rate of return	%		16,2%
Pay back	years		7
Utilisation time	**hours**	**6000**	**6000**
Electricity price	SEK/MWh	955,5	955,5
Net present value	KSEK	0	346 585
Internal rate of return	%	6,0%	7,4%
Pay back	years	13	12
Financial performance for "Extra" investment			
Net present value	KSEK		346 585
Internal rate of return	%		18,6%
Pay back	years		6
Utilisation time	**hours**	**7000**	**7000**
Electricity price	SEK/MWh	908,4	908,4
Net present value	KSEK	0	414 236
Internal rate of return	%	6,0%	7,6%
Pay back	years	13	12
Financial performance for "Extra" investment			
Net present value	KSEK		414 236
Internal rate of return	%		21,0%
Pay back	years		5

When focusing on the "extra investment" i.e. the investment difference between base and advanced case, the result becomes even clearer. Table 30 for 5000 and 6000 h utilisation time, show that the profitability is significant for the extra investment

Table 30; Financial performance for "Extra Investment" for Advanced plants

Plant		100 MWe - Virgin bio
		Adv 2
		LV10.1.1
Utilisation time	**hours**	**5000**
Internal rate of return	%	16,2%
Pay back	years	7
Utilisation time	**hours**	**6000**
Internal rate of return	%	18,6%
Pay back	years	6
Utilisation time	**hours**	**7000**
Internal rate of return	%	21,0%
Pay back	years	5

This result is an indication that advanced steam data is even more interesting for condensing plants where electricity production is the only income. The result is relative and the figures based on the assumption that the base case is profitable, which in this case would mean significant RES support.

No sensitivity analysis has been performed in this phase. This should be done focused on selected countries where condensing plants are of interest.

6.7 Summary of financial performance

For plants using virgin bio mass fuel it can be stated that the CHP 100 MW_e with advanced design without reheat (Adv1) is competitive against the Base plant under normal CHP operational conditions. IRR is 6,1% instead of 6,0% and the IRR for the extra CAPEX is 8,4%. For smaller plants using virgin fuel the Base plant seems to be more profitable than the advanced alternatives. However the differences are small, IRR 5,7% for Adv1 and 6,0% for Base plant.

For CHP plants using a wide fuel mix, 50 MW Adv1 is more profitable than the Base plant, 6,3% compared to 6,0%. It seems also to be robust against reasonable changes in electricity and fuel prices as well as changes in variable cost, as well as unforeseen increases of Capex. It can also be observed that Adv1 50 MW is always better than Adv2 (Reheat) 50 MW and that 25 MW Adv 1 is also competitive against the Base plant if the utilisation time is at least 6000 hours.

For a CHP plant using Virgin fuel, total NPV for fuel is roughly twice as big as NPV for CAPEX, while total NPV for fuel for a plant using wide fuel mix is about the same as NPV for CAPEX for that plant. This indicates that the fuel price is extremely important for the long term financial outcome.

Another observation is that for the wide fuel mix the Variable OPEX increase is twice as big as the increase in CAPEX. This means that it is as important to focus on the differences in Variable OPEX and not only on the differences in CAPEX.

The presented assessment also indicated that where biomass based condensing plants is of interest and could be profitable for conventional steam data, it will be significantly more profitable to go for more advanced steam data.

7 Findings

7.1 General conclusion

Operational conditions are important for total profitability. Over dimensioning of a base load unit results usually in short utilisation times and bad profitability.

Fuel and Electricity prices are important for the total profitability and changes in those can result in changed priority between the reference plant and the advanced.

Virgin Biomass fuels

- Both selected target (175 bar 600 °C, 175/46 bar 585/585 °C) cases look technically feasible.
- Reheat will improve efficiency by about 1,2-1,4 %-units, but an expensive measure that will require long utilisation time, as for condensing plants
- The most advanced steam data studied 190 bar 600/600 °C, with an net efficiency of 35,1 %. The pressure will require assisting circulation pumps which will add which will have an impact on availability and maintenance. The temperature will have some drawbacks in part load performance, and will hereby be more of interest for condensing plants than for CHP. For CHP the recommendation is to limit the pressure to 175 bar and the temperature for reheat concepts to 585/585 °C.
- For the 600 °C concepts (LV1.0-3 and LV11) the life time has not yet been proven in a real environment with renewable fuels.
- Steam turbine temperature of 600 °C is proven for large plants but not proven in smaller sizes. Data is here based on existing modules and experience from big steam turbines.
- From the financial point of view we can state that:
    - 100 MW_e with advanced design without reheat (Adv1) is competitive against the Base plant under normal CHP operational conditions.
    - Smaller plants are not competitive against the Base plant. However the differences are small.

Wide fuel range

- Reheat will improve efficiency by about 1 %-units. The same conclusion is valid as in the virgin fuel case, i.e. an expensive measure that will require long utilisation time. The performance problems at part load will however not be that pronounced as in the virgin fuel case due to lower temperatures. This has to be studied further.

- The efficiency improvement for main advanced steam data options compared to benchmark is higher for wide range fuels than for virgin fuels, 2,8 % - 3,8 % compared to 2,3 % - 3,1 %. This is of course dependent on the definition of the benchmark steam data. Compared with the first of the kind CYMIC boiler for waste wood to be commissioned in Delfzijl the steam data for the proposed benchmark is a bit more conservative as regards the temperature (-20 °C) although the pressure a bit higher (+10 bar). Compared to the Delfzijl the range of improvement would decrease about 0,2 %-points.
- Both selected target (160 bar 560 °C and 160/44 bar 560/560 °C) cases look technically feasible, but the increase in pressure causes a temperature increase of about 40 C. The effect of the temperature increase has not been evaluated in a real environment yet.
- The reheat alternative looks promising (+3,8 % efficiency). There is heat enough available from flue gas to reheat steam. Mid temp corrosion ($PbCl_2$) at part load (critical temperature window) for primary reheater and other sections have to be further studied.

- From the financial point of view we can state that:
  - 50 MW Adv 1 is more profitable than the Base plant. It seems also to be robust against reasonable changes in electricity and fuel prices as well as changes in variable cost, as well as unforeseen increases of Capex.
  - Adv1 50 MW is always better than Adv2 (Reheat) 50 MW.
  - 25 MW Adv1 is also competitive against the Base plant if the utilisation time is at least 6000 hours.

Virgin / Wide fuel

There are no doubt about that plants with an electric generation capacity of 50 MW and below that using a wide fuel mix seem to be more interesting than similar plants using Virgin fuel.

The major challenges for future development ought to be to:

1. Lower the differences in variable Opex between the advanced design and the Base plant.
2. Lower the differences in Capex between the advanced design and the Base plant.

Condensing plants

- Condensing plants have been studied for the largest capacity (> 100 MWe) for Virgin fuels in the process analysis. The financial assessment has been focusing on CHP plants. Additional calculation for one selected case indicates that where condensing plants could be profitable, an extra investment in advanced steam data would be very profitable.

- If there is an interest for condensing plants this should be studied further in next phase of the programme, in terms of different, capacity, steam data and sensitivity analysis.

8 Suggestions for future research work

The following activities have been presented at conferences with the participants in the KME program to support the realisation of a demonstration plant. Some projects have been initiated but more tests an evaluations needs to be done.

1. A test with super heater tubes with varies materials in a loop seal super heater at steam temperature up to 620 °C. Installation and test with probes with varies materials in a loop seal compartment. The purpose is to demonstrate and validate that it's possible.
2. Validate strength in super heater tubes corresponding to an internal operational pressure of 175 bar at operational material temperature. The outer material surface of a super heater tube in a loop seal installation may reach temperatures up to 100 °C above steam temperature.
3. Evaluate easy and frequent replacement vs. expensive materials
4. Corrosion memory in SH tube deposits from fuels with higher content of corrosive species. (see KME 608)
5. Cleaning techniques of SH deposits if "gliding" temperature control is used. (see KME 608)
6. Tools to evaluate changes in fuel composition and fuel mixtures vs. "corrosiveness". Equilibrium calculation could be used to evaluate the change in corrosiveness versus changes in fuel mixtures.
7. Test of new measures and chemicals to be used as additives. (see KME 512)
8. Tools to evaluate additives – different fuel spec and conditions. Equilibrium calculation could be used to evaluate the change in corrosiveness for different additives. (see KME 512)
9. Measures for controlling furnace corrosion (primary) and protection measures (secondary), at pressure levels of 160-190 bar. (see KME 508 and 515)

9 Administration

9.1 Documentation

The "Projectplace" was used for documentation handling during the project on courtesy of E.ON Värme.

9.2 Project economy

The project was financed without founding from the Swedish Energy Agency since the work was to be done solely by the industry. During the project Fortum and Kraftringen could not participate actively in the project. Fortums contribution was changed from 350 kSEK in kind and 100 kSEK in cash to 200 in kind and 250 kSEK in cash. E.ON Värme changed their in kind contribution from 350 to 150 kSEK and included E.ON C&R with an in kind contribution of 300 kSEK, see Table 31, thereby compensating for Kraftringen.

Table 31; Budget

	Budget			Modified budget		
	In kind	Cash	Total	In kind	Cash	Total
Siemens	400		400	400		400
Metso	300	100	400	300	100	400
Vattenfall	400	300	700	400	300	700
E.ON Värme	350	100	450	150	100	250
E.ON C&R				300		300
Fortum	350	100	450	200	250	450
Kraftringen	100	100	200	0	100	100
Svensk Fjärrvärme		500	500		500	500
Göteborgs Energi		300	300		300	300
Mälarenergi		200	200		200	200
Skellefteå Kraft		200	200		200	200
Växjö Energi		200	200		200	200
Öresunds Kraft		200	200		200	200
Söderenergi		100	100		100	100
Total from industry	1 900	2 400	4 300	1 750	2 550	4 300
From KME		0			0	
Project costs						
Erik Skog AB		-860			-860	
Vattenfall Power Consulant/Pöyry		-1 540			-1 660	
Olle Mårdsjö / Bengt Wegemo					-30	
Industrial work in kind	-1 900			-1 750		
Total cost	-1 900	-2 400	-4 300	-1 750	-2 550	-4 300

The accumulated cost for the companies in kind contribution are summarised in Table 32. The contribution from Metso exceeds the budget with a factor of about 3. The decrease of in kind work from the utilities of about 80 kSEK had to be compensated by work from the consultants.

Table 32; Accumulated cost

	Modified budget			Accumulated			Diff
	In kind	Cash	Total	In kind	Cash	Total	Total
Siemens	400		400	367		345	-55
Metso	300	100	400	936	100	984	584
Vattenfall	400	300	700	398	300	698	-2
E.ON Värme	150	100	250	231	100	331	81
E.ON C&R	300		300	340		340	40
Fortum	200	250	450	0	250	250	-200
Kraftringen		100	100		100	100	
Svensk Fjärrvärme		500	500		500	500	
Göteborgs Energi		300	300		300	300	
Mälarenergi		200	200		200	200	
Skellefteå Kraft		200	200		200	200	
Växjö Energi		200	200		200	200	
Öresunds Kraft		200	200		200	200	
Söderenergi		100	100		100	100	
Total from industry	1 750	2 550	4 300	2 272	2 550	4 748	448
From KME		0			0		
Project costs							Diff
Erik Skog AB		-860			-619		241
Vattenfall Power Consulant/Pöyry		-1 660			-1 901		-241
Olle Mårdsjö / Bengt Wegemo		-30			-30		0
Total cost		-2 550			-2 550		0

10 References

1. Efficient Power Generation from Renewable Fuels – Elforsk report 2483 (Maj 2010)
2. KME 609 Technical and economical risks for plant concepts with advanced steam data for biomass-fired CHP demonstration plant

11 Attachments

1. KME 601-Heat balance calculations
2. KME 601-Boiler delivery scope

ELFORSK

SVENSKA ELFÖRETAGENS FORSKNINGS- OCH UTVECKLINGS - ELFORSK - AB

Elforsk AB, 101 53 Stockholm. Besöksadress: Olof Palmes Gata 31
Telefon: 08-677 25 30, Telefax: 08-677 25 35
www.elforsk.se