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BIOMASS-BASED COMBINED HEAT AND POWER PLANT WITH INTEGRATED BIOMASS DRYING AND SUBSEQUENT FAST PYROLYSIS

Steady-state simulation with multiperiod district heating model and environmental performance in European conditions

Hubert Hadera

PROJEKT PL0460
eea grants iceland liechtenstein norway
UNIVERSITY OF ICELAND
University of Akureyri

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A 30 ECTS credit units Master´s thesis

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A Master´s thesis done at

RES | The School for Renewable Energy Science

in affiliation with

University of Iceland &

University of Akureyri

The Master Thesis was supported by a grant from Iceland, Liechtenstein and Norway through the EEA Financial Mechanism - Project PL0460

Akureyri, February 2011

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ABSTRACT

Climate change and green energy policies are driving the pursuit for environmentally friendly and thermodynamically efficient technologies. This research work combines renewable energy with the energy efficient concept of combined heat and power (CHP) and the emerging technology of biomass fast pyrolysis. The latter produces valuable bio-oil that can be further upgraded to e.g. transportation fuels or be used in heavy fuel oil boilers.

This thesis focuses on developing steady-state simulation models of different biomass-based CHP integration options with biomass drying and fast pyrolysis. Integration options include the use of a grate fired boiler and a circulating fluidized bed with a boiler-integrated pyrolysis process.. These systems are then analyzed from a thermodynamic and environmental point of view using a multiperiod district heating load model. Assuming the free boiler capacity in part loads is used for the highest possible yields of slurry, bio-oil yield is estimated.

Models developed in this work follow the logic of the previous study on bubbling fluidized bed boiler. The research approach adopted includes a simulation in steady-state thermal power plant simulation software. Environmental performance calculations use modified Primary Energy Factors and CO2 emissions coefficients according to EN15603 and EN 15613-4-5 standards. Results for all studied boiler types are then compared to results from the previous studies and conclusions are drawn. The implementation of the concept in Poland is analyzed.

The key findings provide evidence that by co-generation of a pyrolysis product, operation hours and thus electricity and heat, production can be improved. The integration also improves the district heating network‘s primary energy efficiency and lowers its carbon dioxide emission coefficient. The boiler type does not affect the basic integration concept. Moreover, the benefits of the integration already found for the bubbling fluidized bed plant in previous research apply also for the boiler types analyzed in this work.

This research is a base for further investigation of fast pyrolysis integration into biomass CHP production. Future work should include analysis of potential economical benefits going along with findings stated in this thesis.

ABSTRAKT

Zmiany klimatyczne oraz polityka dotycząca zielonej energii napędzają dążenie ku przyjaznym środowisku i sprawnym termodynamicznie technologiom. Niniejsza praca łączy pole odnawialnych źródeł energii i efektywny energetycznie koncept produkcji ciepła i elektryczności oraz nową technologię szybkiej pyrolizy biomasy. Ta ostatnia generuje cenny bio-olej, który może być przetworzony na paliwo stosowane w transporcie, albo użyty w kotłach opalanych olejem ciężkim.

Praca skupia się na stworzeniu modeli symulacji stanu ustalonego różnych opcji integracji suszenia oraz szybkiej pyrolizy biomasy z procesami produkcyjnymi w elektrociepłowni opalanej biomasą. Opcje integracji dotyczą pieca rusztowego oraz obiegowego złoża fluidalnego ze zintegrowanym procesem pyrolizy. Stworzone systemy są następnie przeanalizowane pod względem charakterystyk termodynamicznych oraz wpływu na środowisko, używając wielookresowego modelu obciążenia sieci ciepłowniczej. Zakładając, że wolna zdolność produkcyjna podczas niepełnego obciążenia elektrociepłowni jest użyta do produkcji jak największej ilości zawiesiny pyrolitycznej, produkcja bio-oleju jest oszacowana.

Metodologia badań użyta na potrzeby niniejszej pracy opiera się na symulacjach stanu ustalonego przy użyciu komputerowego oprogramowania symulacyjnego. Obliczenia wplywu na środowikso uwględniają zmodyfikowany koncpet współczynnika energii pierwotnej oraz współczynnika emisji dwutlenku węgla według standardów EN15603 oraz EN1513-4-5. Wyniki dla wszystkich rodzajów kotłów są porównane z wynikami wcześniejszych badań nad elektrociepłownią wykorzystującą złoże z wrzeniem pęcherzykowym, a następnie wyciągnięte zostają wnioski. Implementacja technologii w Polsce jest przeanalizowana.

Uzyskane dane dostarczają dowodów na to, iż poprzez kogenerację produktów pyrolizy czas produkcyjny elektrociepłowni może zostać wydłuzony oraz w następstwie zwiększona produkcja ciepła oraz elektryczności. Integracja poprawia współczynnik energii pierwotnej oraz emisji dwutlenku węgla dla wszystkich badanych przypadków, bez względu na rodzaj kotła.

Niniejsza praca stanowi podstawę do dalszych badań nad integracją szybkiej pyrolizy z procesami elektrociepłowni opalanej biomasą. Dalsze prace powinny skupić się na analizie potencjalnych korzyści ekonomicznych związanych z uzyskanymi danymi w niniejszym opracowaniu.

PREFACE

The work for this thesis is a contribution to the Primary Energy Efficiency project carried out under the auspices of Nordic Energy Research (NER). NER is the funding institution for energy research under the Nordic Council of Ministers. The project is carried out at the Energy Engineering and Environmental Protection research group at Aalto University in Finland. This report is my final thesis for the Master of Science degree at RES, The School for Renewable Energy Science in Iceland awarded jointly by University of Iceland and University of Akureyri.

The instructor for this work, Thomas Kohl is warmly thanked for the coordination, every-day help and fruitful discussions. Professor Carl-Johan Fogelholm is gratefully acknowledged for the supervision and for giving me the opportunity to be a part of the research on this emerging concept. I would like to also thank the whole research group for the friendly atmosphere.

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LIST OF ABBREVIATIONS

ACFB	Atmospheric Circulating Fluidized Bed
AFB	Atmospheric Fluidized Bed
BFB	Bubbling Fluidized Bed
BTF	Biomass-To-Fuel
BTL	Biomass-To-Liquid
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DH	District Heating
DHN	District Heating Network
EEA	European Environment Agency
ENY	Energy Engineering and Environmental Protection Research Group
EPA	Environmental Protection Agency
EU	European Union
FBC	Fluidized Bed Combustion
FZK	Forschungszentrum Karlsruhe
GHG	Greenhouse Gases
GMES	Global Monitoring for Environment and Security
HHV	Higher Heating Value
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
NER	Nordic Energy Research
NO_x	Nitrogen Oxides
PEF	Primary Energy Factor
PFB	Pressurized Fluidized Bed
R&D	Research and Development
RF	Radiant furnace
SET	Strategic Energy Technology
SO_x	Sulphur Oxides
UN	United Nations
UNEP	United Nations Environment Programme

LIST OF SYMBOLS

$\dot{E}_{in}$	energy entering the unit over time
$\dot{E}_{out}$	energy leaving the unit over time
$\dot{m}_{in}$	mass entering the unit over time
$\dot{m}_{out}$	mass leaving the unit over time
$E_{F,i}$	chemical energy of the fuels used
$E_{P,in}$	primary energy input to the system
E_{Pyro}	chemical energy of the pyrolysis slurry
E_{pyro}	chemical energy of the pyrolysis product
P_n	heat produced at *n* partial load
$\dot{Q}$	energy flow
Q_{BM}	chemical energy of the biomass burned
Q_{CHP}	total heat produced by the CHP plant
Q_{DH}	heat delivered at the border of the supplied system
Q_{Gas}	chemical energy of the gases produced by pyrolysis process
Q_{Oil}	chemical energy of the heavy oil burned
Q_{WetBM}	chemical energy of the biomass fed for drying
$c_{CO_2,Pyro}$	carbon dioxide coefficient of the pyrolysis slurry
$c_{CO_2,BM}$	carbon dioxide coefficient for the biomass burned
$c_{CO_2,DH}$	carbon dioxide coefficient of the system in question
$c_{CO_2,El}$	carbon dioxide coefficient of the electricity
$c_{CO_2,F,i}$	carbon dioxide coefficient of the fuels
$c_{CO_2,Oil}$	carbon dioxide coefficient for the heavy oil burned
f_{BM}	Primary Energy Factor of the biomass burned
f_{DH}	Primary Energy Factor of the studied system
f_{El}	Primary Energy Factor of the generated power
$f_{F,i}$	Primary Energy Factor of the fuels used
f_{Oil}	Primary Energy Factor of heavy oil used in back-up boilers
$f_{P,dh}$	Primary Energy Factor of the system in question
f_{pyro}	Primary Energy Factor of the pyrolysis product
$\dot{m}$	mass flow rate of a given stream
t_n	duration of the *n* load

$\Delta\dot{E}$	change in energy over time
g	grams
GWh	gigawatt hours
h	specific enthalpy
kg	kilogram
kJ	kilojoule
m	meters
MJ	megajoule
MW	megawatt
MWh	megawatt hours
sec (or s)	second
yr	years
P	electricity generated by the studied system
tot	total operation time of the CHP plant

1 INTRODUCTION

The introduction part of this thesis gives general information on the research done for this report. The parts *Background* and *Research Motivation* describe in short the parties responsible for the project and the main drivers for the work, respectively. The *Goal and scope* of this thesis is explained next, following the information on methodology applied in the research. Finally, the outline of the thesis is presented.

1.1 Background

The work done for this thesis was conducted at the Aalto University School of Engineering, Department of Energy Technology, Energy Engineering and Environmental Protection group (ENY) between September 2010 and January 2011. The research group led by Professor Carl-Johan Fogelholm has been carrying out a research project on Primary Energy Efficiency since 2007. The project is co-founded by Nordic Energy Research. The project worker and this thesis' instructor is Thomas Kohl, researcher at the ENY group and a PhD candidate. His work focuses on investigation of the potential integration options of a Combined Heat and Power (CHP) plant with bio-refinery processes.

In this thesis steady-state simulations are done for small scale biomass-based CHP systems and possible integration of fast pyrolysis. This concept is very new and ideas emerging from it have virtually no comprehensive studies or extensively published literature. The research in this thesis investigates different boilers' deployment in the plant as well as environmental consequences related to the integration. Environmental performance of the cases studied is expressed by the primary energy and carbon dioxide rating. This work is a continuation of the project thus results from previous work are an important input that shapes and partly defines the research described in next chapters.

1.2 Research Motivation

The topic of sustainable power and heat generation is gaining increasing importance and international attention. Global warming and rising awareness of environmental issues can be easily seen in new policies and renewable energy promotion. The world is seeking to deploy new and more environmentally friendly technologies. Combined Heat and Power production (or cogeneration) is not only energy-efficient and renewable, but it is also considered to be among the most economically feasible technologies nowadays.

The debate over cogeneration in Europe has never been more important. Studies on new renewable technologies and ideas that could be implemented to CHP generation will have a long term future if Europe is to meet its climate change related targets. Deployment of biomass utilization technologies in CHP production can especially contribute to the reductions of harmful emissions. Organic matter is foreseen to significantly contribute in meeting Greenhouse gas reduction targets.

Another aspect of CHP production that is making it an interesting field for study is Primary Energy Efficiency. Cogeneration improves the efficiency considerably in comparison to traditional separate heat and power production, especially in Central and Eastern Europe where there are many opportunities in this field. Although most of the large power plants (especially in Northern and Western Europe) have been converted into CHP units, there is still a significant potential in converting smaller, regional DH plants into CHP together with improving their efficiency and CO_2, and other pollutants emission reduction.

Integration of fast pyrolysis into a CHP plant has a potential to raise new additional opportunities and benefits for cogeneration. Firstly, the thermo-chemical process of biomass decomposition generates pyrolytic oil. Derived from almost any kind of biomass, this bio-oil can be easily transported and is a valuable byproduct which can be used to produce fuels and other important chemical substances. Another aspect of the integration of this advanced technology is considering it as an implementation of bio-refinery processes locally. Since small scale biomass-based CHP plants serve local purposes, the integration would not only contribute to dispersed production by cogeneration, but also for densification of biomass via pyrolysis process.

There are very few literature descriptions of the integration concept. From the very few that deal with this subject it has been shown that the integration of pyrolysis into CHP can bring new opportunities for the plant. The integration may improve the operation hours of the seasonal CHP production. This can increase the financial attractiveness of the sustainable cogeneration. Another benefit for the plant is that it could generate a bio-oil product that is independent of the power and heat market, and also other end-products markets.

To sum up, the most important motivation drivers for the pyrolysis integration into Combined Heat and Power production are:

- may contribute to the mitigation of the climate change through reduction in GHG emissions;
- may lead in helping to meet EU targets for renewable generation in the medium term future;
- may lead in helping to meet EU targets for CHP production;
- the concept has a potential for reductions in primary energy use;
- may contribute to more efficient scarce biomass utilization;
- potential increase in economical feasibility due to improved economical performance of CHP and pyrolysis integrated systems;
- may strengthen small scale biomass-based cogeneration in the market resulting in increase of distributed generation and security of supply issues;
- may help to improve the Biomass-To-Liquid (BTL) scheme for transportation fuels in the future through simple biorefineries process integration in local markets;
- DH networks may face lower heat loads in the future which could be compensated by shifting the available capacity to the new process;
- biomass prices can be expected to raise (because of e.g. production of biofuels) which threatens the economy of biomass-based CHP production - by producing a platform product the CHP operator could benefit from the new market opportunities.

Finally, the ultimate motivation for all of us is to investigate technologies that have the potential of helping to preserve our mother Earth.

1.3 Goal and Scope

The goal of this thesis is to investigate different biomass drying and subsequent pyrolysis integration options for a utility biomass-based combined heat and power plant. These options should include the Combined Heat and Power plant deploying different boiler technologies:

- Grate fired boiler (simulated with a radiant furnace model);
- Circulating Fluidized Bed boiler.

The investigation criteria should make it possible to compare the result from this thesis with previous work done on a bubbling fluidized bed boiler integrated with fast pyrolysis done by Thomas Kohl presented in Kohl et al. 2010. Within the scope of this thesis is also the comparison itself. Therefore, steady-state simulations of the studied systems should be compared and basic cycle characteristics derived. As a consequence the environmental performance of the systems studied should be analyzed. This includes the Primary Energy Factor (PEF) and the carbon dioxide coefficient calculations according to related European (EN) standards such as EN15603. As in the previous work (Kohl et al. 2010) the studied CHP systems are assumed for European conditions.

Considering the fact that this thesis is submitted as a final report for the Energy Systems and Policies specialization at RES, later in the text special mention is made to the policy section of the thesis scope and motivation behind it.

Potential implementation of the integration concept for Poland is emphasized in the thesis as this paper is submitted for the degree carried out under the EEA Financial Mechanism Grant and the Polish-Icelandic project PL0460.

1.4 Methodology

As stated in the scope of the thesis a crucial part of this work is the steady-state simulation models. They will provide a basis for further comparisons and calculations of the plant performance with different boilers used. Simulation work is carried out with a state-of-the-art thermal power plant simulator, ProSim. This software also gives information on the power cycle thermodynamic performance, thus extraction of data is needed.

Assumptions and work methodology follow the previous work described by Kohl. The type of data extracted and elaborated from the simulation cases are determined by the previous work as well. Environmental calculations methodology is taken from the EN 15603 standard, as in Kohl's paper.

For the assumptions made and the concept development process, a literature review was carried out. The novel fast pyrolysis integration idea is almost not existent in published literature. The review includes the scope and motivation background and CHP technology specific publications, as well as the manuals for the power plant simulator.

1.5 Research Outcomes

Achieving the goal of the thesis within its scope should result in certain research outcomes. For this thesis work anticipated direct outcomes include simulation models in the first place. The simulation cases' structure consists of the on-design and then off-design models at design load of the CHP plant. Furthermore, from this point the partial load simulation cases, according to the multiperiod model, should be developed. These models' structure applies for both, to the base cases of the power plant set up without pyrolysis as well as the integration cases with biomass drying and pyrolysis within the power cycle. The goal and scope of this thesis gives also an indication to investigate two different boilers and compare anticipated results with the previous work done on the third boiler. Hence, the simulation structure applied to both the radiant furnace boiler plant and the Circulating Fluidized Bed boiler plant will result in obtaining simulation models for both boilers. For the simulation models environmental calculations will give comparable Primary Energy Factors and CO_2 emission coefficients of the district heat supplied by the power plants.

From the above mentioned, general anticipated research outcomes include the following:

- the study shows how the Combined Heat and Power cycle may be affected by the integration of biomass drying and subsequent pyrolysis – this includes cycle characteristics i.e. fuel efficiency; possible problems with working fluid streams characteristics i.e. pressures, temperatures; and also potential operation hours improvement;
- possible influence of the boiler type deployed in the cycle;
- possible level of environmental benefits from the integration of the pyrolysis process, both compared to the plant without integration and to the integration cases with different boiler types – this includes influence on Primary Energy and CO_2 emission ratings;
- possibilities for the concept implementation in Poland.

The anticipated outcomes from this study should create a base for further investigation of the topic.

1.6 Thesis Outline

This thesis consists of four main parts. Each part is a logical consequence of the previous one. Additionally, each chapter begins with a short summary.

The first chapter is an introduction to the work done and described later in the thesis. It gives general information about the project and motivation behind it. The goal and scope together with applied research methodology is explained as well. Finally, anticipated research outcomes are presented followed by the thesis outline.

The second chapter describes the background behind the motivation and scope of this thesis. It explains the main drivers for this work being a part of the renewable energy research. Policies concerning the CHP production and biomass usage are presented. The chapter also gives general information on the technology status. Principles and benefits of the CHP generation are presented. Then, more detailed information about the research specific subjects is given. This includes the background on boiler technology with the emphasis on the boilers used in further simulations. Next, power cycle simulation connected to the methodology of the research is explained. Finally, the environmental performance of the concepts analyzed in the research part is presented. This includes environmentally friendly biomass CHP technology and description of the background of Primary Energy and Carbon Dioxide emission ratings.

The third chapter of this thesis is the core of the research. In this part the simulation of the integration of biomass drying and subsequent fast pyrolysis is described. Firstly, the assumptions and input data for the steady-state simulation are presented. Then, the detailed description of the simulations performed is given. This includes simulation cases for radiant furnace and fluidized bed boilers. For the models developed there is a description of environmental performance calculations presented further. The integration concept suggestions for implementation in Poland are explained next. Finally, the results and discussion of the simulation output and environmental calculations are presented.

The last chapter summarizes the main conclusions that can be drawn from the research part. The challenges encountered during the work are mentioned as well. Lastly, limitations of the study and recommendations for future work are discussed.

2 MOTIVATION AND INTEGRATION BACKGROUND

This part of the thesis is a general state-of-the-art review on the topics related to the goal and scope of the research. Explanation of the main research theme behind this thesis is presented. In the following text special attention is given to the motivation of the study having its reflection in general societal concerns and in European legislation as well.

The purpose of this chapter is as follows:

- give the reader the context of the research related to the goal of this thesis (chapter 2.1);
- give the basic overview and explanation on the technology status in relation to the goal of this thesis (chapters 2.2, 2.3, 2.4, 2.6);
- describe the motivation and prove the need for this research in relation to the goal of this thesis (chapters 2.1, 2.2, 2.3, 2.6);
- explain basic concepts that are used directly in further research part (chapters 2.5, 2.6).

The chapter gives the reader a general background related to the research part of the thesis. It begins with a description of current energy conversion concerns in the world. Further it continues with explanation concerning resources and technologies used for heat and power production that are relevant for the goal and scope of the thesis. The chapter closes with a description of subjects related to methodology of the research from the third part of the thesis.

2.1 Energy Related Issues

As the research scope of this work is related to novel energy technologies the following chapter will explain current energy situation in the world and main concerns related to climate change. Some implications of counter measures in terms of renewable generation and its promotion are described. Next, Combined Heat and Power policy and key market facts are presented as the core of the research with special attention paid to the situation in Europe, the main theme behind the goal of the thesis.

Energy demand and climate change

Energy is one of the most important drivers of all natural and man-made processes. Mankind is capable of converting energy into useful forms to sustain technological and socio-economical growth. As the population grows the energy demand and supply grow as well. One of the indicators that measure energy consumption is related to the primary energy. Primary energy is a term describing energy as found in nature, not subjected to any transformation. Thus it can give a good view on how energy is extracted from nature. According to scientists, primary energy of origin from variety of sources has more than doubled only for the past four decades. Total primary energy supply in the world from main energy sources for recent decades is shown in Figure 2.1.

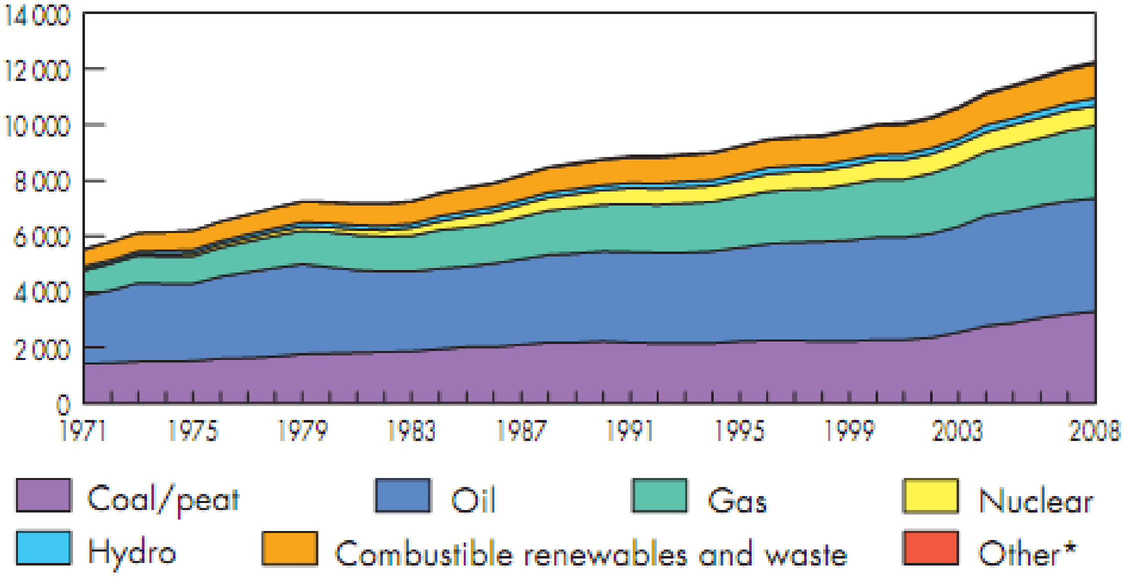


Figure 2.1 Total primary energy supply in the world from 1971 to 2008 (IEA 2010a)

Wide research and forecasts show that world energy use will continue to grow in the future. This fact is resulting in the "energy problem" that is mainly threefold: some countries became more and more energy import dependent resulting in international tensions and concerns; need and depletion of fossil fuels are causing environmental and political problems; increasing amount of fossil fuels combusted is generating increasing amounts of harmful gas emissions (Colonna 2007). These gases are called green house gases (GHG's) and include carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and others. They trap heat in the atmosphere, keeping the heat emitted by the planet from escaping into space. This in return causes a raise in temperature on Earth and the global warming effect.

The Intergovernmental Panel on Climate Change (IPCC) predicts that global temperatures may increase by 1.4 to 5.8 degrees Celsius by the end of the century in the absence of policy measures (IPCC 2007). Technological development and introduction of climate friendly policy measures can influence global warming. Six illustrative scenarios with and without additional climate policies for global GHG emissions are presented in Figure 2.2.

As it can be seen from the diagram, even the most optimistic IPCC's scenarios as B1 and B2 predict that the global GHG emission level will continue to rise in the upcoming decades.

Climate change caused by the temperature rise has the potential to bring many serious irreversible and even catastrophic consequences associated with business-as-usual (BAU) paths for emissions (Stern 2006). The European Environment Agency (EEA) report from 2004 lists the dangers: more frequent and economically costly storms, floods, droughts and other extreme weather events. More frequent and intense heat waves which can be of a lethal threat to the elderly and frail. Melting of glaciers is already observed, including three-quarters of those in the Swiss Alps that are likely to disappear by 2050. Global temperature increase is causing ocean water to expand, thus rising sea levels for centuries to come (EEA 2004).

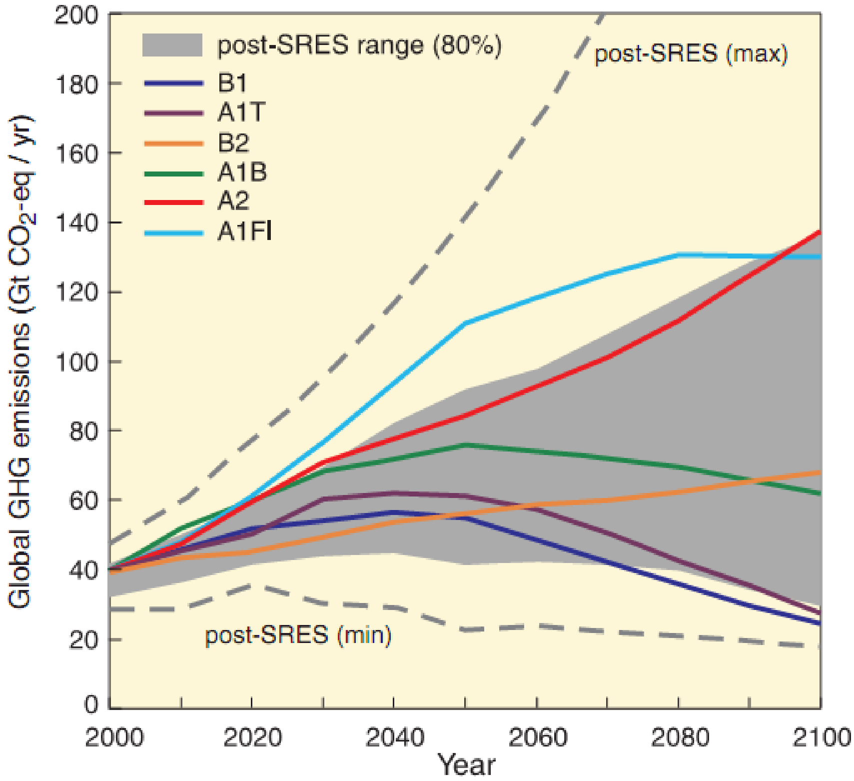


Figure 2.2 Predictions on global GHG emissions for different policy scenarios (IPCC 2007)

Many other impacts on flora and fauna are expected to occur as well as the socio-economical implications related. According to findings of PESETA research project on climate change impacts in Europe without adaptation to climate change and if the climate of 2080s occurred today, the change impact would resulted in 20 to 65 billion € of GDP loss (depending on the level of temperature increase). Regions in which damages would occur the most are Southern Europe and Northern parts of Central Europe. Annual welfare loss of EU countries could reach 1% and result in only 1% of welfare improvement (Ciscar 2009).

There is now a growing consensus among scientists and the climate change policy community to prevent global warming of 2 degree Celsius or more over pre-industrial temperatures. This corresponds to concentration of 450 parts per million of CO_2 in the atmosphere (WWF 2004). In order to achieve that, markets need clear and long term signals for the deployment of clean, efficient and renewable technologies.

Renewable generation and promotion

The destructive nature of highly polluting technologies forced many governments to pursuit changes in their current status related to energy supply and use. The most crucial part of those changes is promoting renewable energy over traditional fossil fuels. Renewable based technologies make use of energy sources such as: wind, solar, water, geothermal and biomass.

Renewables are sustainable - they are used to meet human needs while preserving the environment so that these needs can be also met by generations to come. Therefore many countries recognize the need of increasing renewable generation in energy consumption. As a result, renewable-based energy use has increased over the last years with wind, solar and biomass as the most rapidly growing markets. As for 2008 the renewable energy share in the global final energy consumption amounts to 19 %, as shown in Figure 2.3 below.

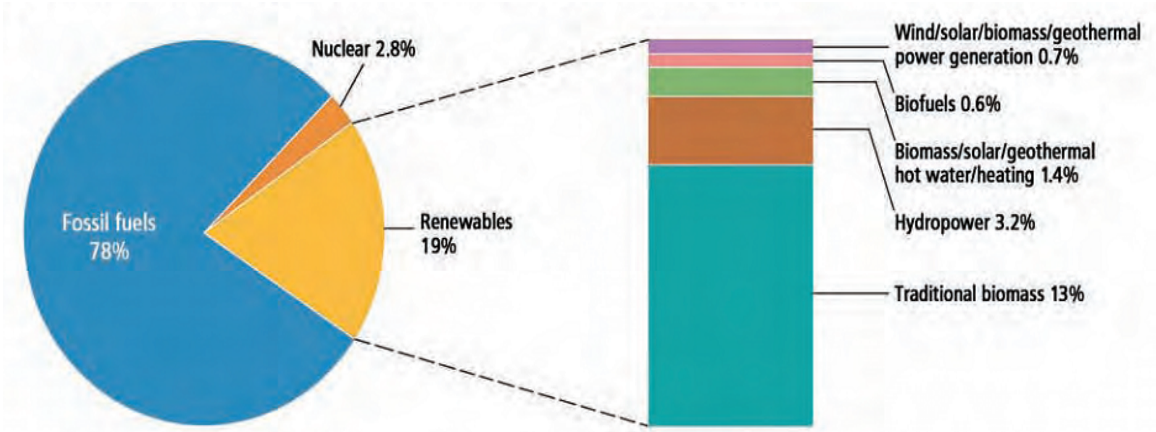


Figure 2.3 Renewable energy share in consumption of global final energy (REN21 2010)

Biomass plays an important role in the renewable share, mainly due to the traditional use of firewood for cooking and heating. Other renewables account only for 6% of which only around 4% is electricity production. This is particularly disturbing, because the world electricity demand is expected to continue to grow more strongly than any other final form of energy (IEA 2010b). The global power generation capacity is estimated to be 4800 GW (data for 2009) of which only 1230 GW coming from renewable sources (REN21 2010). Electricity generation market is entering a transformation period as investments shifts to low emission technologies. This is a result of increasing fossil-fuel prices and government policies to enhance energy security and to cut emissions of Greenhouse Gases (IEA 2010b).

International climate change research activities are explicitly encouraged by the United Nations Framework Convention on Climate Change and the Kyoto Protocol. The two agreements call on their signatories to promote, and to cooperate in scientific, technological, technical, socio-economic and other research fields, and in systematic observation and development of data archives as well. More and more governments decide to implement formal policies addressing climate change and renewable generation. Nowadays, 41 developed or transition countries and 42 developing countries in the world have some kind of policy to promote renewable power generation. Among the most common policy types are (REN21 2010):

- feed-in tariffs;
- renewable portfolio standards;
- capital subsidies or grants;
- investment tax credits;
- sales tax or VAT exemptions;
- green certificate trading;
- direct energy production payments or production tax credits;
- net metering;
- direct public investment or financing;
- public competitive building.

Policy options for supporting the reduction in pollution by installation of new renewable based power capacity include binding and non-binding targets for certain percentage of renewables in final energy. By early 2010, policy targets at national levels were present in at least 85 countries worldwide (REN21 2010). All European Union member states have established binding targets by 2020 as shown in Figure 2.4 below.

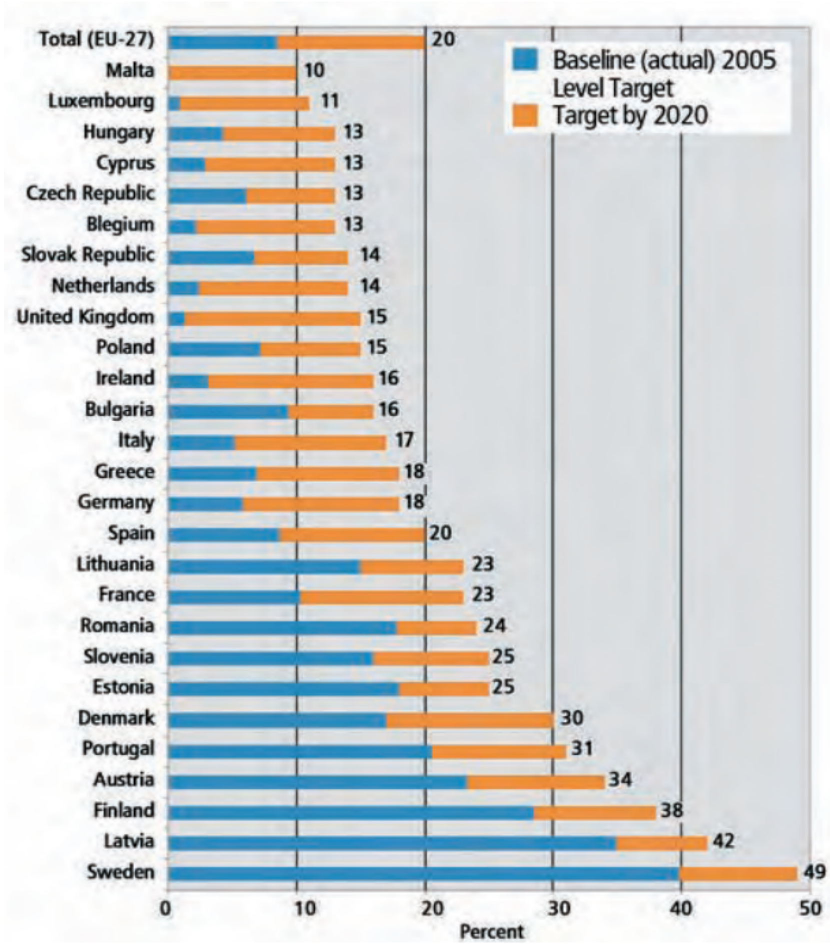


Figure 2.4 EU's member states renewable energy targets in share of final energy by 2020 (REN21 2010)

Without proper investments in new technologies some countries may not meet their targets, as it is predicted for the case of 2010 targets. The EU's total share of electricity from renewables in 2008 was estimated for 16.7 %, still far from the EU's-average target of 21 % by 2010 (REN21 2010). Extensive research and use of environmentally friendly and more efficient technologies could improve this situation in the future.

Energy policies and CHP production in EU

The European Union has taken the world's lead in pursuing sustainable energy use. EU's decision makers recognize the threat of climate change and commit member states to adopt targets and put price on carbon through the Emissions Trading Scheme. For the past decade one could observe implementation of new ambitious policies aiming for preserving the environment.

The EU recognizes four main fronts on which its energy system has to improve (Commission of the European Communities 2007a):

- decreasing energy intensity and improve efficient conversion of energy;
- increasing the share of renewable and low carbon technologies for electricity, heating and cooling production;
- decarbonisation of transportation by alternative fuels use;
- liberalisation and interconnection of energy systems.

Pursuing those the EU has set the following targets of improvement to be achieved by 2020, so called "20/20/20 targets" (Böhringer, Rutherford & Tol, 2009):

- greenhouse gas emissions reduction to 20 % below their 1990 levels;
- 20 % penetration of renewable energy sources in final energy consumption (House of Lords 2008);
- energy efficiency improvement by at least 20 % from 2005 level.

These goals are directly related to the greater ambition of reducing greenhouse gas emissions by 60 - 80 % by 2050 and supporting the prevention of dangerous global temperature rise (Commission of the European Communities 2007b).

In order to reach these targets, markets need clear and long term signals for the promotion of renewable and efficient energy technologies – mainly wind, biomass and solar thermal. In response the Strategic Energy Technology Plan (SET-Plan) was adopted in November 2007. This document is considered to be the technology pillar of the EU's energy and climate change policy. The objective of the SET-Plan is to accelerate the development of innovative low carbon technologies leading to their market introduction (Lequeux 2009).

That kind of rapid turn towards sustainability requires new investments. Therefore funding for climate-relevant research has been substantially increased to €9 billion in the EU's Seventh Framework Programme (FP7) covering 2007-2013. Climate-relevant research under FP7 is focused on four main thematic areas: environment, transport, Space and Global Monitoring for Environment and Security (GMES), and energy. The last one with the total budget €2.35 billion, is suppose to support the development of more environmentally sustainable energy systems (European Communities 2007).

Among of those more sustainable energy technologies recognized by EU's decision makers is Combined Heat and Power. In February 2004 the Directive 2004/8/EC on "the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/62/EEC", better known as the "CHP Directive", entered into force. Member states have adopted the first obligations of the directive by 2007 (Claverton Group 2010). It is intended that the directive will have a significant impact on legislation and use of energy efficient cogeneration and district heating technologies in Europe. The directive obliges member countries to release reports on the state of CHP in their own countries, to promote and show what is being done to promote CHP. Moreover, governments are obliged to report on and remove barriers of the technology implementation and monitor the progress of cogeneration within their energy market. Although some parties pointed out weaknesses and inaccurateness of definitions implemented in the directive (Cogen Europe 2005), the document itself is considered to be a milestone in promotion of CHP in the European Union.

The EU's 27 member states average share of CHP in total electricity generation was 11 %, corresponding to electrical capacity of 100 GW and 3041,7 PJ of heat production in 2008 (Loesoenen 2010). This is comparable to global average of 10 % of electricity produced by the technology. Only a few countries in the world (all coming from Europe) have expanded their CHP production to the level above 20 %, as shown in Figure 2.5 below.

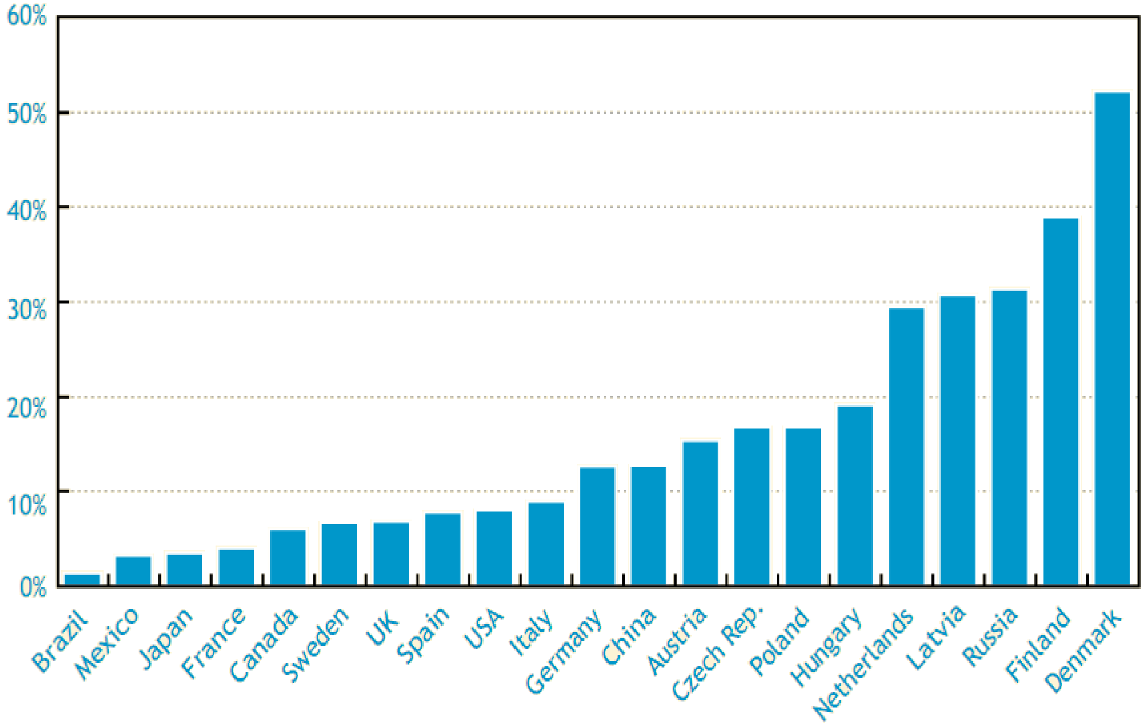


Figure 2.5 CHP technology share in total electricity production of selected countries (IEA 2010b)

These leaders have successfully implemented their own unique approach to high-efficient CHP technology based on strong governmental policy on electricity and heat supply. This is also due to the fact, that the potential for CHP is seen to be increasing each year and could almost double by 2030 only for the G8+5 countries (IEA 2010b).

Combined Heat and Power can utilize biomass as fuel, therefore it is not only efficient, but can also be treated as renewable technology. Long term commitment of EU for this technology resulted in the lead in Research and Development activities in the field. This thesis is also a contribution to those activities. The research theme behind this thesis easily fits in the main energy-related fronts of improvement in the EU policy. Not to mention that the pursuit of more environmentally friendly technologies is our moral duty to the mother Earth and future generations.

2.2 Biomass Based Technologies

One important aspect of the system studied in the research part is biomass. Organic matter is used as a fuel for the CHP system and for the pyrolysis process producing valuable bio-oil. The following text will give the context of the biomass use. Furthermore theoretical background on the fast pyrolysis process is presented. The pyrolysis product is the main determinant in the set up of the cycle parameters in the simulation models. This is due to the maximization of the pyrolysis bio-oil yield which characteristics and possible use paths are presented in this chapter as well.

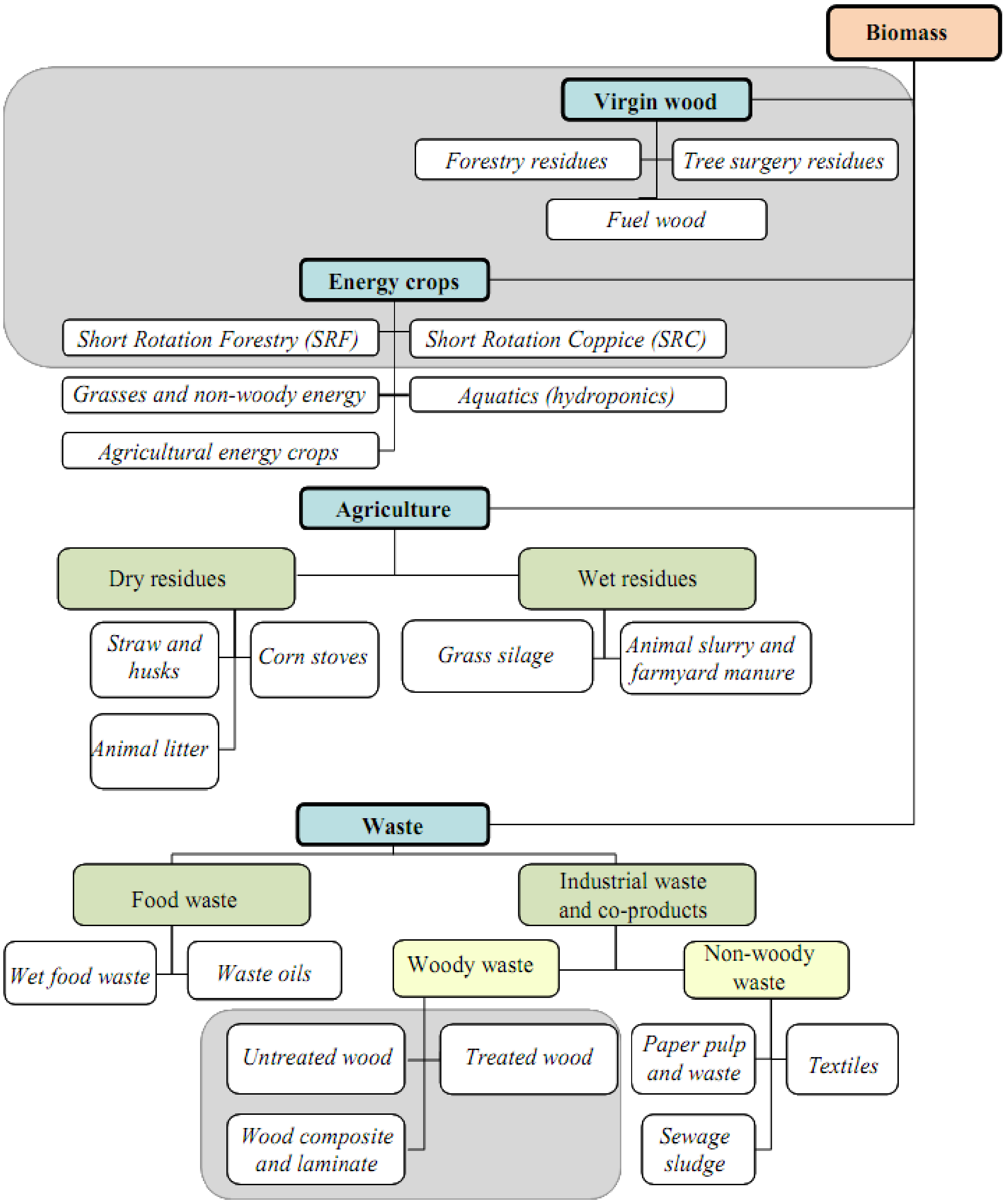
Biomass as renewable fuel

Biomass resources originating from forests and agriculture is the oldest form of renewable energy used by mankind. This fuel was used almost exclusively for meeting the energy needs of civilizations before the industrial revolution (UNEP 2007). Biomass is defined as non-fossil, organic material with biological origin having intrinsic chemical energy content (Kautto 2005). Biomass as fuel is considered to be carbon neutral. Plants and trees remove and store carbon dioxide from the atmosphere while they grow. When burned, for example for heat and power generation, the stored CO_2 is released causing unbalance in the net-zero carbon cycle. However by growing a new plant the gas is recaptured again. Therefore, if properly managed, biomass is a renewable energy source.

Biomass can be classified into four main types: woody biomass, agricultural sources, energy crops and biomass wastes. More detailed classification is show in Figure 2.6.

In the past decades, a number of countries has increased rapidly the use of biomass for provision of energy (Ladanai & Vinterbäck 2009). The global use of biomass for energy increases continuously and has doubled in the last 40 years to more than 50 EJ (Ladanai & Vinterbäck 2009). Combustible renewables and waste supplied 10 % of the total primary energy supply in 2008 (IEA 2010a). This amounts to around 80 % of all renewable supply (Ladanai & Vinterbäck 2009). However, this figure hides a big disparity between developed and developing countries. Concrete estimates concerning biomass future usage vary widely. Some sources predict that even up to 50 % of global primary energy supply could be met with this fuel by 2050 (UNEP 2007). There is a common agreement in the EU that biomass sources are the most important renewables in the short to medium-term (Kautto 2005). For many member countries biomass-based energy is the main path for achieving the Kyoto Protocol obligations. This growing trend in the biomass use is a result of national renewable energy targets and biomass-based technology advantages. Major benefits of its use include (based on Kautto 2005):

- reduces GHG emission allowing for meeting renewable energy targets and improving air quality;
- contributes to strengthening of the security of supply;
- activates local employment creating opportunities in rural areas;
- allows for utilization of waste.



Note: Biomasses from woody materials are in the shaded areas.

Figure 2.6 Biomass classification (Ladanai & Vinterbäck 2009)

Biomass is relatively easy to store and thus can be used in many processes for generation of many different products. As a multipurpose feedstock, it can serve for production of electricity, heat, liquid based fuels and chemical feedstock. For instance, today, about 90 % of bioenergy in the EU is used for heating applications, while the remainder is used for electricity generation, transportation fuel, and chemical applications (Ladanai & Vinterbäck 2009). Biomass can be transformed in thermo-, physical-, and bio-chemical processes, depending on the final product need. Major paths of biomass conversion are shown in Figure 2.7.

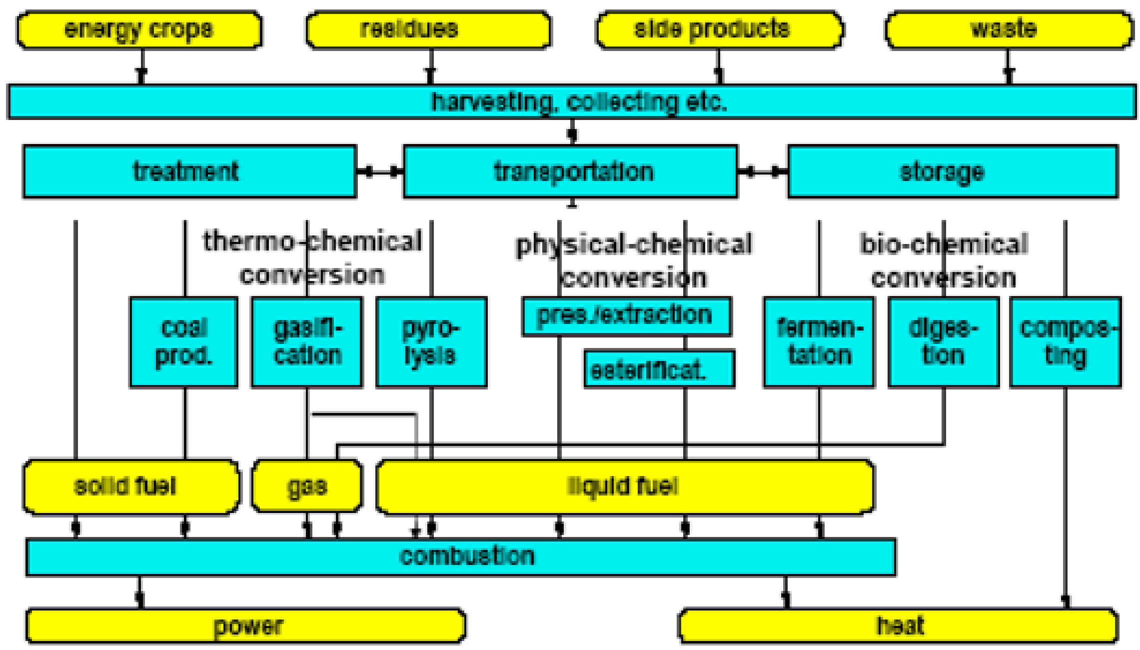


Figure 2.7 Major paths of biomass conversion to power and heat (Thrän 2006)

Although biomass importance is growing, non-technical issues such as public acceptance, socio-economic as well as ecological externalities of biomass may obscure its benefits (Kautto 2005). Unsustainable biomass management may result in negative environmental and socio-economic impact. However, the scientific world sees the opportunities in biomass-based technologies and puts a lot of effort in R&D activities. This thesis contributes to the research in efficient biomass use for cogeneration and interesting option of bio-product generation through fast pyrolysis.

Fast pyrolysis of biomass

There are three main thermal processes available for converting biomass to a more useful energy form – combustion, gasification and pyrolysis. Those processes are related to each other and differ in oxygen and temperature requirements. Pyrolysis, unlike combustion, takes place in absence of oxygen (Basu 2010). Pyrolysis is the thermal decomposition of biomass into liquid, gas and solids. Among others, depending on the products and temperature, and time of the process, pyrolysis has three main variations (Basu 2010):

- torrefaction or mild pyrolysis;
- slow pyrolysis;
- fast pyrolysis – up to 75% of liquid products.

In fast pyrolysis small particles of biomass are rapidly heated to high temperatures in the absence of oxygen. Yielded vapors are condensed into liquid (Bradley 2006). The primary goal of the fast pyrolysis is to maximize the production of the liquid product referred to as bio-oil. Very high heating rate, reaction temperature within the range of 425 to 600 °C, short residence time of vapor of less than 3 seconds in the reactor and rapid quenching of the product gas are the factors responsible for maximization of the bio-oil production from the process (Basu 2010). Other products are 10 % of gas and 15 % of char, although the final percentage of them strongly depends on the process conditions. Char is the remains of solid biomass that has been incompletely combusted, similar to charcoal (Bradley 2006). One important advantage of the product gas is that when recycled can produce approximately 75 % of the energy required for the pyrolysis process (Bradley 2006).

Technologies for biomass pyrolysis processes include the use of: fluidized beds, circulating fluid beds and transported bed, ablative pyrolysis, entrained flow, rotating cone, vacuum pyrolysis (Bridgwater 2002a). These can include heat carrier e.g. hot sand, or use direct heating. Pyrolysis technologies and their classification are shown in Figure 2.8.

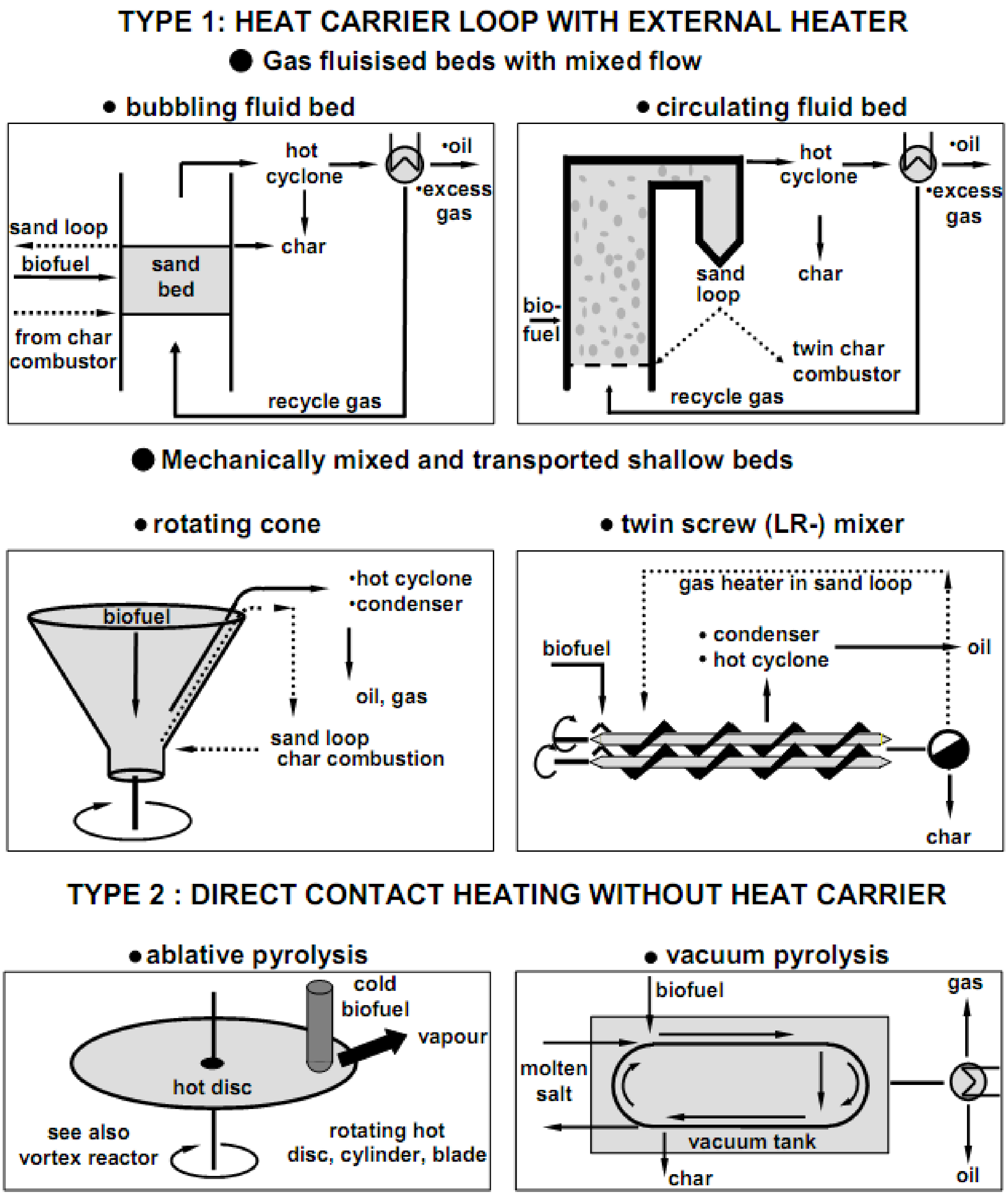


Figure 2.8 Various reactor types for fast pyrolysis and their classification (Henrich 2007)

Two concepts from the showed above are assumed to be integrated into CHP production in the research part of this thesis: twin screw pyrolysis and Circulating Fluidized Bed (CFB) boiler integrated pyrolysis. For the former, required heat could be drawn from the hot flue gases available within the power cycle. According to previous research (Kohl, Järvinen & Fogelholm 2008) this is promising technology for fast pyrolysis integration. In the latter case of CFB boiler integrated pyrolysis the process is done through hot sand extraction from the boiler. Both technologies are described later in the thesis.

Bio-oil product

Pyrolysis oil is a dark-brown, free flowing liquid fuel that contains about 25 % of water. Pyrolysis oil ignites and burns readily when properly atomized. Once ignited it burns with a stable, self-sustaining flame. It is flammable only at extremely high temperatures what makes it good for storage. On the other hand if left standing for long periods, lignin will eventually precipitate. However it can be stirred back into the bulk (Bradley 2006).

As energy prices reach record levels and environmental concerns importance is growing, pyrolysis oil presents a strong potential as a partial fuel alternative (Bradley 2006). Bio-oil is capable of substituting light and heavy fuel oil. For co-firing, the pyrolysis oil is easier for handling, storage and sometimes even combustion comparing with solid biomass and/or gasification (Bridgwater 2002b). The pyrolysis oil can also be used as a raw material for upgrading processes to synthesize new hydrocarbon compounds (Sipilä et al. 2007). A variety of options of pyrolysis products showing the possible use paths of the bio-oil are shown in Figure 2.9.

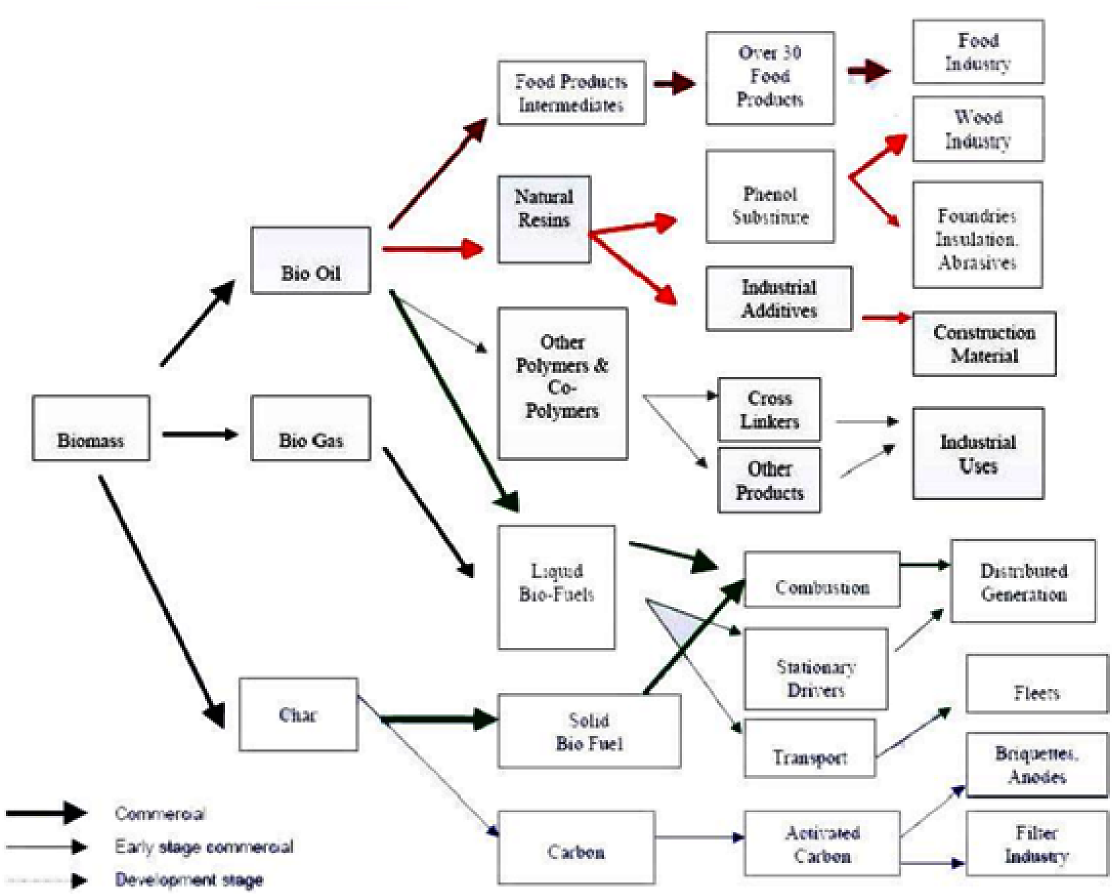


Figure 2.9 Pyrolysis products options of use (Zajec 2009)

From available technologies for fast pyrolysis, process integration into a CHP cycle could positively influence development and deployment of both technologies. This promising concept has a number of potential benefits that are explained further in the thesis.

2.3 Combined Heat and Power Production

The following chapter starts with explanation of the Combined Heat and Power production technology. General description of the concept use along with its benefits is presented. Next, thermodynamic background of the CHP production and power cycle are briefly explained. Lastly, the concept of pyrolysis integration and its potential benefits are described.

CHP in District Heating network

There are slight differences between definitions of Combined Heat and Power (CHP) production in literature. In general, CHP also referred to as cogeneration is a sequential or simultaneous generation of usable heat and power (usually electricity) in a single integrated process (EPA 2007; COGEN Europe 2001). Major components of a CHP system include (MAC & Avalon Consulting 2003; COGEN Europe 2001):

- Prime Mover technology driving electrical generators – typically indentify the CHP system;
- heat recovery technology allowing for heat utilization – direct or indirect recovering of heat from hot exhaust gases, steam or hot water;
- thermally-activated technologies – used in e.g. absorption chillers, desiccant dehumidifiers, space and process heaters.

Cogeneration is widely used in industrial processes: mainly in the paper, chemical, wood products and food processing industries. Furthermore CHP can serve in communal applications by providing electricity and heat when connected to district heating networks. Their purpose and environment of use determines the Prime Mover technology used in the system. The most common ones are (EPA 2007; MAC & Avalon Consulting 2003):

- reciprocating internal combustion engines;
- gas (combustion) turbines, including microturibnes;
- fuel cells;
- stirling engines;
- steam turbines.

Depending on the prime mover a CHP system can use large variety of fuels. Typical energy sources used in the technology include natural gas, coal, light and heavy fuel oils, solid and gaseous biomasses, and waste fuels (Sipilä et al. 2005). Fuel options together with popular prime movers technologies overview are shown in Figure 2.10.

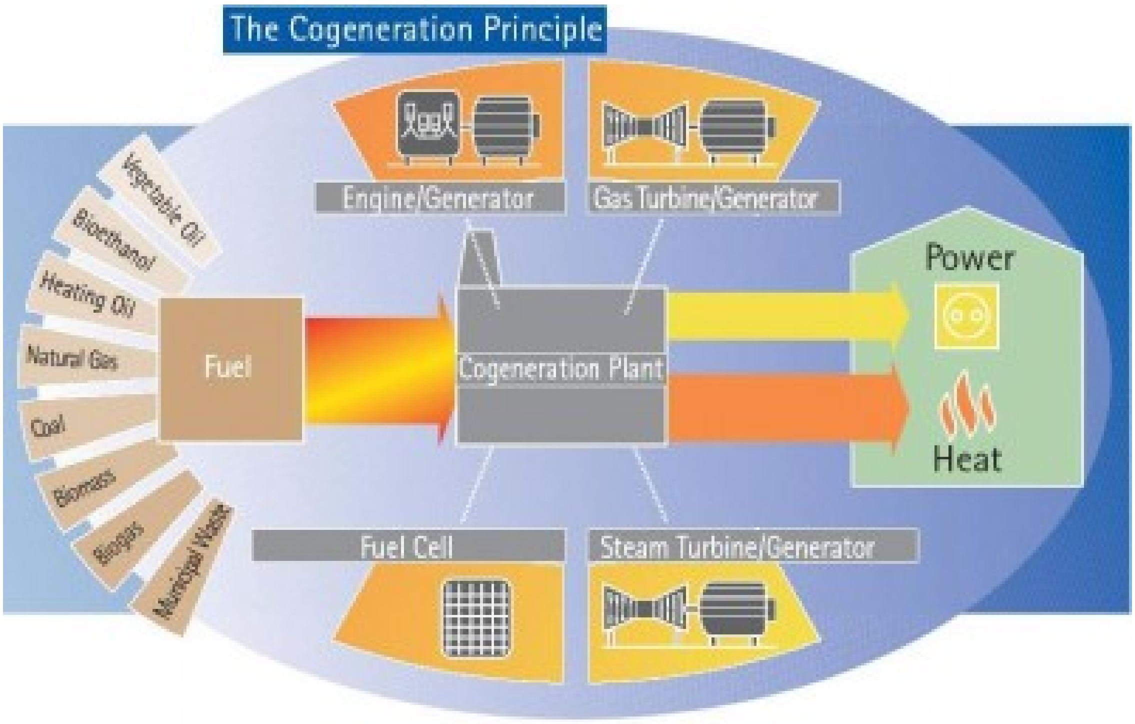


Figure 2.10 Commonly used fuel options and prime mover technologies for CHP applications (COGEN Europe 2009)

The most often employed processes for utility systems connected to DH networks are gas turbines with recovery boilers, internal combustion engines with heat recovery, gas turbines with combined steam cycle, and steam cycle alone (Sipilä et al. 2005).

The use of cogeneration can provide important benefits in comparison to other technologies for heat and power production. Compared to conventional central station of power generation and heat-only boilers, CHP has higher energy efficiency. It requires typically only three-quarters or less of the primary energy needed by separate heat and power systems (EPA 2008). Additionally, reduced overall demand from centralized power sources is lowering losses and stress on the electricity grid. Reduced fuel consumption means lower GHGs emissions and savings in natural resources. Lower fuel consumption contributes also to cost savings. Another advantage of the CHP technology is the fact that it can contribute to the increase in the security of energy supply. This is due to its fuel flexibility and thus ability to use local fuel sources e.g. biomass. This high efficient technology is mature and robust, but the upfront investment cost is high.

A utility Combined Heat and Power system is usually connected to a District Heating network. The heat is produced by the plant, and in the form of hot water it is pumped through a network of underground pipes to the houses, where it is used for heating and/or production of hot sanitary water (MGM Engineering & Contracting n.d.). District Heating networks are the most commonly present in densely populated urban areas since it is economically favorable to deploy such a network where there is a high demand both for heat and power. This fact can create huge opportunity for DH and CHP technology in the future due to the fact that according to United Nations, by 2050 more than 70% of global population is foreseen to live in cities (UN-HABITAT 2008).

Power cycle in CHP production

Combined Heat and Power solutions, especially small-scale, utilize the well-known Rankine Cycle thermodynamic concept (Savola 2007). The closer the real cycle parameters are to the ideal cycle the better the efficiency. From thermodynamic point of view, in the ideal cycle the working fluid undergoes the following series of internally reversible processes shown in Figure 2.11 below (Moran & Shapiro 2006):

- process 1-2: isentropic expansion – working fluid is expanded in the turbine from the state of saturated vapor to the condenser pressure level;
- process 2-3: isobaric heat rejection – working fluid is condensed to saturated liquid state;
- process 3-4: isentropic compression – working fluid is compressed by the pump to elevated pressure;
- process 4-1: isobaric heat addition – working fluid is heated in the boiler to reach saturated vapor state.

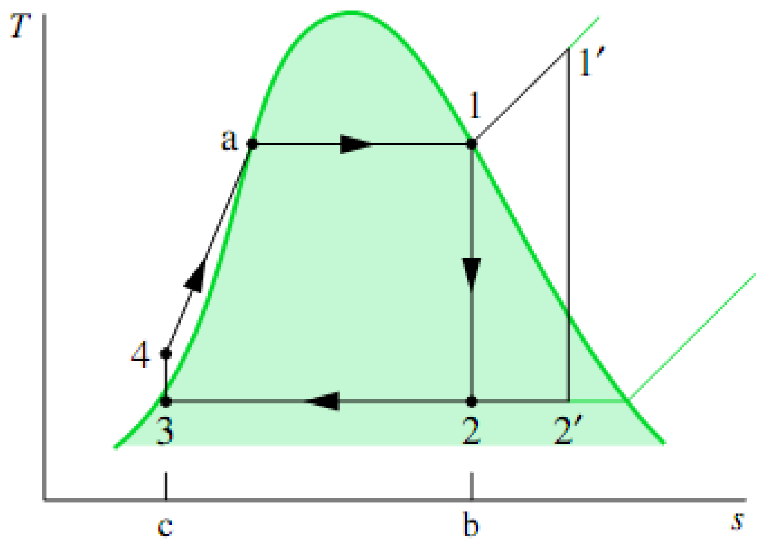


Figure 2.11 Temperature versus entropy diagram of the ideal Rankine Cycle (Moran & Shapiro 2006)

The cycle is the basis of today's conventional electricity generating plants. Main components of the cycle are: the heat source (boiler) and heat to mechanical work converter (steam turbine). The boiler turns water into high-pressure steam. The enthalpy from the steam is next extracted by the turbine that drives an electricity generator. The steam expansion in the turbine can reach only a certain level due to the moisture content of the steam after the turbine. The maximum value for the moisture is around 12 % (Savola 2007). Higher values can lead to the corrosion problems of the turbine's blades. In CHP production the exhaust steam is then condensed in the District Heating (DH) heat exchanger. Moreover, the heat demand of the DH network demand has to be fulfilled in the first place. The temperature of the steam/water mixture entering the DH heat exchanger has to be at least higher than 85 – 110 °C, depending on the outdoor temperature (Savola 2007). This is also defining the required minimum pressure of the exhaust steam after the expansion in the turbine. Simple Rankine Cycle in cogeneration is shown in Figure 2.12.

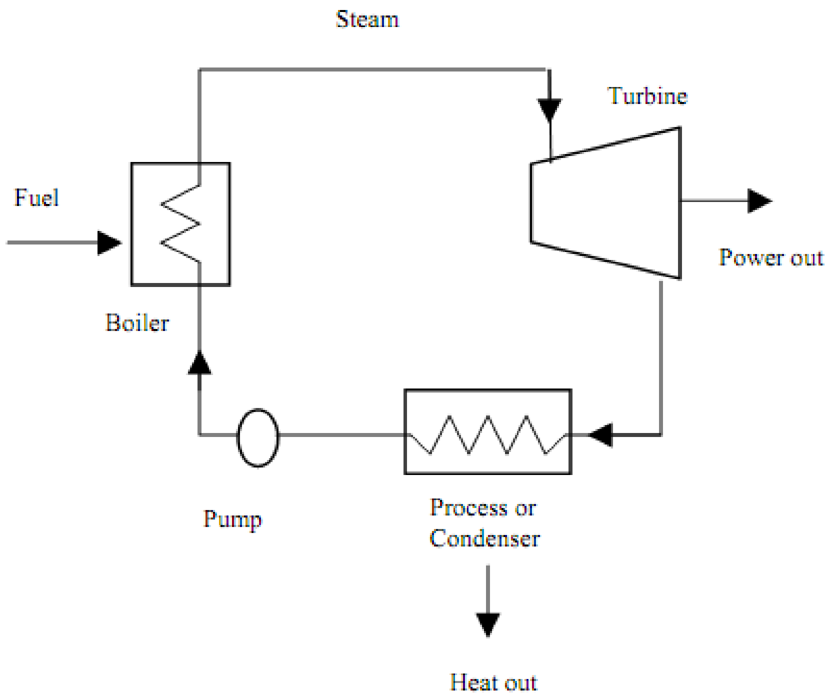


Figure 2.12 Simple Rankine Cycle model (EPA 2008)

In general, the higher the pressure and temperature of the steam entering the turbine, the higher is the electrical output of the generator. Due to this fact, and due to the fact that it is much more efficient to compress liquid water than gaseous steam, the feedwater entering the boiler is in elevated pressure. To increase the efficiency of the plant it is common to preheat the feed water using flue gases from the boiler. In a CHP plant fuel combustion in the boiler heats up the water and results in the production of hot steam. This steam is often further superheated by the flue gases and expanded in the steam turbine. The case of steam superheating before entering the turbine is marked with 1' and 2' in Figure 2.11. The steam turbine itself consists of a set blades installed within a casing and mounted on a shaft that is connected to the generator (EPA 2008). Special design of the blades accelerates and expands steam to lower pressure turning the shaft in result. Three main types of steam turbines used are (ONSITE SYCOM Energy Corporation 1999; EPA 2008):

- non-condensing turbine (back-pressure) – exhausts the entire steam flow at pressure close to the atmospheric for downstream processing;
- extraction turbine – characterized by openings in its casing for extraction of steam either for process or feedwater preheating;
- condensing turbine – used for power-only generation, where steam is exhausted at sub-atmospheric pressure, maximizing power output.

Depending on the type of a CHP system, in reality, the power cycle is being handled by a number of hardware components. This may include: control equipment, fuel handling equipment, ash removal systems, feedwater tank, boilers, pumps, air fans, flue gases treatment systems, steam turbines, generator, ducts and pipes for steam/water and gases, heat exchangers network and many other components integrated into heat and power production system. More detailed boiler technology is explained in the next chapter of this thesis.

CHP with integrated pyrolysis

Combined Heat and Power production offers different options of process integration for increasing its energy efficiency. A successful example is in Sweden where conventional biomass CHP plant has an integrated pellet production and part of the heat is used for biomass drying (Wahlund, Yan & Westermark 2002). In this thesis biomass pyrolysis integration is investigated. The fast-pyrolysis integration into cogeneration cycle could possibly be done in few ways:

- heat extraction from steam for heating up a heat carrier used in the pyrolysis process;
- heat extraction from flue gases for heating up a heat carrier used in the pyrolysis process;
- heat extraction from the hot medium within the boiler e.g. sand heated.

At present, there is no assessment on the first two mentioned above. In Kohl's research (Kohl et al. 2010) it is proposed to use the flue gases, but this is still not proven technology. The third option is relatively more mature in comparison to the latter, although still a lot has to be done in the field since it is an emerging technology. Bed integration of pyrolysis concerns two fluidized bed technologies: bubbling and circulating. In Europe promising studies on CFB boiler with hot sand used for biomass pyrolysis are being done in biomass and CHP research leader - Finland. The integration structure developed in the finish research project is shown in Figure 2.13 below.

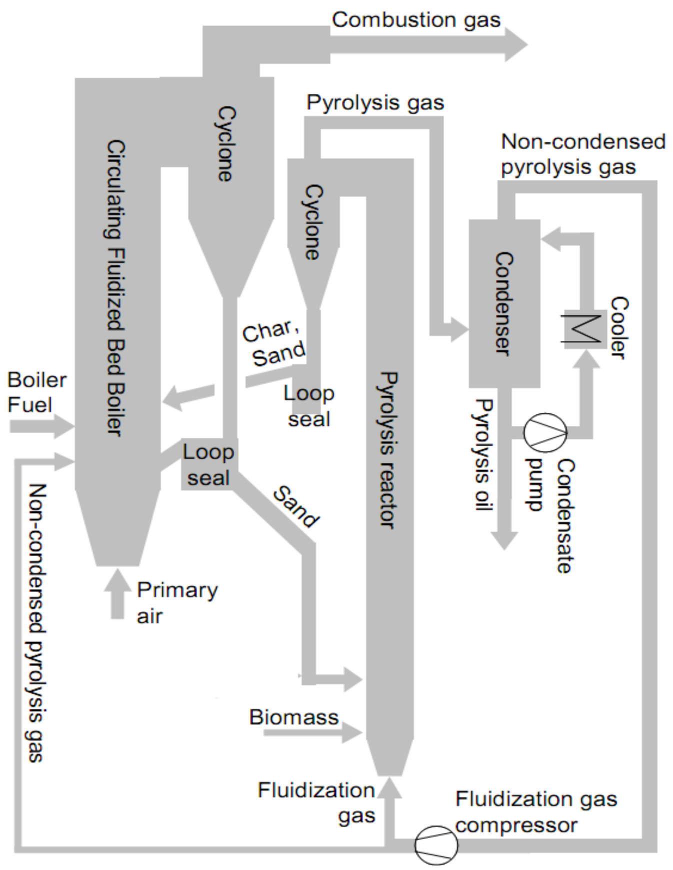


Figure 2.13 Pyrolysis process integrated with CFB boiler developed by Metso and Tampere University of Technology, Finland (Yrjö et al. 2010)

Metso together with UPM, Fortum and Technical Research Center of Finland (VTT) has built the world's first integrated pyrolysis plant placed in Finland. Small pilot plant successfully produced bio-oil in several campaigns during 2009 and 2010 (Lehto et al. 2010).

The promising technology for potential integration of pyrolysis into a CHP plant is the production of pyrolysis slurry with the help of a twin screw pyrolysis. The process seems to be well established, easy to implement and control (Kohl, Järvinen & Fogelholm 2008). Other two technologies are Bubbling Fluidized Bed (BFB) and Circulating Fluidized bed concepts (CFB). A brief comparison of these two is presented in Table 2.1.

Table 2.1 Fast pyrolysis with BFB and CFB - characteristics comparison (Bridgwater 2002a; Henrich, Dahmen & Dinjus 2009)

BFB pyrolysis technology characteristics	CFB pyrolysis technology characteristics
• Simple in construction and operation	• Char in is more attrited due to higher gas velocities
• Hydrodynamics is less complex	• Suitable for very large throughputs
• Smaller particle size of biomass is needed to achieve high biomass heating rates	• Heat transfer at large scale still has to be proven and investigated

Pyrolysis integration offers benefits, but also carries issues to solve. Some characteristics advantages of potential CHP integration with fast pyrolysis include (Bridgwater 2002a, Kohl, Järvinen & Fogelholm 2008; Kohl & Fogelholm 2009; Kohl et al. 2010; Henrich, Dahmen & Dinjus 2009):

- pyrolysis in reactors is a well understood technology;
- pyrolysis within the CFB boiler still need high investment in research and commercialization;
- pyrolysis slurry production is a robust technology and simple to apply;
- temperature control with changing biomass feed might cause reaction instability;
- pyrolysis integration has in general potential for old plant efficiency improvement;
- by producing bio-oil the operation hours of a CHP plant can be increased;
- carbon dioxide emission can be reduced when bio-oil is used in co-firing or in backup boilers instead of heavy oil;
- bio-oil can be produced in small biomass-based plants and then easily transported to big bio-refineries for further upgrade enhancing Biomass-To-Fuel (BTF) scheme;
- pyrolysis products can be gasified in syngas production processes;
- integration make the CHP plant generating products that can serve for different upgrading processes such as ethanol, methanol, hydrogen, biodiesel and other chemicals;
- pyrolysis products can be directly combusted within the plant;
- CHP plants could produce bio-oil that is independent of the electricity and heat market;

- as the biomass prices is foreseen to increase due to increasing demand biomass-based CHP could produce pyrolysis oil more economically effectively than in separate production.

Potential benefits make the integration concept an interesting field of study. Mature cogeneration technology, allowing for different scenarios of improvement, and fast pyrolysis integration with its valuable products may play an important role in the future.

2.4 Steam Boiler Technology

In the research part of this thesis there are CHP plants simulated, all of them deploying different steam boilers. Comparison of their performance and influence on the cycle is within the scope of the thesis. Thus, the following chapter describes briefly the steam boiler technology principles. Next, it goes into more details and explains the boiler types simulated in the research part: grate-fired boiler, Bubbling Fluidized Bed and Circulating Fluidized Bed boilers.

Boiler technology

In technical context, the steam boiler is a system that provides means for heat from combustion to be transferred into the working fluid. For typical biomass-based CHP technology the working fluid is water/steam, therefore the steam boiler is the whole system for producing steam for use. This includes different phases of heat transfer from flames to the working fluid in e.g. economizer, boiler, superheater, reheater and air preheater. Also different auxiliary systems e.g. fuel feeding, water treatment, flue gas channels, boiler system control etc. (Teir 2003)

Fuel combustion takes place in the furnace part of the boiler. Combustion releases heat that is absorbed by the boiler and through radiation, conduction and convection the heat is transferred to the water. Intensity and relative percentage of the heat transfer mechanism depends strongly on the boiler design. Steam boilers types can be classified by their combustion method, application, type of steam/water circulation, fuel used etc. Based on the type of firing adopted in the unit, the most commonly used boilers are (Sathyanathan 2009):

- stoker fired (grate furnaces etc.)
- pulverized coal fired;
- fluidized bed boilers;
- cyclone fired;
- chemical recovery boilers;
- incinerators.

Of those above, for biomass cogeneration with steam turbine the grate fired boilers and fluidized bed boilers are the most commonly used (Yin, Rosendahl & Søren 2008). These technologies are also used for the concept of the pyrolysis integration in further investigation in this thesis.

Grate-fired boiler

The easiest way to produce heat from biomass is to simply burn the biomass in a furnace (Asthana 2009). Then, generated heat can be exploited in a boiler to produce steam. This wide spread approach called direct firing is implemented in stoker boilers. In this technology solid fuels are burned with excess air, producing hot flue gases. These are further used to produce steam in the heat exchange section of the boiler (EPA 2007). The radiant heat plays an important role in the heat transfer, thus the expression "radiant furnace" is used. Modern stokers consist usually of four elements (EPA 2007):

- fuel supply system;
- a grate with primary combustion air pathway;
- secondary air system;
- ash discharge system.

The fuel is supplied automatically to the boiler. Then, moving grates allow for continuous ash collection and even spread of fuel (Sims 2004). Primary air in above stochiometric ratios is supplied and the combustion occurs in stages producing heat from the fire and combustion gases (EPA 2007). This heat is transferred to water tubes on the straight or bull nose walls of the boiler (Sims 2004). Secondary air is supplied usually above the bed to complete combustion and lower harmful emissions. An example of a grate-fired boiler is shown in Figure 2.14.

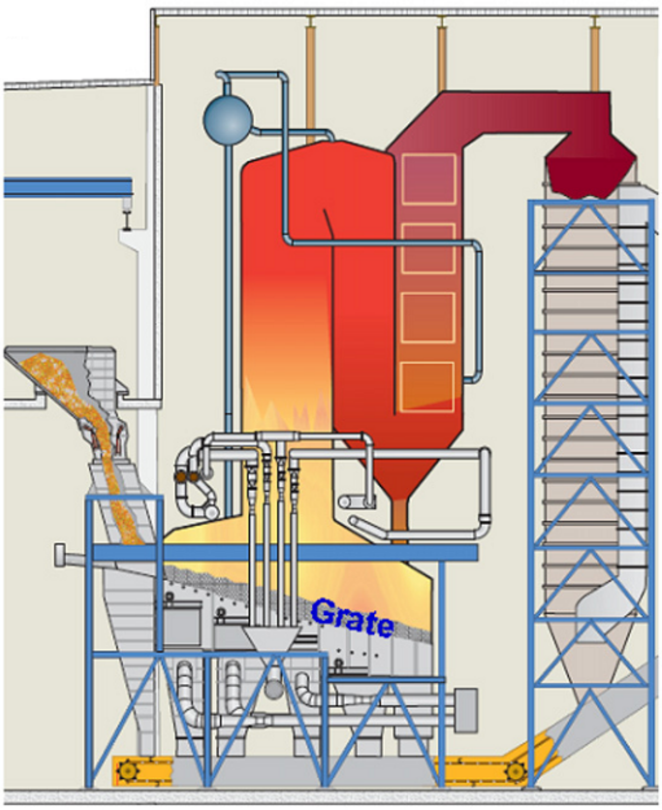


Figure 2.14 Grate-fired boiler (Yin, Rosendahl & Søren 2008)

The radiant furnace boilers are characterized by high combustion temperatures and high temperature of the flue gases from the boiler. Their advantages include: relative simplicity and low investment costs, fuel flexibility, possibility to burn high moisture solids and low fly ash carryover. For these reasons these boilers are widely used for biomass combustion.

Fluidized Bed boilers

Fluidized bed boiler concept is one of the most rapidly developing and put in use boiler technology in cogeneration. Fluidization process was invented in the first half of the 20th century and used for coal burning in the 1960s. The fluidized bed technology is based on the concept of a layer of sand or similar media, where potential fuel is injected and combusted. Through the sand layer the combustion air is blown from the bottom of the boiler. Depending on the velocity of the air there are different properties of the fuel-sand mixture achieved. As the gas velocity increases the fluidization phenomenon occur, where fine solids are transformed into fluid-like state. At low velocities the gas is flowing through a fixed bed of particles, while at high the solid particles become entrained in the gas stream. (Teir 2003)

In the last few decades the technology presence in the market is growing. Mainly due to important advantages in comparison with other technologies, these include (Teir 2003; UNEP 2007):

- high combustion efficiency – even over 95% and around 84% of overall boiler efficiency;
- high fuel flexibility – different types of fuel can be injected into the bed, including low grade fuels;
- good performance with high moisture and ash content fuel – moreover no clinker formation from ash has to be maintained;
- low NO_x emission – due to low combustion temperature of 750°C to 950°C;
- easy and cheap SO_x emission control – possible through direct injection of limestone into the combustion bed;
- fuel particle size flexibility;
- simple operation and quick start-up – even fully automated start-up is possible;
- fast respond to load fluctuations – both fuel load and heat demand fluctuations;
- high reliability and reduced maintenance – due to high level of automation, low level of moving part in the bed, low corrosion and erosion effects in low combustion temperatures;
- relatively small installation – high heat transfer rate over heat transfer area in the bed.

Depending on the fluidization degree Fluidized Bed Combustion (FBC) can be categorized into three basic types (UNEP 2007):

- Bubbling Fluidized Bed (BFB) - also called Atmospheric Fluidized Bed (AFB);
- Pressurized Fluidized Bed (PFB);
- Circulating Fluidized Bed (CFB) - also called Atmospheric Circulating Fluidized Bed (ACFB).

The classification is based on the on the gas velocity of the combustion air. Its dependence is shown in Figure 2.15.

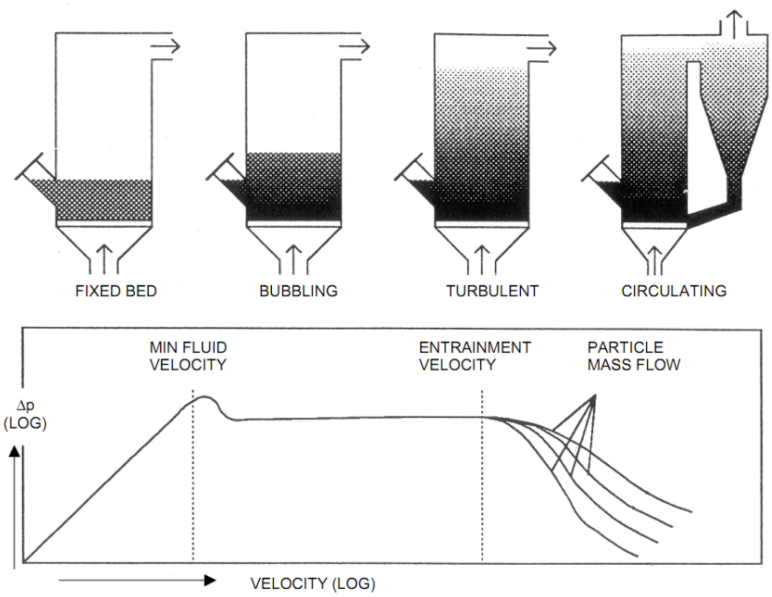


Figure 2.15 Fluidized bed boiler regimes depending on the velocity of the combustion air and pressure drop (Teir 2003)

The Bubbling Fluidized Bed and Circulating Fluidized Bed are most commonly used for combined heat and power generation from biomass, apart from the grate fired boiler. Many of the boiler system components are present in both technologies. In BFBs the velocity of fluidizing air is in the range of 1.2 to 3.7 m/sec. This rate determines the amount of fuel that can be reacted – the more air the more biomass can be combusted. Most of the bubbling beds are equipped with in-bed evaporator tubes. This enables heat extraction from the bed of sand, limestone and fuel particles (UNEP 2007). Typical arrangement of the bed components is shown in Figure 2.16.

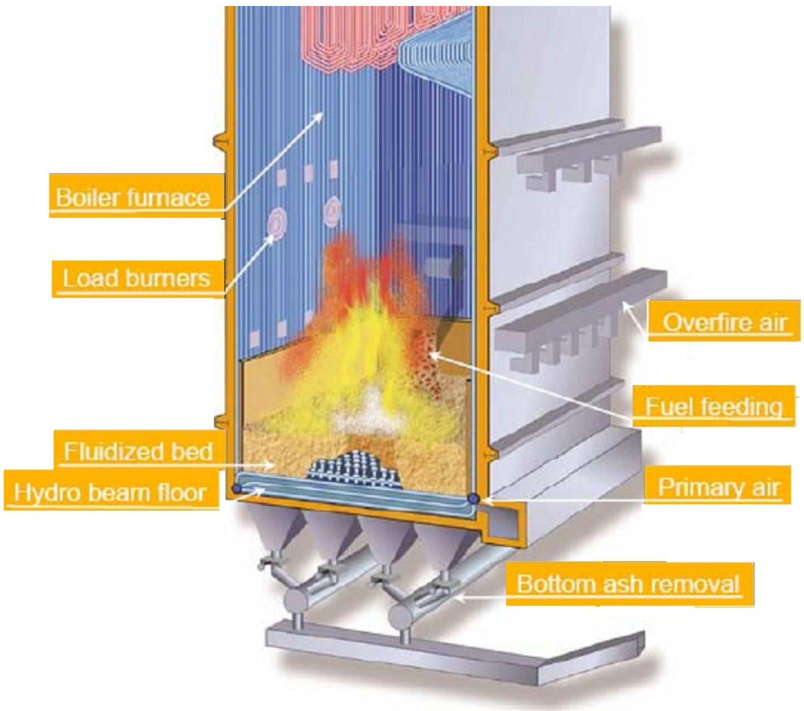


Figure 2.16 Typical Bubbling fluidized Bed (UNEP 2007)

The bubbling bed is usually of a 0,9 to 1,5 m in depth and very little material leaves the bed. In the bubbling bed about 2 to 4 kg of solids is recycled per ton of fuel burnt (UNEP 2007).

A Circulating Fluidized Bed evolves from the conventional BFB technology. CFB operates under special fluid dynamic condition. In this type of the boiler, fine particles of solids are transported and mixed through the furnace. This is due to the high gas velocity, as it is exceeding the average terminal velocity of the solid particles (Teir 2003). The fluidizing velocity in circulating beds ranges from 3.7 to 9 m/sec (UNEP 2007). The particles are then collected by the solids separators and circulated back into the furnace. Solids are recycled in the rate of about 50 to 100 kg per kg of fuel burnt (UNEP 2007). Consequently a lot more solids are moved out of the furnace area that is resulting in achieving most of the heat transfer outside of the combustion zone. A cutaway of a CFB boiler is shown in Figure 2.17.

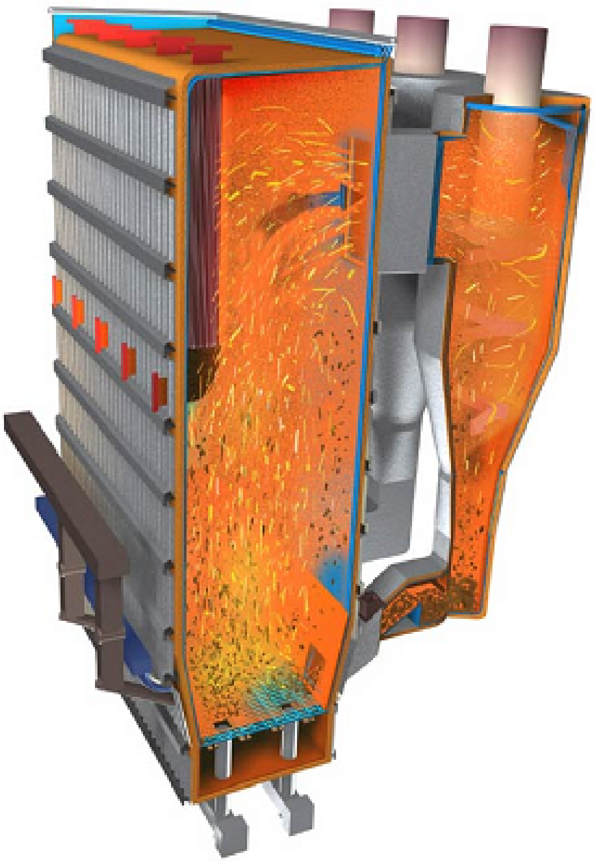


Figure 2.17 Circulating Fluidized Bed combustion (Teir 2003)

In a CFB system two sections of the boiler can be distinguished. First is the furnace, solid separator, recycling device and possible heat exchanger surfaces. There are no steam generation tubes immersed in the bed. The second section called back-pass is the section in which the heat from flue gases is absorbed by reheaters, economizer and air preheater, usually installed in downstream order. (Teir 2003; UNEP 2007)

A combined heat and power system utilizing CFB technology with integrated pyrolysis is simulated in this thesis. Similar BFB system is used for the purpose of comparison with CFB model in the research part.

2.5 Power Cycle Simulation

The following chapter is related to the methodology of the research applied in this thesis. The core of the work is to develop simulation models using thermal power plant simulation software. Thus the software and simulation methodology is explained in the following chapter.

Simulation software

The process simulation software used in the thesis research on the CHP plant power cycle is ProSim, version 5.4. The simulator is installed on Autodesk AutoCad. ProSim, used by a number of academics and professionals around the world, is gaining on popularity and it is considered to be state-of-the-art software in its class. Currently, it has more than 700 customers in 63 countries. (ProSim 2010)

ProSim is a software package. This versatile tool is designed for simulation of thermal power plants, advanced furnace simulation and simulation of utility boilers (Endat Oy 2010). The software allows for calculation and performance simulation of complex combined cycle plants at both nominal and partial loads. It performs mass and energy balance calculations of thermal plant steady-state processes. ProSim can be used for designing purposes as well as monitoring, optimization and troubleshooting of existing power plants. (Endat Oy 2010)

The software includes libraries of power cycle modules, properties of different fuels and working fluids that can be used for modeling. In the research conducted within this thesis ProSim is used for the simulation of the CHP cycle and integration of a biomass pyrolysis and drying processes.

Simulation methodology

Different simulation software incorporates different simulation concepts. Flowsheet simulation concepts include equation oriented approach, sequential modular methods and combination of these two. Simulation software based on equation-oriented approach builds up unit equations and solves them simultaneously. Sequential modular methods simulators build up separate unit operation blocks and solve them in a certain sequence. ProSim software is an example where sequential modular method is used for process simulation. (Savola 2007)

The software is based on the concept of black-box unit modules and the calculation of mass and energy balances of each unit. The software sets up a topology of the units and - having input data and defined calculation order of the unit modules in the process - tries to solve balances for each unit. Using physical properties stored in the software's database, the simulator calculates the physical properties of streams as e.g. enthalpies. This approach is widely used in modular simulators.

Steady state simulation allows for simulations in off-design mode at the loads differing from the design load. Since small-scale systems are operated according to district heating demand (Savola 2007) this is an important tool. The design point usually is set at the 100% of the fuel and DH load, but long periods of the plants operation is covered by partial loads. Technical construction of the cycle modules are fixed in part loads, thus allows seeing how the cycle model reacts to load changes. Heat exchange areas once set in the design case are fixed in partial loads to this value. Therefore, when analyzing the model at lower loads the heat transfer area of the unit modules is “oversized” resulting in less efficient heat transfer. Furthermore, the steam turbine is set to work at the highest efficiency in the design model. Then, at lower loads the turbine will work less effectively due to changed, lower steam parameters.

On- and off-design features are used in the research on the pyrolysis integration into CHP cycle further in this thesis. More detailed description of the simulation methodology applied here is described in the research part later in the thesis.

Unit modeling

In ProSim the model has to be build up from components – unit modules – that are connected with nodes. The user has to determine the component and the node input data. If the input data is not specified by the user, the software automatically uses default values. Then, the simulation units from the software's library used for building up the model in ProSim are calculated on the basis of steady-flow. Steady state of the streams is reached when their properties do not change over time. Thus the units are in equilibrium state. Therefore for each unit a set of mass and energy balances are assigned and calculated by the software. Under the principle of mass and energy balance for steady-flow processes a general model of a unit can be constructed, as shown in Figure 2.18.

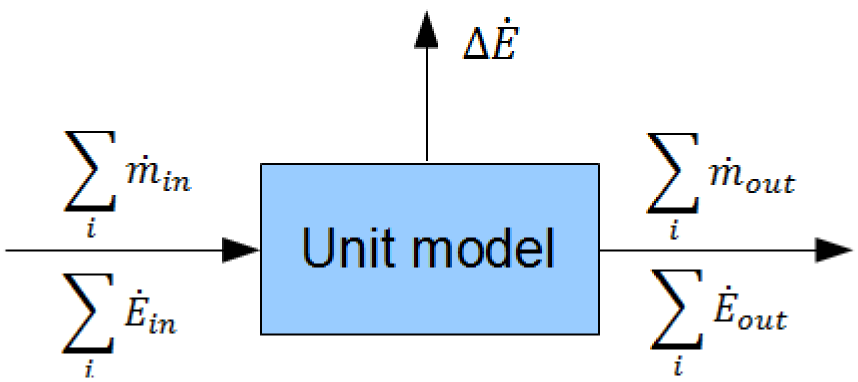


Figure 2.18 Unit model for the steady-state simulation

Conservation of mass principle gives the total amount of mass entering the unit has to equal to the total amount of mass leaving the unit. Similar statement is true for conservation of energy. The amount of energy entering the unit in all forms (heat, work) must be equal to the amount of energy leaving the unit for a steady-flow process. These principles can be described by following equations:

$$\sum_i \dot{m}_{in} = \sum_i \dot{m}_{out} \qquad (1)$$

and

$$\sum_i \dot{E}_{in} = \sum_i \dot{E}_{out} + \Delta\dot{E} \qquad (2)$$

where,

$\sum_i \dot{m}_{in}$ is the total mass entering the unit over time;

$\sum_i \dot{m}_{out}$ is the total mass leaving the unit over time;

$\sum_i \dot{E}_{in}$ is the total amount of energy entering the unit over time;

$\sum_i \dot{E}_{out}$ is the amount of energy leaving the unit over time;

$\Delta\dot{E}$ is the change in energy over time.

Each unit model is calculated in this manner by ProSim in a given order. Hence the whole simulation model, when correctly built by the user, reaches thermodynamic equilibrium. Combustion processes in the software are calculated on a basis of minimizing the Gibbs free energy of the chemical reactions of the process that is dependent of the fuel ultimate analysis. The simulation model build by the user is correctly created when the compilation results in:

- net-zero energy balance of the simulation model – all energy inputs to the model must be equal to all energy outputs from the model;
- net-zero energy balance of the single unit modules – all energy inputs to the unit module must be equal to all energy outputs from the module, as shown in the figure earlier;
- net-zero mass balance of the single unit modules – all mass inputs to the unit module must be equal to all mass outputs from the module, as shown in the figure earlier;
- no problems with pressure in streams;
- no negative flows in the module.

This applies for the on-design mode and off-design mode as well.

2.6 Environmental Performance of Biomass CHP

Important determinant of the environmental performance of the studied systems is the fuel used – biomass. Thus, the following chapter focuses on the explanation of the biomass-based CHP systems in general. Then, their environmental performance is briefly described. Lastly, the chapter focuses on the background of the use of European standards for the environmental performance rating used further in the research part of this thesis. The comparison of the different boiler options and their performance with the pyrolysis integration has to be investigated from an environmental point of view, according to the goal and scope of the thesis. In order to make the results comparable with previous studies (Kohl et al. 2010) this is done by applying the concept of the Primary Energy Factor and the Carbon Dioxide emission coefficient.

Biomass based CHP systems

The biomass-based Combined Heat and Power system is a cogeneration plant using biomass as fuel. The different technologies for biomass conversion and CHP production are characterized by different scales of the thermal and electric capacity, different efficiencies and stages of development. CHP review of the technologies utilizing biomass is shown in Figure 2.19. From these shown in the figure the direct combustion technologies are of the interest in the research part of this thesis, including fixed bed and fluidized bed boilers.

Energy Conversion Technology	Conversion Technology Commercialization Status	Integrated CHP Technology (Prime Mover)	Prime Mover Commercialization Status
Anaerobic Digestion			
Anaerobic digester (from animal feeding operations or wastewater treatment facilities)	Commercial technology	Internal combustion engine	Commercial technology
		Microturbine	Commercial technology
		Gas turbine	Commercial technology
		Fuel cell	Commercial introduction
		Stirling engine	Emerging
Direct Combustion—Boilers			
Fixed bed boilers (stoker)	Commercial technology – Stoker boilers have long been a standard technology for biomass as well as coal, and are offered by a number of manufacturers.	Steam turbine	Commercial technology
Fluidized bed boilers	Commercial technology – Until recently fluidized bed boiler use has been more widespread in Europe than the United States. Fluidized bed boilers are a newer technology, but are commercially available through a number of manufacturers, many of whom are European-based.		
Cofiring	Commercial technology – Cofiring biomass with coal has been successful in a wide range of boiler types including cyclone, stoker, pulverized coal, and bubbling and circulating fluidized bed boilers.		
Modular* direct combustion technology	Commercial technology – Small boiler systems commercially available for space heating. A small number of demonstration projects in CHP configuration.	Small steam turbine	Commercial technology
		Organic Rankine cycle	Emerging technology – Some "commercial" products available.
		"Entropic" cycle	Research and development (R&D) status
		Hot air turbine	R&D status
Gasification			
Fixed bed gasifiers	Emerging technology – The actual number of biomass gasification systems in operation worldwide is unknown, but is estimated to be below 25.	Gas turbines – simple cycle	Prime movers have been commercially proven with natural gas and some medium heating value biogas. Operation on low heating value biogas and the effects of impurities on prime mover reliability and longevity need to be demonstrated.
Fluidized bed gasifiers	A review of gasifier manufacturers in Europe, USA, and Canada identified 50 manufacturers offering commercial gasification plants from which 75 percent of the designs were fixed bed; 20 percent of the designs were fluidized bed systems.	Gas turbines – combined cycle	
		Large internal combustion (IC) engines	
Modular* gasification technology	Emerging technology – A small number of demonstration projects supported with research, design, and development funding.	IC engine	Commercial technology – But operation on very low heating value biogas needs to be demonstrated.
		Microturbine	
		Fuel cell	Commercial introduction
		Stirling engine	Emerging technology
Modular* hybrid gasification/combustion	Emerging technology – Limited commercial demonstration.	Small steam turbine	Commercial technology – But integrated system emerging.

Figure 2.19 Status of biomass-based conversion systems for heat and power generation (EPA 2007)

Major technologies include anaerobic digestion, gasification and direct combustion in boilers. Elements of a communal biomass-based cogeneration system with FBC boiler as example are shown in Figure 2.20. A similar concept is used in the development of the simulation models described later in the research part.

The most commercialized utility biomass-based CHP options are based on biomass combustion. Biomass-fueled systems producing less than 20 MW of electricity are usually based on the steam Rankine Cycle (Sipilä et al. 2005) Electrical efficiency can reach more than 30% on the Higher Heating Value basis of the fuel. Operation of such a system is characterized by high reliability, long life cycle with options for retrofitting.

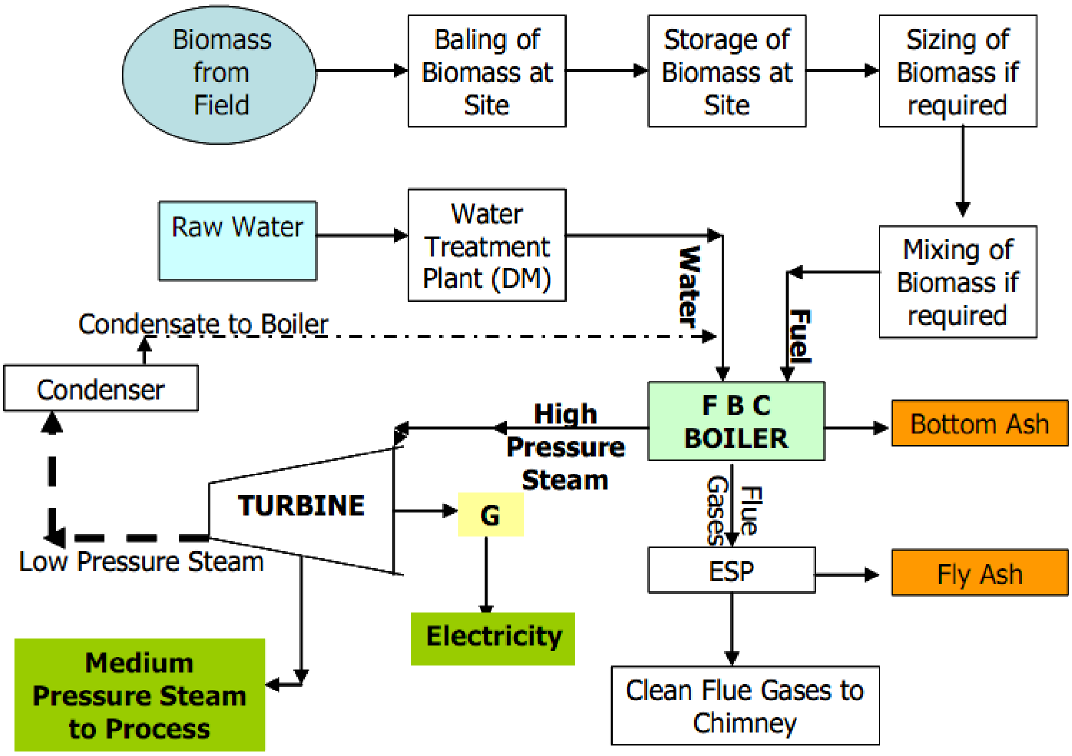


Figure 2.20 Scheme of a Biomass-based cogeneration system (UNEP 2007)

The fuel often requires some preparation steps, but in return the technology can utilize variety of feedstock. Fuel types may include: forest residues, wood wastes, crop residues energy crops, urban wood waste, municipal solid waste and food processing residue (EPA 2007). Short summary of basic parameters for biomass-based CHP systems are listed in the Table 2.2 below.

Table 2.2 Typical characteristics of a biomass-based CHP system (Lako 2010)

Electric efficiency [%]	Total efficiency [%]	Construction time [months]	Technical lifetime [yr]	Load (capacity) factor [%]	Max. (plant) availability [%]
16 – 36	40 – 85	18-30	25	76 – 91	93

Biomass fired systems are used not only due to their technological advantages, but also due to their sustainability. Biomass combustion is a renewable technology. Biomass-based CHP systems environmental performance is therefore important to evaluate.

Environmental performance

There are a lot of factors influencing environmental performance of a biomass-based CHP system. They can include: fuel characteristics, size and vintage of the combustion equipment, combustion technology itself, pollution control equipment, ambient environment conditions, operation and maintenance practices etc. (EPA 2007) In general biomass-based CHP technology is considered to be environmentally friendly for two main reasons:

- it utilizes renewable fuel – biomass;
- it make use of primary energy savings – by utilization of a low-grade heat.

Carbon dioxide emissions associated with biomass are low due to the carbon neutrality of the combusted fuel (see chapter 2.2). Other emission depends on the technology and fuel. Typical values for a biomass-based cogeneration are presented in the Table 2.3 below.

Table 2.3 Emission ranges for biomass-based CHP systems (Lako 2010)

CO_2 or other GHG [kg/MWh]	SO_2 [g/MWh]	NO_x [g/MWh]	Particulates [g/MWh]	Solid waste (fly ash) [kg/MWh]
negligible	30 – 60	60 – 65	11 – 24	0,07 – 0,08

The key of the environmental benefits in CHP systems is reduced primary energy consumption through reduced fuel consumption in comparison to separate heat and power production. An example explaining the reason for it is shown in Figure 2.21.

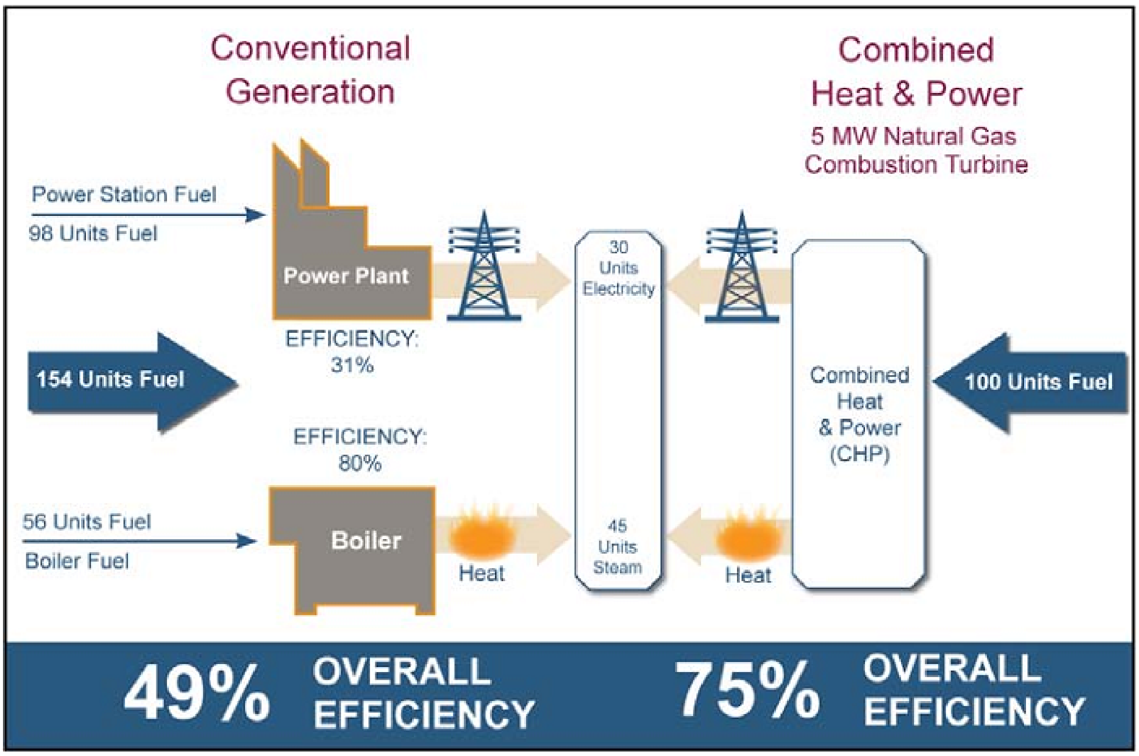


Figure 2.21 Separate heat and power production in comparison to a CHP production in terms of energy consumption (EPA 2008)

Environmental performance characteristics of power and heat generating systems can be evaluated using different methods. Some projects calculate emissions associated with the life cycle of the fuel and combustion processes. This labor intensive approach, although very appropriate, is generally not used in most of the major international protocols. Some regulation documents require calculation of emission that would have been occurred in the absence of the new cogeneration project. European Union standards give another method for evaluation of the environmental performance. Formal instructions for it are issued in the EN15603 standard and other related documents.

Primary energy and CO_2 emission according to EN-standards

European standards maintained by appropriate standardization committees give instructions for measuring environmental performance of buildings that can be applied for a Combined Heat and Power technology. Two general documents from a set of standards on the method for calculation system energy efficiencies and requirements are:

- EN 15603:2008 "Energy performance of buildings Overall energy use and definition of energy ratings" (European Committee for Standardization 2008);
- EN 15217:2007 "Energy performance of buildings. Methods for expressing energy performance and for energy certification of buildings" ((European Committee for Standardization 2007a).

The standards recommend using special indicators to express energy and emission performance of buildings in the 21st century. These indicators are:

- Primary Energy Factor;
- Carbon Dioxide Coefficient.

The EN 15603 explains important definitions concerning systems to be studied by the recommended method. Primary Energy is defined as "energy that has not been subjected to any conversion or transformation process" (European Committee for Standardization 2008). If energy in question includes all sources, including renewable and non-renewable, the calculated energy can be called Total Primary Energy. Furthermore, Primary Energy Factor is "for a given energy carrier, total primary energy divided by delivered energy, where the primary energy is that required to supply one unit of delivered energy" (European Committee for Standardization 2008). The CO_2 emission coefficient is defined as: "quantity of CO_2 emitted to the atmosphere per unit of delivered energy" (European Committee for Standardization 2008).

For Combined Heat and Power production more detailed standard applies: EN 15316-4-5:2007 "Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 4-5: Space heating generation systems, the performance and quality of district heating and large volume systems" (European Committee for Standardization 2007b). The method described in the document applies to district heating and any other kind of combined production for space heating or cooling or domestic hot water purposes. The Primary Energy concept according to "Energy Performance of Buildings Directive" and mentioned above EN-standards is shown in Figure 2.22.

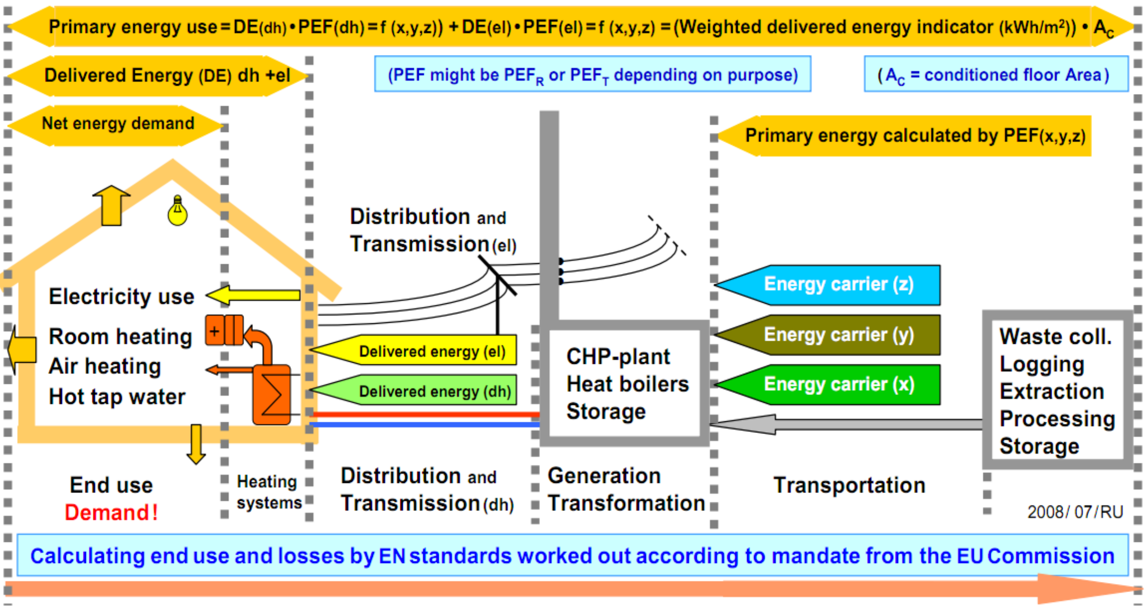
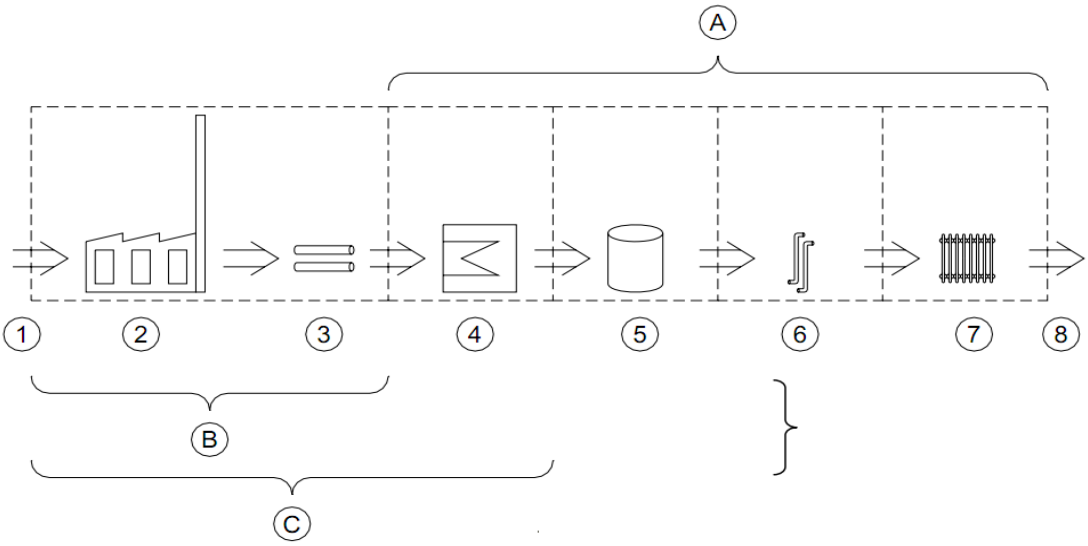


Figure 2.22 The Primary Energy concept implemented in the set of EN-standards (Ulseth 2009)

The method is independent from the use of the heat supplied. The calculation is based on the performance data of the district heating system which can be calculated or measured according to this standard. For the calculation purposes the system is evaluated by dividing it into two subsystems: outside and inside part. As it can be seen in Figure 2.23, combined heat and power plant together with the district heating network is included in the outside part.



1	fuel input	7	Emission
2	heat (and power) generation	8	heating demand of the building
3	heating network		
4	building substation	A	building heating system
5	storage	B	district heating system
6	distribution	C	covered by this standard

Figure 2.23 District Heating systems in the EN methodology for evaluation of buildings (European Committee for Standardization 2007b)

Depicted by "B" in figure, the system to be studied consists of the heat generation appliances and the district heating network up to the primary side of the building substation. In this thesis the system to be studied does not include DHN losses, because there is no need for it when the scope of the thesis covers the comparison of the studied systems. Therefore, the system boundary for the cases described in the research part can be thought to end at the heat and power generation boarder. All elements required to operate the system are included. According to the standard, the primary energy factor of a district heating system is defined as the primary energy input to the system divided by the heat delivered at the border of the supplied buildings. Therefore all energy inputs and all energy outputs have to be considered. The "power bonus" method can be implemented to the calculations. This allow including the electrical power produced by the cogeneration in the total energy delivered by the CHP system. Energy input to the system is weighted by its specific primary energy factor. Some examples of the primary energy factors and accompanying CO_2 emission coefficients for different fuel combustion options are shown in Table 2.4. The table gives a good overview of the environmental performance of different technologies for electricity production.

Table 2.4 Primary Energy Factors and CO_2 coefficients (European Committee for Standardization 2008)

	Primary energy factors		CO_2 production
	Ressource	Total	[kg/MWh]
Fuel oil	1.35	1.35	330
Gas	1.36	1.36	277
Anthracite	1.19	1.19	394
Lignite	1.40	1.40	433
Coke	1.53	1.53	467
Wood shavings	0.06	1.06	4
Log	0.09	1.09	14
Beech log	0.07	1.07	13
Fir log	0.10	1.10	20
Electricity from hydraulic power plant	0.50	1.50	7
Electricity from nuclear power plant	2.80	2.80	16
Electricity from coal power plant	4.05	4.05	1340
Electricity Mix UCPTE	3.14	3.31	617

The EN 15603 document also gives guidance for calculation of carbon dioxide rating. For a given system, the emitted mass of CO_2 can be calculated on the basis of delivered and exported energy for each energy carrier (European Committee for Standardization 2008). For this purpose a CO_2 emission coefficient shall be used. Those coefficients, for a given technology, include all carbon dioxide emissions associated with the primary energy utilized by the system in question.

In the research part of this work, both Primary Energy Factors and CO_2 coefficients are derived for studied cases. This will allow comparing the environmental performance of biomass-based CHP with integrated pyrolysis to simulated base cases without integration.

3 INTEGRATION RESEARCH

This chapter is the main research part of the thesis. It starts with the assumptions and input data and goes through the simulation research and related environmental calculations with their principles to arrive at the results and discussion. As the scope of the thesis deals with simulations of power plants with three different boilers the chapter is structured to clearly differentiate the work done for each of them.

3.1 Assumptions and Input Data

The following text presents the main assumptions needed to perform the research within the scope of the thesis. Thus, the connection with previous work is explained. Next, the input data concerning the District Heating load is presented and heat duration curve derived. Then, the Bubbling Fluidized Bed plant base case without pyrolysis process is presented as it is the basis of the further research. Lastly, the biomass drying and pyrolysis models are presented.

3.1.1 General Assumptions

The goal and scope of this thesis is the comparison of the work previously done by Thomas Kohl from Aalto University. The study treated the potential of pyrolysis integration with Combined Heat and Power plant. In the research a Bubbling Fluidized Bed was simulated in the CHP base cycle. Next, the biomass steam drying and wood pyrolysis process was integrated resulting in the integrated case. This thesis work aims for the simulation of the grate fired (using ProSim's radiant furnace unit model – thus called radiant furnace boiler in this thesis) boiler and the Circulating Fluidized Bed boiler and integration of the same pyrolysis drying and pyrolysis as in Kohl's study. Potential integration options covered in both studies are shown in Figure 3.1.

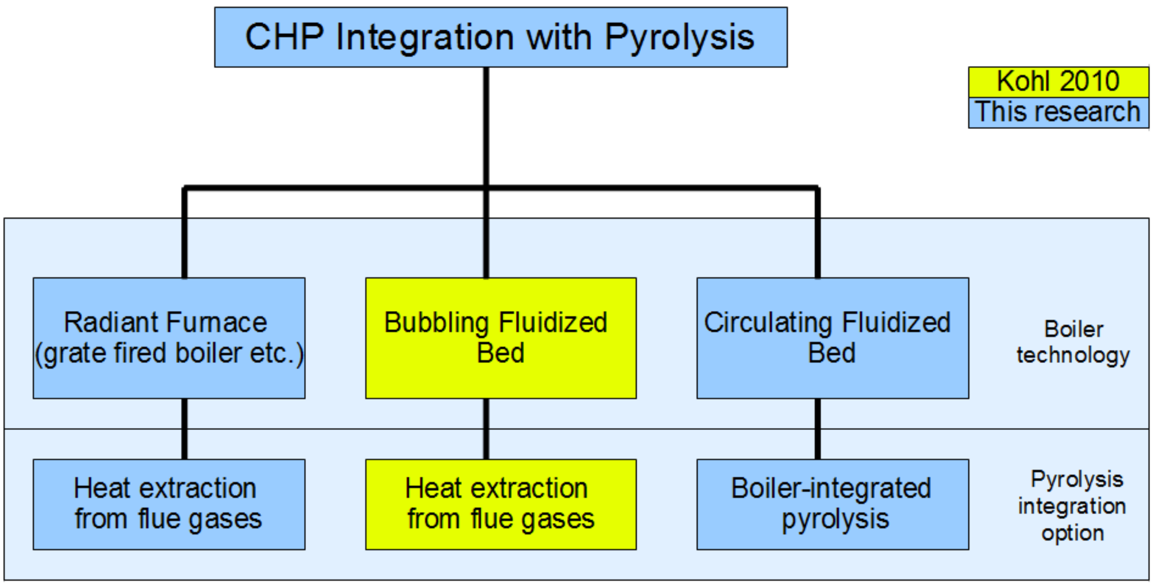


Figure 3.1 Potential integration options within the scope of the thesis

The need for simulation of the different boilers arises from their different performance in the cycle. The CFB integration case has a different temperature and location of the heat extraction for the pyrolysis in the cycle comparing to the BFB boiler case. In the radiant furnace integration case temperature distribution at the heat extraction point differs from the BFB integration case. Moreover, in the radiant furnace case the temperature fluctuation within the boiler is considerable, while in the BFB boiler it is close to a constant level. Therefore there is spraying of water to cool down the live steam when the temperature is above a desired level in the radiant furnace case. More detailed description of the differences between different boiler simulations is given later in the text.

Simulation work done within the scope of this thesis includes developing design models for base and integrated cases of both boilers. Outgoing from the design point it was possible to create off design cases when certain unit models characteristics are fixed, e.g. areas of heat exchangers. Next, simulation models at part loads were developed under assumptions concerning the minimum allowed fuel input into the boiler. For better understanding of the connection with the previous simulation used in this research and the structure of developed models see Figure 3.2.

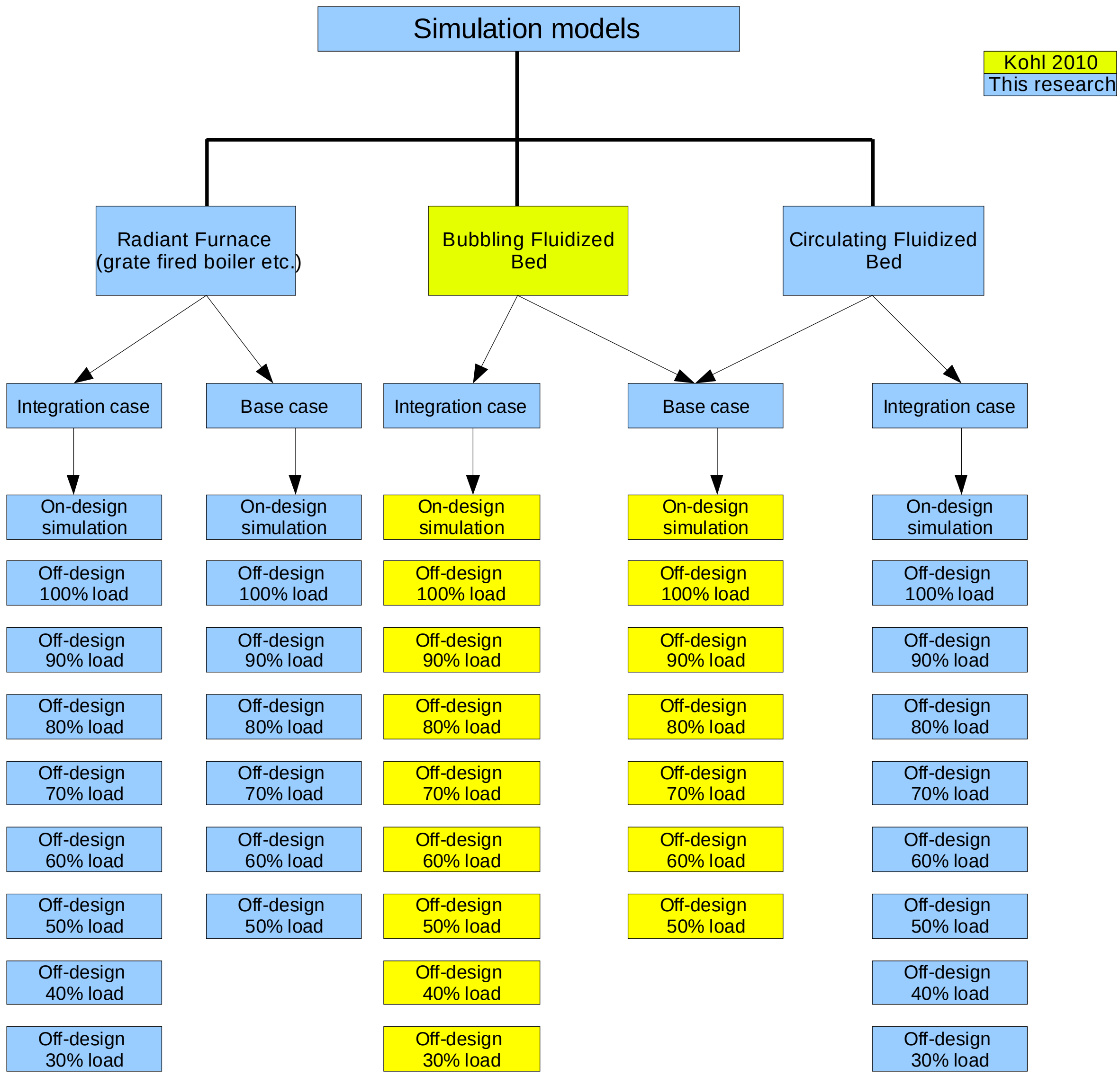


Figure 3.2 Simulation models developed and their connection with previous research

In this thesis, to make the comparison possible, the same assumptions as in the Kohl's study had to be implemented. The most important data derived and assumed for this work include:

- input streams characteristics, e.g. fuel composition, air parameters, chemical composition of the biomass to be dried etc.;
- district heating demand data;
- power cycle structure, e.g. arrangement of the unit modules, type of the turbine;
- simulated unit modules characteristics, e.g. the turbine efficiency curve, losses and pressure drops in heat exchangers etc.;
- stream parameters, e.g. steam pressures and temperatures.

Following the logic in Kohl's research this thesis work will include simulation of two boilers – radiant furnace boiler and CFB boiler – in base case configuration of the cycle and with pyrolysis integration for both boilers. ProSim software forces using one and the same unit model for simulation of BFBs and CFBs. Therefore, the base case for simulation of the CFB boiler without pyrolysis process is the same as for the base case of the BFB boiler in Kohl's study.

Separately from the assumptions made to the power cycle itself, it is necessary to derive data for the input streams. As shown in Figure 3.3 this includes characteristics of the fuel burnt in the boiler for the base case and fuel characteristics of the biomass fed to the dryer for the case of pyrolysis integration. It is assumed that these two are the same feedstock – pine wood.

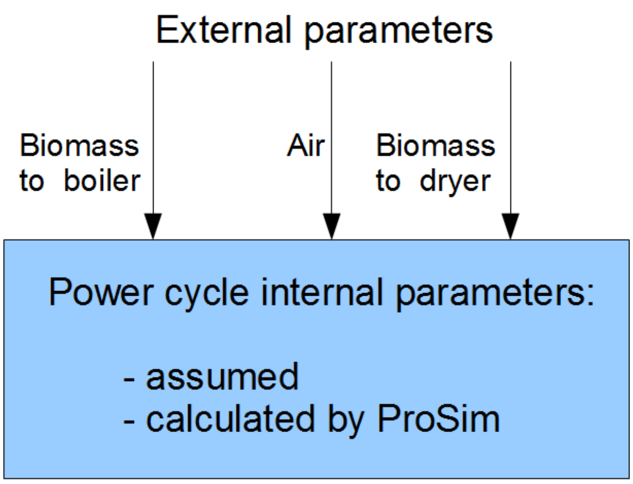


Figure 3.3 Power cycle parameters for the simulation

Fuel characteristics derived from Kohl's study are used to make the comparison of cases possible. Therefore, fuel input specifications are as shown in the Table 3.1.

The moisture content of the fuel is set to 50 % (Kohl et al. 2010). The Higher Heating Value (HHV) of the biomass burned is 18,8 MJ/kg and has been calculated by the ProSim simulator based on the fuel's chemical composition. Biomass used in the integrated cases is assumed to have the same properties as the feedstock biomass.

Table 3.1 Ultimate analysis of the biomass fuel

Fuel compostition	Weight % dry ash free
C	50,64
H	6,10
O	42,22
N	0,16
S	0,08

Another input stream to the simulation model that has to be determined by the user is the air stream. This, similarly to the fuel, is derived from Kohl's study. Air analysis is shown in the Table 3.2. The air is assumed to be supplied at the temperature of 20 °C. The relative moisture content is set to 80 %.

Table 3.2 Ultimate analysis of the air

Air content	Volume %
CO_2	0,03
H_2O	0,98
O_2	20,74
N_2	78,25

The simulation work will start with developing models in on-design mode. This will allow creating the simulation model of the CHP plant at design point – with maximum thermal output. From this model, the off-design case will be created. Then, partial load simulations are supposed to be modeled using the simulations that are already in place. This procedure applies to both base case simulations and integration simulations as well.

3.1.2 DH Load Characteristics

Small biomass-based Combined Heat and Power plants are usually set to operate according to a given heat demand determined by the District Heating Network (DHN) (Savola 2007). Therefore in the power plant simulation, the heat demand data are an important input. The power plant must be able to fulfill the heat demand. When the heat demand exceeds the capacity of the plant back-up boilers are assumed to be in use. Lower demand of the DHN side requires lower fuel input in the boiler resulting in lower steam parameters. This lower fuel input can only go down to a certain level, because of the unstable combustion in the bed that occurs at lower fuel loads. Therefore in case of the power plant shut-off when heat demand is too low, boilers are started up. The back-up boilers are assumed to be heavy oil fueled heat-only boilers with overall efficiency of 85 %.

The District Heating data for the research in this thesis is derived from previous studies done by Kohl. This fact is directly related to the thesis goal and scope. The use of the same input data will allow comparing simulation cases from this thesis with the results obtained by Kohl. Furthermore this will enable to observe different characteristics of the studied systems.

The input data of the Distract Heating demand is taken from real DH Network (DHN) performance measurements. The data was scaled down so that the CHP provides 60% of the hourly peak demand of the DHN while operating on full 100 % load (Kohl et al. 2010). The full load in this case means also that the fuel load is at 100 %. To be consistent with Kohl, it is assumed that the power plant thermal capacity is 16,5 MW. For those assumptions the heat duration curve can be plotted. The diagram is shown in Figure 3.4. The heat load duration curve illustrates the relationship between generating capacity requirements and capacity utilization for each increment load. The demand data is ordered in descending order of magnitude.

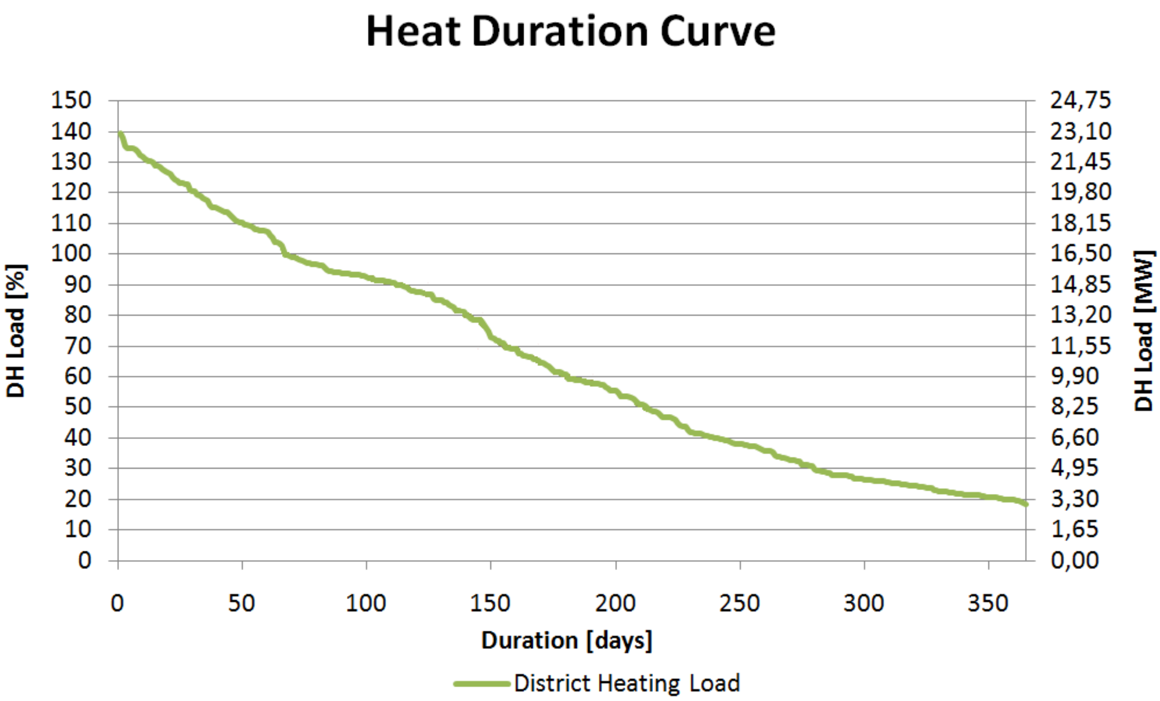


Figure 3.4 Heat duration curve for the heat demand data used in the study

The maximum heat needed to be supplied to the DHN corresponds to around 23 MW. The lowest values are about 3,3 MW. Annual heat needed to be supplied by the DH system amounts to 94,5 GWh.

The power plant for the base case without pyrolysis integration in Kohl's research is assumed to be shut off at 50% of its fuel load due to the unstable combustion. This is a typical shut down level for solids fired power plants. The same assumptions have been made for the two studied base cases in this work: radiant furnace boiler and Circulating Fluidized Bed boiler. Consequently, for the 50 % of the fuel load the plant has 50 % of the thermal output that corresponds to 30% of the heat maximum heat demand. These parameters are representative for communal CHP's based on solid fuel combustion (Kohl et al. 2010).

For the further simulation the multiperiod model of District Heating load was developed. This allows simulating power plant and integrated system performance in partial loads. The multiperiod model is based on the assumption that part loads are equal in duration. Together with full load duration period the operation time has to match the total operational hours of the real CHP case. Additionally the amount of days covered by the studied CHP production system is equal to the amount of days from kick-in at the lowest part load (50 % of the thermal load and 50 % of the fuel load) to maximum load of 16,5 MW. These assumptions can be expressed by mathematical formulas as:

$$Q_{CHP} = P_{100} \cdot t_{100} \cdot \ldots \cdot P_n \cdot t_n \qquad (3)$$

$$tot = t_{100} + \cdots + t_n \qquad (4)$$

and

$$t_{90} = \cdots = t_n \qquad (5)$$

where

Q_{CHP} is the total heat produced by the CHP plant at all load levels;

P_n is the heat produced at *n* partial load (where 100 is 100 % of the load);

t_n is the duration of the *n* load;

tot is the total operation time of the CHP plant.

For the input data, set assumptions and the model described above the multiperiod approximation of the plant's heat supplied to the network can be developed. The duration of the given loads for the base case from Kohl's study is shown in the Table 3.3.

Table 3.3 Plant heat load levels and their duration for the base case in Kohl's study (Kohl et al. 2010)

DH Load [MW]	DH Load [%]	Duration [hours]
16,5	100	2440
14,85	90	530
13,2	80	530
11,55	70	530
9,9	60	530
8,25	50	530

Partial loads are set to differ by 10 % between next loads. This is also applied in further research in this thesis following Kohl.

3.1.3 Power Cycle Simulation

Simulations developed further in this study are based on the main concept of a biomass-based Combined Heat and Power plant introduced by Kohl. From the base case of a standard small-scale system there is a potential integration case developed. All these include simulation at part loads using the multiperiod District Heating model. Therefore, in this thesis the power cycle in the studied plant is already determined by previous research work. This approach will allow comparing all the integration options.

The base case of the simulation model with Bubbling Fluidized Bed from Kohl’s study is also the base case for the simulation of the model with Circulating Fluidized Bed described later. This is due to the fact that ProSim software does not distinguish from those two technologies and one may use a general fluidized bed unit model from the library to represent both technologies. The software unit mode does not include the fluidizing agent, there are only energy and mass balances calculated for the boiler. The simulation model for BFB and CFB case with no pyrolysis integration is shown in Figure 3.5. The power cycle consists of the following unit modules listed in the Table 3.4 below.

Table 3.4 BFB base case power cycle components

No.	Unit
1	Air blower
2	Burner
3	Fluidized bed reactor
4	Steam generator
5	Superheater with spraying
6	Superheater
7	Economizer
8	Air preheater
9	Water splitter
10	Steam turbine – regulation stage
11	Steam turbine – extraction stage
12	Steam turbine
13	District Heating heat exchanger
14	Pump
15	Feedwater tank
16	Feedwater pump
17	Electricity generator

In the presented model of the power cycle the air is supplied under slightly higher than standard atmospheric pressure with chemical characteristics explained before. Then it is preheated in the air-preheater by exhaust flue gases before entering the burner. The biomass with given characteristics as described before is burned producing a hot flue gas stream. Then the heat created in the burner is used to evaporate water in the steam generator unit model. The steam leaves the boiler at pressure of 60 bars. Next, the steam is superheated by the flue gases leaving the boiler. The remaining heat available in the boiler is used for further superheating of the steam in the in-bed superheater. Now, the live steam at the temperature of about 510 °C is directed into the steam turbine. The turbine itself is modeled as an extraction turbine with three stages. The first one is a regulation stag. Then steam enters the extraction part of the turbine where small fraction of the flow is redirected to the feedwater tank. The remaining steam goes through the last turbine stage where the pressure is dropped to 0,69 bars.

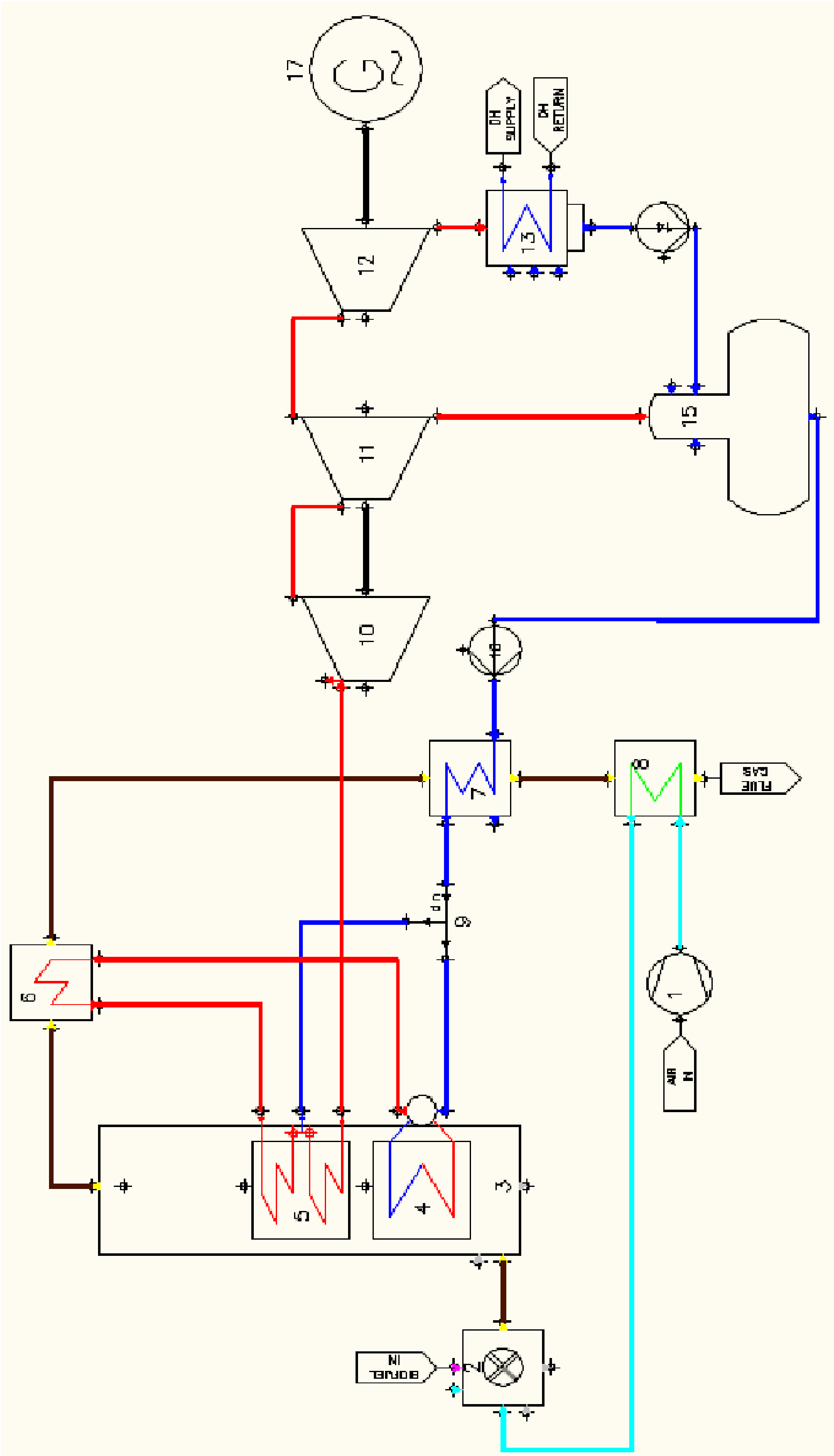


Figure 3.5 BFB and CFB base case model (Kohl et al. 2010)

The alternator model unit (17) from ProSim's library is connected to all turbine stages (10, 11, 12). The steam from the turbine is condensed using in a DH heat exchanger model unit (13). Cooling water enters the model unit at 2 bars and 55 °C and is then heated up to 85 °C. The water from the power cycle that is leaving the heat exchanger is then pressurized to 2 bars and enters the feedwater tank (15), maintaining the tank's design pressure at 2 bars as well. Here it is preheated to saturated conditions by extracting the appropriate amount of steam from the extraction stage of the turbine (11). Next, the water leaving the tank is pumped to a pressure of 60 bars (16). Finally, before it enters the boiler (3), the water is preheated (7) using the remaining heat available in flue gases.

The described cycle is applied to all simulation cases developed in this thesis. Any changes done to the cycle are highlighted. Integration concept, similar in the simulation technique for all cases is also described later in the text.

3.1.4 Biomass Pyrolysis and Drying Models

Simulation models for both boiler types with integrated biomass drying and pyrolysis developed have been. Implementation of those two processes is modeled by using standard unit models from ProSim's library.

Biomass pyrolysis model

Biomass pyrolysis is modeled as an additional evaporator unit. The chemical process of fast pyrolysis is not modeled in details here as it is outside of the scope of this thesis. This type of simulation is also not possible with the simulation tool used. For the integrated case with radiant furnace it is assumed that biomass is indirectly heated and pyrolysed with sand. The concept is based on the study of Forschungszentrum Karlsruhe (FZK) described in Heinrich (2007). The same idea for the BFB boiler is implemented in Kohl's study. The heat needed for the pyrolysis reaction is supplied by the flue gases leaving the boiler in the radiant furnace case. For the integrated case with Circulating Fluidized Bed the pyrolysis process is implemented in the boiler, therefore the heat needed for the reaction is taken from the hot flue gases entering the boiler. Both boiler cases have an important assumption that for complete biomass fast pyrolysis 1,87 MJ of energy is needed to process 1 kg of biomass. This represents the heat needed to bring the biomass to the reaction temperature and energy required for the endothermic process. The value is derived from pyrolysis data for pine in Daugaards & Brown (2003) study and used also in Kohl's research. The moisture content of wood before pyrolysis is 10 %. The pyrolysis process yields the following products: gas and bio-oil with char called slurry, with 90 % efficiency of the process. It is assumed that 90 % of the input biomass energy to the pyrolysis is further contained in the bio-slurry product. The remaining 10 % is obtained in gaseous form. This is also an important assumption that is further used in environmental performance calculations. The energy contained in the bio-gas is assumed to be burnt in the boiler, thus it is further subtracted from the biomass input to the boiler. The pyrolysis yield is calculated based on the amount of heat that was extracted from the hot stream in both integration cases.

Heat used by the pyrolysis process in the radiant furnace integration case is supplied by the flue gases from the boiler. Therefore, the temperature is depended on the combustion and fuel input. At maximum boiler load the temperature of the input flue gases is 890 °C. At the lowest partial load this temperature drops to 734 °C. Next, the gases leave the pyrolysis unit model at a temperature of 480 °C and are used further for water and air preheating.

The integration mass and energy balance of the pyrolysis for the radiant furnace simulation model is shown in Figure 3.6.

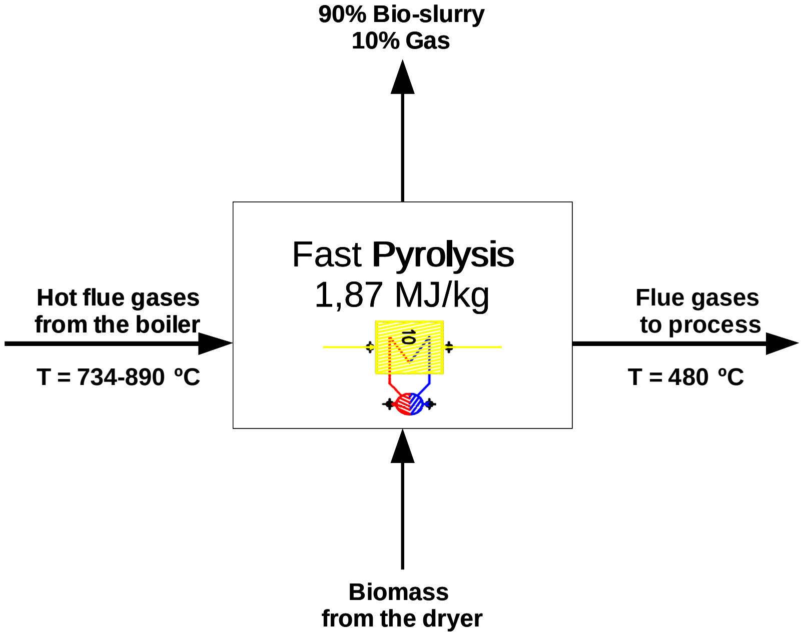


Figure 3.6 Fast pyrolysis in the radiant furnace boiler simulation model

In the simulation model for the CFB boiler with pyrolysis integration the enthalpy needed for fast pyrolysis is extracted from the flue gases before they enter the boiler. This approach represents the case when the hot sand is extracted from the bed and used to maintain the pyrolysis process. Figure 3.7 shows the integration within the CFB boiler case. Biomass and pyrolysis products are drawn only to better understand the concept. In the simulation models they are not represented by any input/output streams, only via heat consumption used to drive the process. The flue gases entering the fast pyrolysis unit are in the temperature range of 1495 to around 1477 °C for the maximum and the lowest load respectively. The outlet temperature is kept at constant level of 850 °C.

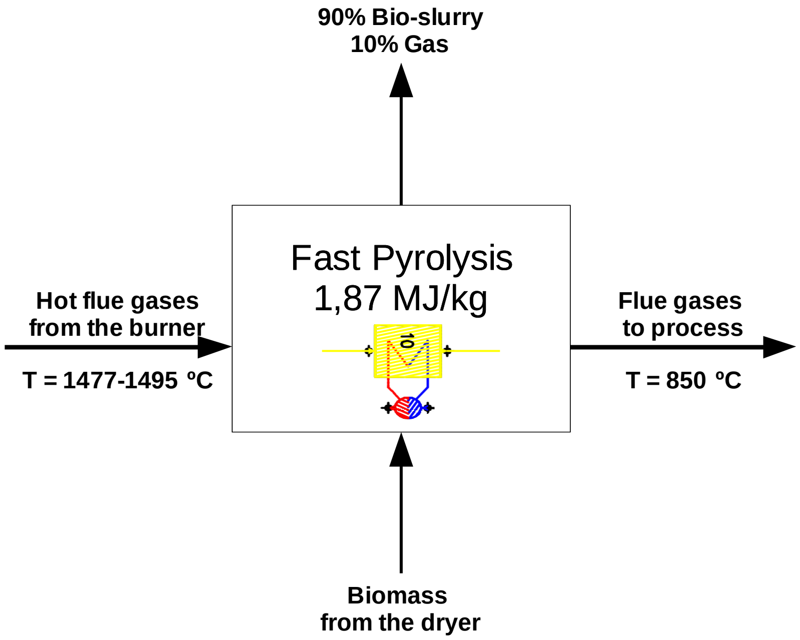


Figure 3.7 Fast pyrolysis integration in the Circulating Fluidized Bed simulation model

Biomass drying model

As the biomass for the pyrolysis process needs to have low moisture content the drying unit is assumed to be deployed in the integration cases. The dryer unit model used in simulation is representing a steam tube dryer for wet biomass (Kohl et al. 2010). Hot flue gases and extracted live steam is used for drying to low moisture content. Dried biomass leaves the unit at wet bulb temperature (Kohl et al. 2010) cooling down the gases to around 120 °C, as shown in Figure 3.8.

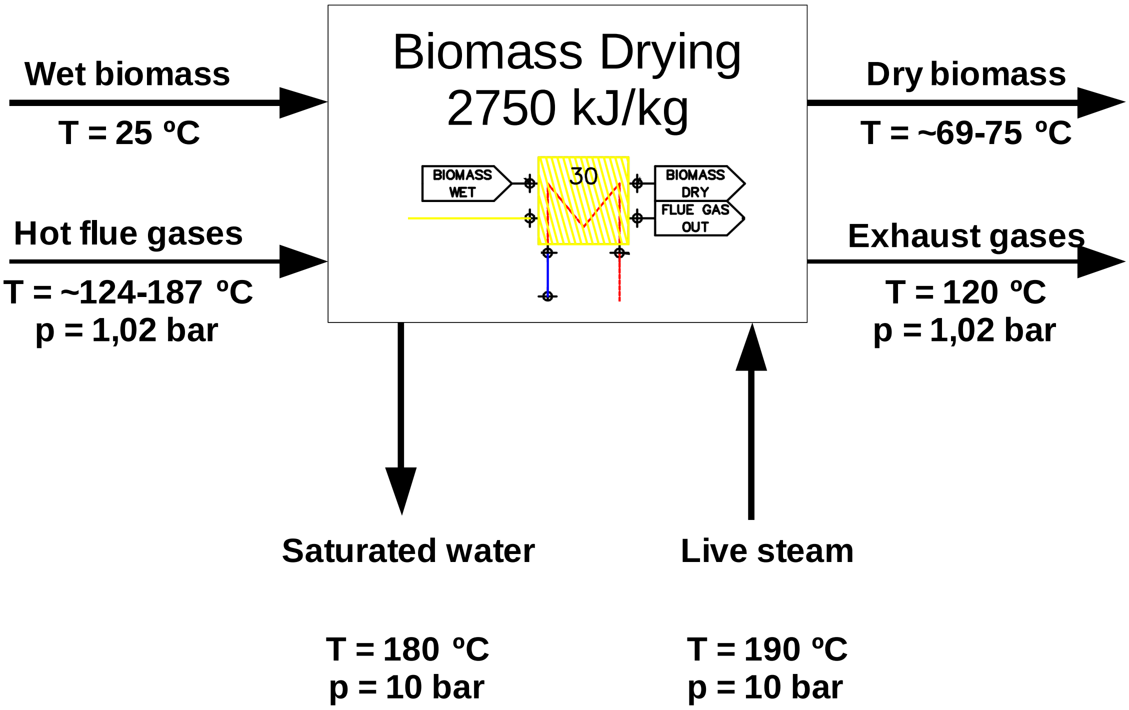


Figure 3.8 Biomass drying integration simulation model

An important assumption that is made for this process is the heat consumption. Originally derived from Brammer & Bridgwater (1999) the value is estimated to around 2750 kJ for each 1 kg of water evaporated in the process (Kohl et al. 2010). This allows creating an energy balance of the dryer. Input streams include wet biomass, hot flue gases and steam. Output streams are dried biomass, exhausted flue gases and condensed steam. The heat consumption and given parameters of the input streams serve for adjustment of the dryer's heat losses. The module allows setting the losses in order to adopt the unit module and reach energy balance.

The biomass drying model is the same for all simulation cases. The simulation models differ in the hot flue gases temperature and thus also in the dry biomass temperature.

3.2 Steady-State Simulation

This chapter describes the core of the research work done in this thesis. As the goal and scope of the thesis states, there is a radiant furnace boiler and Circulating Fluidized Bed simulation presented.

3.2.1 Base Case with Radiant Furnace Boiler

The following text presents the radiant furnace boiler case and the development of simulation models at design load and partial loads. Special attention is paid to the parameters set in the model with maximum thermal capacity. Heat duration curve for the case is developed as well.

Power cycle simulation at design load

For the simulation purposes firstly there is an on-design model created. This allows setting the design point characteristics to heat exchangers areas, steam turbine, boiler and generator. Next, when the design case is created correctly it is possible to create the off-design model. In off-design all previously mentioned characteristics are fixed and by simulating further partial loads, they respond to changed flows resulting in different stream parameters.

The simulation model developed within the scope of this thesis is shown in Figure 3.9. The simulation model had to follow the construction of the cycle developed by Kohl in order to make the comparison reasonable. The main change to the base case with fluidized bed model is the type of the boiler used. Here, the radiant furnace unit model is adopted. In consequence higher temperatures within the boiler are achieved. The power cycle components and parameters set in unit models are listed in the Table 3.5. Some of the values set e.g. pressures, are recalculated by the software during the compilation run. Other values not mentioned below were set to ProSim's default values for a given module unit.

The combustion air with assumed characteristics is supplied to the burner where the feedstock fuel is combusted. Heat created is used within the grate fired boiler to evaporate water. The evaporation pressure is set by the feedwater pump to 60 bars. High temperature flue gases leaving the boiler at 890 °C are further used to superheat the evaporated steam. Then live steam is directed into the turbine. The temperature of the steam is set to be regulated by spraying using feedwater. This maintains stable steam values at low loads. In result the steam entering the turbine has fixed temperature of 510 °C. Similarly to the BFB base case the steam is expanded in the turbine modeled in three stages. The turbine is connected to the generator and exhausts the remaining steam at a low pressure of 0,69 bar. Next, the steam is condensed by the heat exchanger representing the DHN. The water leaving the unit is elevated to the feedwater tank's pressure of 2 bars and then further pressurized to 60 bars.

At this point, by the mean of the splitter unit, part of the water goes to the preheater unit and other fraction is used for spraying. The remaining heat in flue gases is used to preheat the combustion air.

From the cycle described above there is a retrofitted case with biomass drying and pyrolysis developed. The cycle in off-design mode serves also as a basis for creation of simulations at part loads.

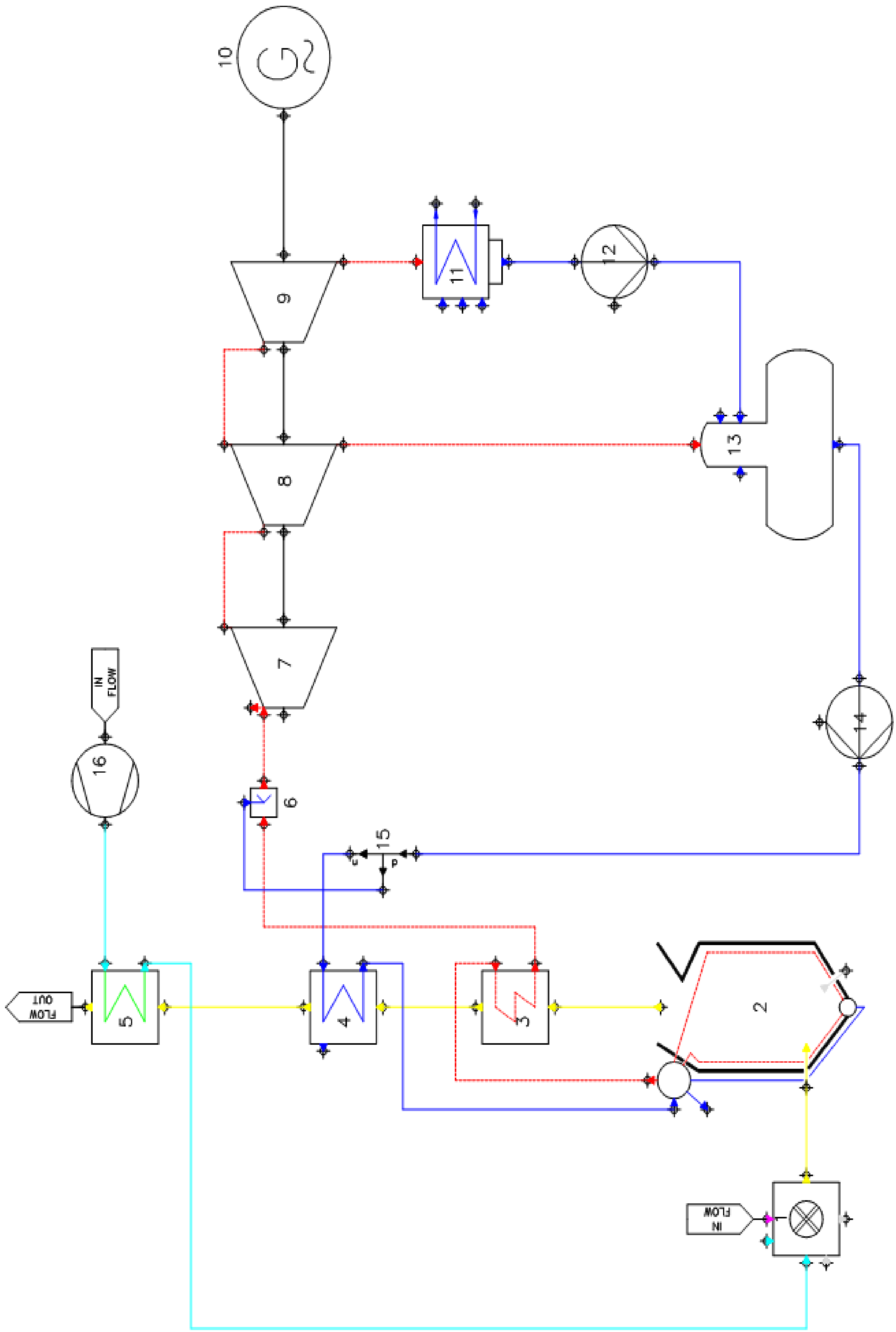


Figure 3.9 Base case simulation model with radiant furnace – power cycle

Table 3.5 Base case simulation model with radiant furnace - parameters

No.	Unit	Stream	Parameters
1	Burner	Fuel in	temperature 25 °C pressure 1 bar mass flow 3,208 kg/s at design point
		Flue gas out	pressure 1 bar
2	Radiant furnace	Flue gas in	pressure 1 bar
		Flue gas out	pressure 1 bar temperature 890 °C
		Feedwater in	pressure 60 bars
		Steam out	pressure 60 bars
3	Superheater	Steam in	pressure 60 bars
		Steam out	temperature 585 °C pressure 60 bars
		Flue gas in	pressure 1 bar temperature 890 °C
		Flue gas out	pressure 1 bar
4	Economizer	Flue gas out	pressure 1,02 bar
		Flue gas in	pressure 1 bar
		Water in	pressure 60 bars
		Water out	pressure 60 bars
5	Air preheater	Flue gas out	temperature 185 °C pressure 1,02 bar
		Flue gas in	pressure 1,02 bar
6	Sprayer	Steam in	temperature 585 °C pressure 60 bars
		Steam out	temperature 510 °C pressure 60 bars
		Spray water	pressure 60 bars
7	Steam turbine – regulation stage	Optimum isentropic efficiency	calculated by new standard curves
		Steam in	temperature 510 °C pressure 60 bars
		Steam out	pressure 54 bars
8	Steam turbine – extraction stage	Steam in	pressure 54 bars
		Steam out	pressure 2 bars
		Preheater	pressure 2 bars
9	Steam turbine – without	Steam in	pressure 2 bars

	extraction	Steam out	pressure 0,69 bar
10	Electricity generator	all default	
11	District Heating heat exchanger	Water in	temperature 55°C pressure 2 bars
		Water out	temperature 85°C pressure 2 bars
		Steam in	pressure 0,69 bar
		Condensate out	pressure 0,69 bar
12	Pump	Water in	pressure 0,69 bar
		Water out	pressure 2 bars
13	Feedwater tank	Steam in	pressure 2 bars
		Condensate out	pressure 2 bars
		Main condenstate	pressure 2 bars
		Feedwater out	pressure 2 bars
14	Feedwater pump	Water in	pressure 2 bars
		Water out	pressure 60 bars
15	Water splitter	Flow 1,2,3	pressure 60 bars
16	Air blower	Air in	temperature 20 °C
		Air out	temperature 20 °C

Power cycle simulation at part loads

The partial loads models are derived one after another from the 100 % base case simulation model. Simulation of lower loads is done by consecutive decrease in the fuel charge. The DH load is matched by iteration of the fuel input. No additional parameters have to be changed in the base case. If the fuel flow decreases the enthalpy of the flue gases within the boiler is lower. This has to result in consecutively lower enthalpy levels in exhaust flue gases streams in partial loads.

For the base case with radiant furnace the lowest fuel input load is assumed to be slightly lower than for the BFB. In the developed model of the cogeneration plant with radiant furnace boiler the lowest possible fuel load is 45 % comparing to the 100 % heat capacity fuel load from off-design. By simulating this level of the fuel load it turned out that the plant's heat production corresponds to 50% of the plant's thermal capacity. Further, by having this result it was possible to draw the heat duration curve with multiperiod model. The model is shown in Figure 3.10.

As there are periods for which additional heat has to be delivered and where the plant has to be shut down due to too low demand, heat-only boilers are assumed to be deployed. The heat supplied by the back-up boilers is marked red in Figure 3.10. The multiperiod model for the radiant furnace is thus the same as for the model deploying BFB boiler developed by Kohl in the case with no pyrolysis integration.

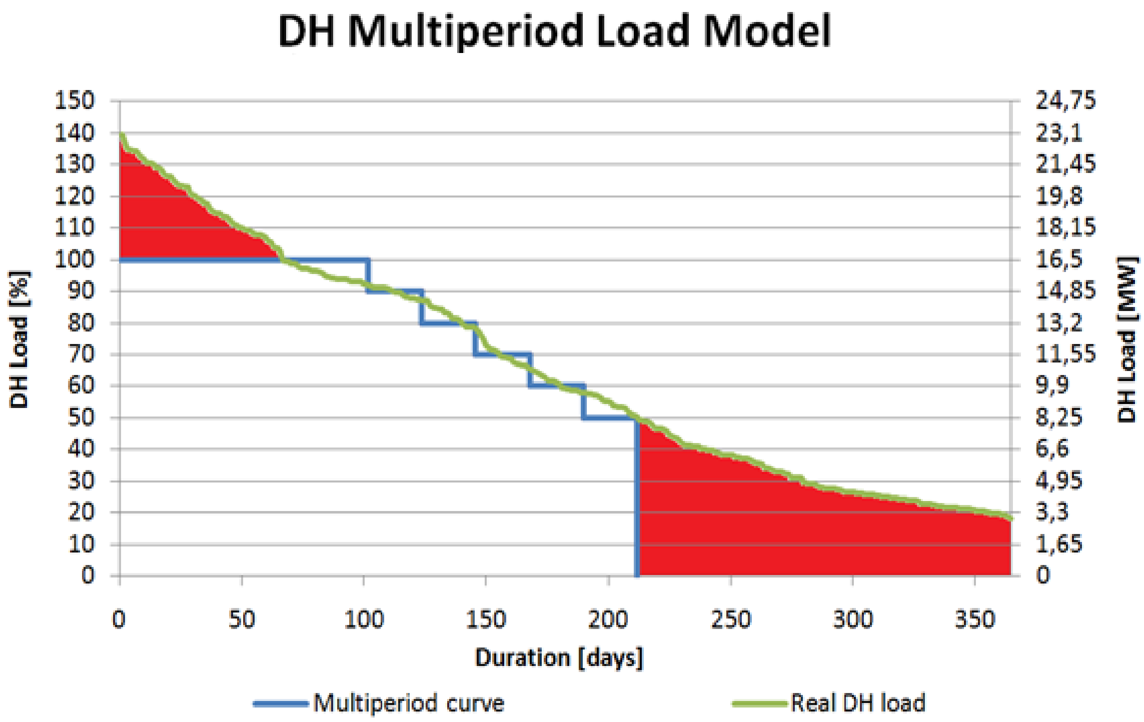


Figure 3.10 Heat duration curve and DH load multiperiod model for the base case with radiant furnace

3.2.2 Biomass Drying and Pyrolysis Integration with RF Boiler

The following text presents the radiant furnace boiler integration case and the development of simulation models at design load and partial loads. Special attention is paid to the biomass drying and pyrolysis unit models. Heat duration curve for the case is developed as well.

Power cycle simulation at design load

Having the base case with the radiant furnace there is a potential retrofitting situation to the cycle previously introduced – integration of biomass drying and pyrolysis. There are new units models implemented compared to the base case. Configuration of the integrated case is shown in Figure 3.12. For the design load the plant is producing at maximum heat generation capacity, thus no flows to pyrolysis and dryer are allowed. Gradually, when the plant heat production is reduced in part loads surplus of heat can be used for biomass drying and pyrolysis.

In order to provide energy for the pyrolysis process the stream of flue gases leaving the boiler is split. The heat is extracted from the flue gases according to the assumptions made. The rest of the flue gases is used for steam superheating as in the base case. Once the heat is extracted by the pyrolysis their temperature is cooled down to 480 °C. This concept is taken from the FZK process (Henrich 2007) shown in Figure 3.11. The sand is thought to be heated up to 550 °C by the hot flue gases (Kohl et al. 2010). Furthermore, the flue gases stream after pyrolysis is mixed back with the flue gases leaving the superheater. This is done with the help of a mixer unit model.

For the drying process live steam is extracted before it enters the steam turbine. The stream is split with the splitter unit under constant pressure. This is creating a problem of the pressure being too high for the drying process, thus the steam flow is throttled to 10 bars by means of a valve. Subsequently the steam is cooled down to 190 °C before it enters the dryer unit. This is done by spraying with water that is leaving the dryer at around 180 °C. The dryer condensate is further throttled to 2 bars and directed to the feedwater tank. The biomass input stream to the dryer is set according to the assumptions with temperature of 25 °C and near atmospheric pressure of 1 bar.

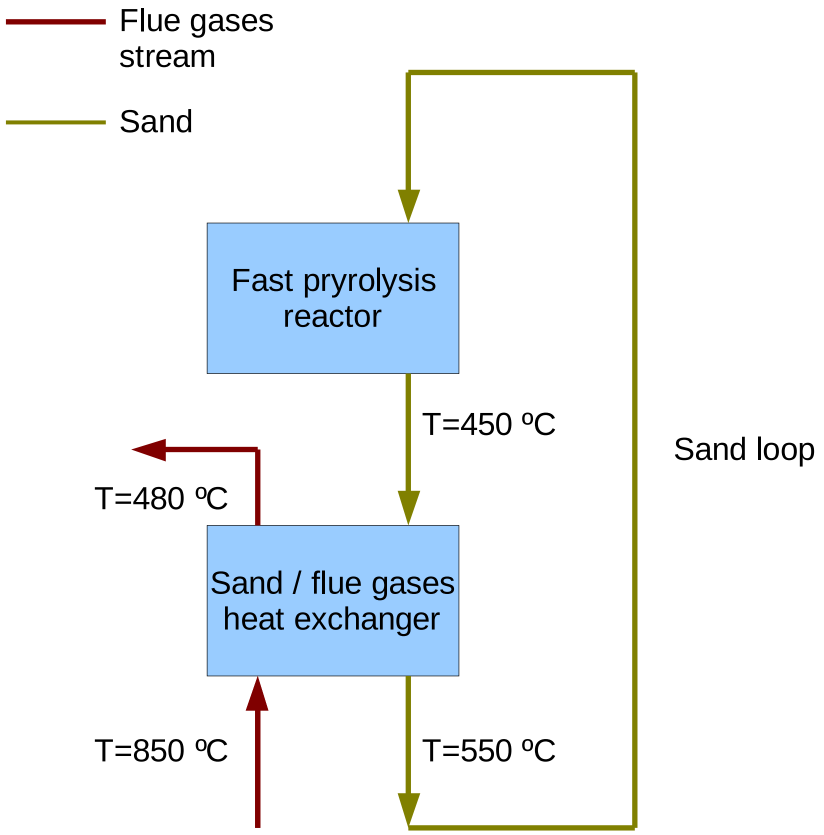


Figure 3.11 FZK Fast pyrolysis concept

In the base case with no integration the flue gases are released after they are used for combustion air preheating. In the integrated case the flue gases are further directed to the drying process. The heat available in this stream is extracted in the dryer and the gases are assumed to be cooled down to 120 °C. This temperature level contributes to corrosion-free process, even if the low-sulphur biomass is used (Kohl et al. 2010).

The integration case yields pyrolysis products at part loads as explained in the next section.

Power cycle simulation at part loads

Partial loads cycle parameters are set to yield maximum pyrolysis product. This can be done by having both steam extraction rate and boiler's maximum burning power as high as possible. These two parameters are on the other hand controlled by the fuel input – the higher the input the higher the enthalpy available for the cycle. Therefore the fuel input for partial loads is kept at constant design level for partial loads above 60%. For lower partial loads the fuel input is decreased, but still kept on a higher level compared to the base case, as it will be explained later. More fuel compared to the corresponding plant's thermal load in the cycle without integration means that the boiler has more heat available for water evaporation. Hence, if the DHN demand is to be satisfied the surplus of heat is set to be dissipated in the drying and pyrolysis process.

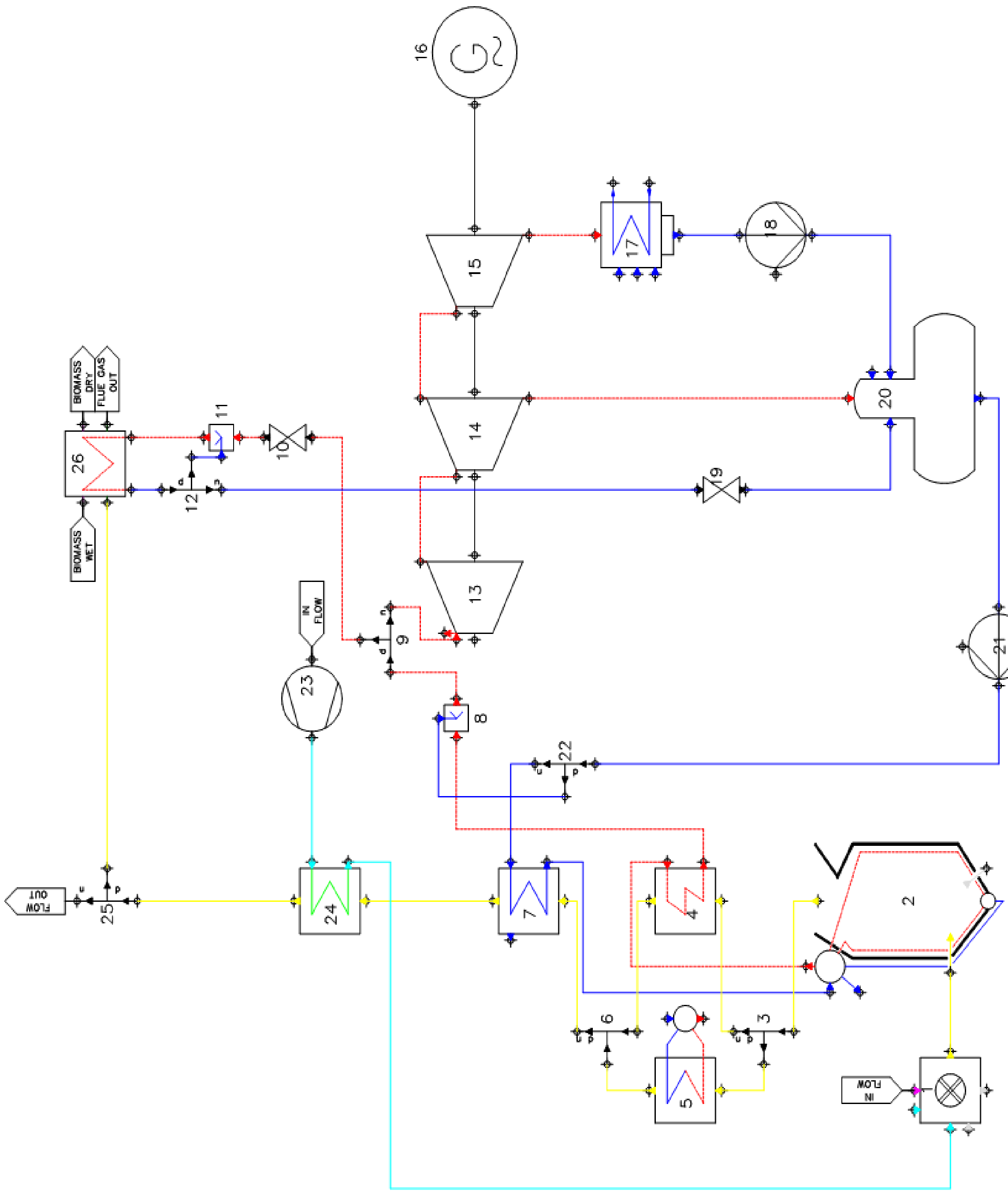


Figure 3.12 Integrated case simulation model with radiant furnace boiler – power cycle

The simulation of the part loads differ between different multiperdiod steps. For all cases the simulation procedure starts with the adjustment of the dryer unit module. Then pyrolysis process is adjusted to match the DH demand. Firstly, the biomass input to the dryer is set. Biomass output can be automatically calculated. Now, with the steam and flue gases entering and leaving the dryer model it is possible to create the energy balance of the unit to match losses. This is due to known enthalpies and mass flows of all input/output streams and also assumed earlier drying process heat consumption (around 2750 kJ/kg water evaporated).

The energy flow of a given stream can be calculated from the formula:

$$\dot{m} \cdot h = \dot{Q} \qquad (6)$$

where

$\dot{m}$ is the mass flow rate of a given stream;

h is the specific enthalpy;

$\dot{Q}$ is the energy flow.

The energy balance model is needed for setting the dryer unit at all partial loads. Stream values calculated are shown in Table 3.6.

Table 3.6 Energy flows of input and output streams of the dryer at partial loads for radiant furnace integrated case

Load	90	80	70	60	50	40	30	[%]
Flue gases to the dryer	3247,49	3110,88	2977,81	2919,32	2209,82	1543,29	1011,09	[kJ/s]
Biomass to the dryer	107,72	181,80	262,53	339,24	280,72	212,19	148,40	
Steam to the dryer	1373,82	3481,47	5763,69	7857,90	6775,21	5308,93	3837,61	
Flue gases from the dryer	-2360,96	-2461,41	-2578,19	-2692,42	-2214,09	-1686,16	-1201,83	
Biomass from the dryer	-99,07	-172,50	-256,21	-338,59	-280,40	-211,65	-147,76	
Condensates from the dryer	-373,91	-947,54	-1568,69	-2138,66	-1843,99	-1444,92	-1044,47	

For these values there are dryer's heat losses variable adjusted to match the assumed heat consumption. Another parameter that changes depending on the simulation case is temperature of gases leaving the dryer. This temperature is expressed as wet temperature added to a variable that needs to be set by the user. This value allows setting the flue gases leaving the dryer unit to the temperature of 120 °C. Both dryer's losses and the variable are summarized in Table 3.7.

Table 3.7 Dryer's losses and wet temperature at partial loads for radiant furnace integrated case

Load	90	80	70	60	50	40	30	[%]
Dryer losses	5,5	9,5	14	18,5	20,5	22	23,5	%
Wet temp.+	52	49,5	47,5	46	46	45,5	46	°C

Once the drying unit is solved the pyrolysis process can be adjusted. According to the amount of the dried biomass the heat needed for the pyrolysis is known due to initial assumptions on the heat consumption of the process. Hence, given amount of the heat can be extracted from a fraction of flue gases leaving the boiler under the assumption that the stream is cooled down to 480 °C.

Pyrolysis heat flow through the evaporator unit model representing pyrolysis process is shown in the Table 3.8. According to initial assumptions the heat is dependent on the amount of the dried biomass.

Table 3.8 Heat flow to the fast pyrolysis process for the radiant furnace integrated case

Load	90	80	70	60	50	40	30	[%]
Heat flow to pyrolysis	1,6044	2,7078	3,9101	5,0527	4,1811	3,1605	2,2103	[MW]

The mass flow entering the turbine decreases with decreased partial load. This is because more steam is directed to the drying process. In result the mass flow and pressure of the steam extracted from the turbine decreases as well. At a certain point the extraction stream is cut-off and the pressure of the throttled steam from the dryer has to be adjusted. This fact is introducing yet another variable to be set by the user in order to achieve the equilibrium in the simulation model. Consequently in the partial loads of 70 % and lower the steam is no longer extracted from the turbine. The change in the cycle is shown in Figure 3.13, where the general unit modules arrangement and stream values for 70 % simulation case is shown.

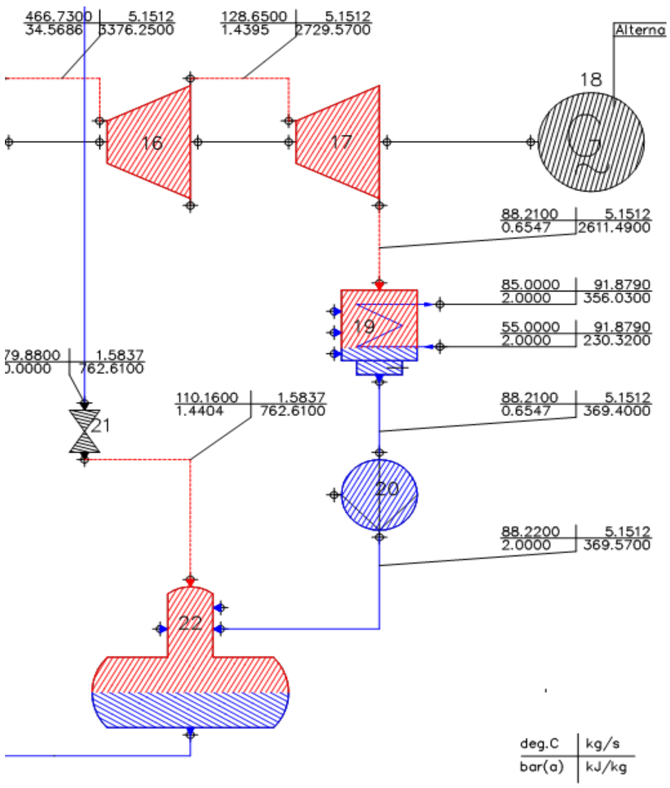


Figure 3.13 Feedwater tank input streams arrangement change

At this point as the partial load goes down, the pressure in the feedwater tank rise due to the increasing throttled pressure of the condensates from the dryer. This allows for maximization of the heat that can be used for drying and pyrolysis. At the same time there is a restriction of the feedwater tank design pressure of 2 bars. Therefore at a certain point the throttled pressure is set to this value. This occurred in the partial load of 50 % and onwards. For these loads the fuel input has to be gradually decreased. This action allows overcoming too high dryer condensate heat flow which would bring the feedwater tank beyond saturation state.

The lowest partial load is determined by the lowest possible fuel input. For the integrated case the lowest possible fuel input assumed for the cycle with radiant furnace is resulting in 30 % of the plant's heat capacity that is 4,95 MW of thermal power. Now, it is possible to develop the multiperiod model for this case. By applying the calculations mentioned in the assumptions chapter it is possible to derive the values presented in Table 3.9.

Table 3.9 Plant heat load levels and their duration for integration cases

DH Load [MW]	DH Load [%]	Duration [hours]
16,5	100	2266
14,85	90	633
13,2	80	633
11,55	70	633
9,9	60	633
8,25	50	633

For these the multiperiod load model can be drawn, in similar manner as it is in the base case. The curve is shown in Figure 3.14. The heat needed to be supplied by the back-up boiler is marked in red. The multiperiod model for the radiant furnace integrated case is thus the same as for the model deploying BFB developed by Kohl in the case with pyrolysis integration.

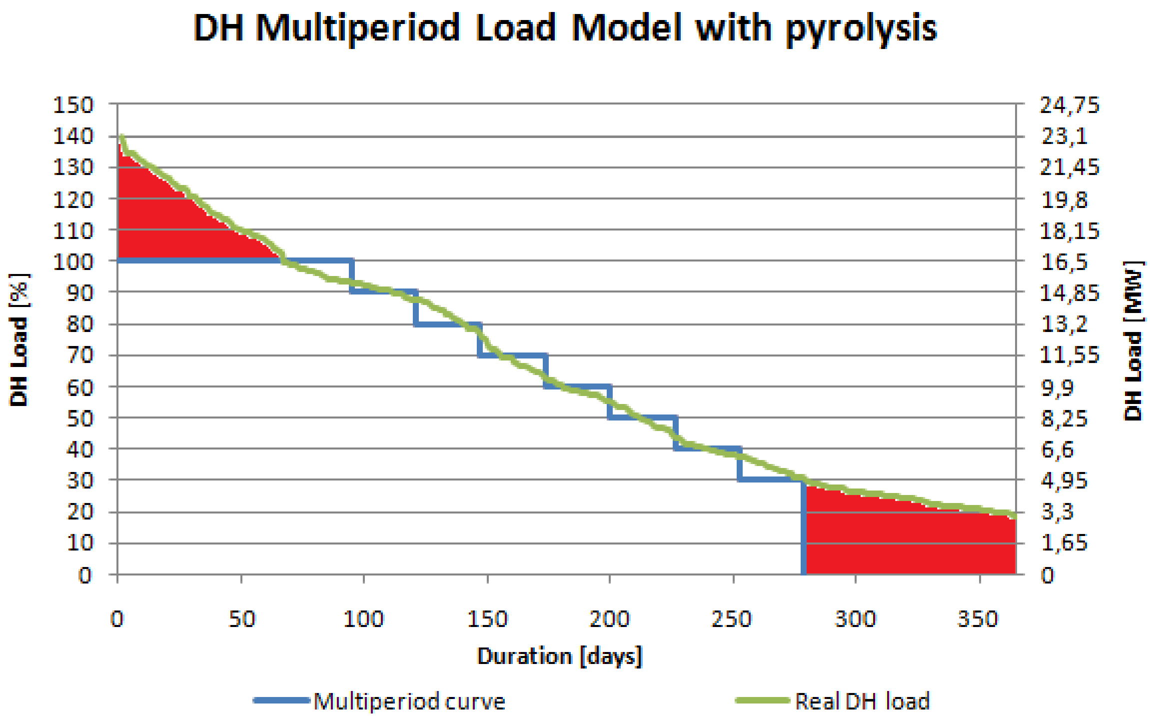


Figure 3.14 Heat duration curve and DH load multiperiod model for the integrated case with radiant furnace

3.2.3 Base case with Circulating Fluidized Bed Boiler

As it was mentioned in the assumption part earlier, the Circulating Fluidized Bed base case is the same simulation model as the Bubbling Fluidized Bed modeled by Kohl. The simulation model described in *3.1.3Power Cycle Simulation* served as a basis for creation of other models. The simulation procedure for the base case was similar as the procedure described in the radiant furnace base case. At part loads fuel input had to be decreased in order to match the decreased District Heating demand. In consequence of the lower steam parameters the electrical output of the plant had to decrease either. The lowest possible fuel load determined the lowest part load. The plant's lowest heat production level was 50 % of the plant thermal capacity. In consequence the multiperiod district heating load model is the same as it is shown in Figure 3.10 for the radiant furnace base case.

Summary of the main cycle characteristics for the base case including plant's operation time at given partial load is shown in Table 3.10.

Table 3.10 Summary data for the base case with BFB and CFB (Kohl et al. 2010)

Load	100	90	80	70	60	50	[%]
Time	2440	530	530	530	530	530	[h]
Fuel input	25,90	23,19	20,39	17,47	14,58	11,91	[MW]
Power	6,29	5,64	4,91	4,06	3,22	2,54	[MW]
District Heat	16,50	14,85	13,20	11,55	9,90	8,25	[MW]

From this model an integration option that represents Circulating Fluidized Bed has been developed.

3.2.4 Biomass Drying and Pyrolysis Integration with CFB Boiler

Power cycle simulation at design load

The Circulating Fluidized Bed integrated case is created with a Fluidized Bed unit model of the ProSim's module library. The configuration of the cycle is derived from the base case.

At the design point the biomass drying is integrated in the same way as the drying for the radiant furnace model. The pyrolysis process is represented by additional evaporator. The difference in the integration as compared to the BFB integrated case shown in Figure 3.15 is the placement of the evaporator numbered 19.

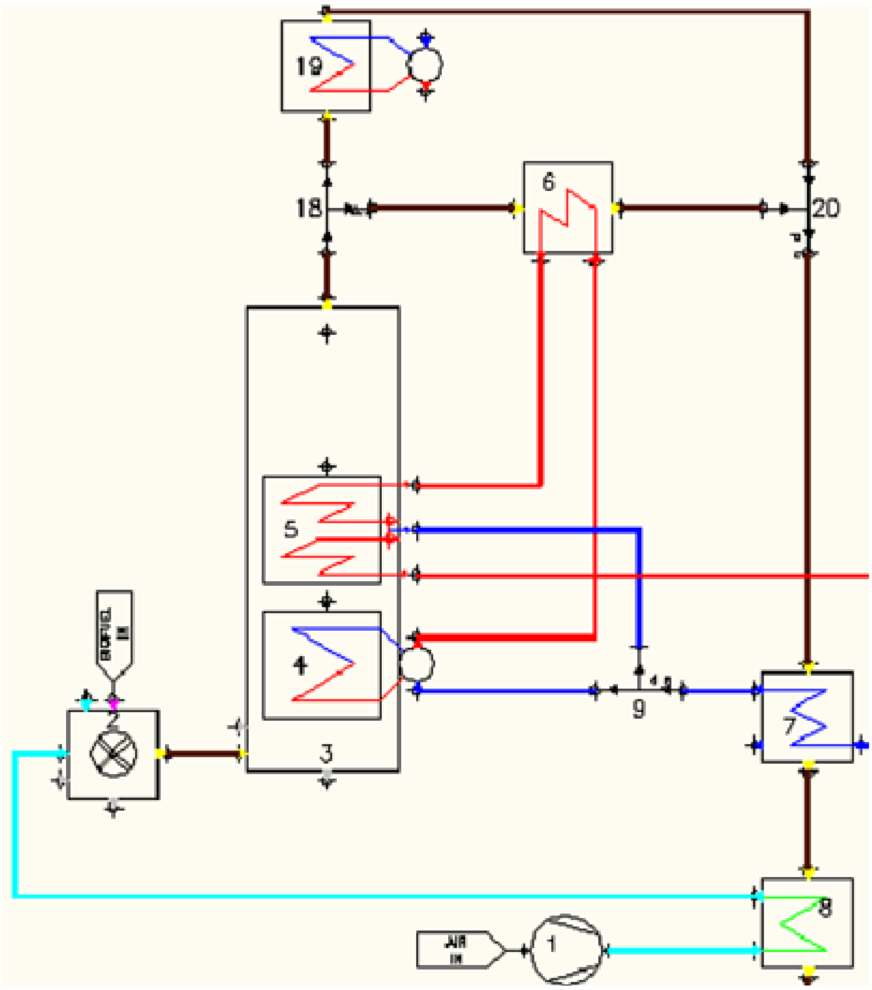


Figure 3.15 Fast pyrolysis unit module placement in the BFB integration case (Kohl et al. 2010)

The simulation model developed in this research is shown in Figure 3.16.

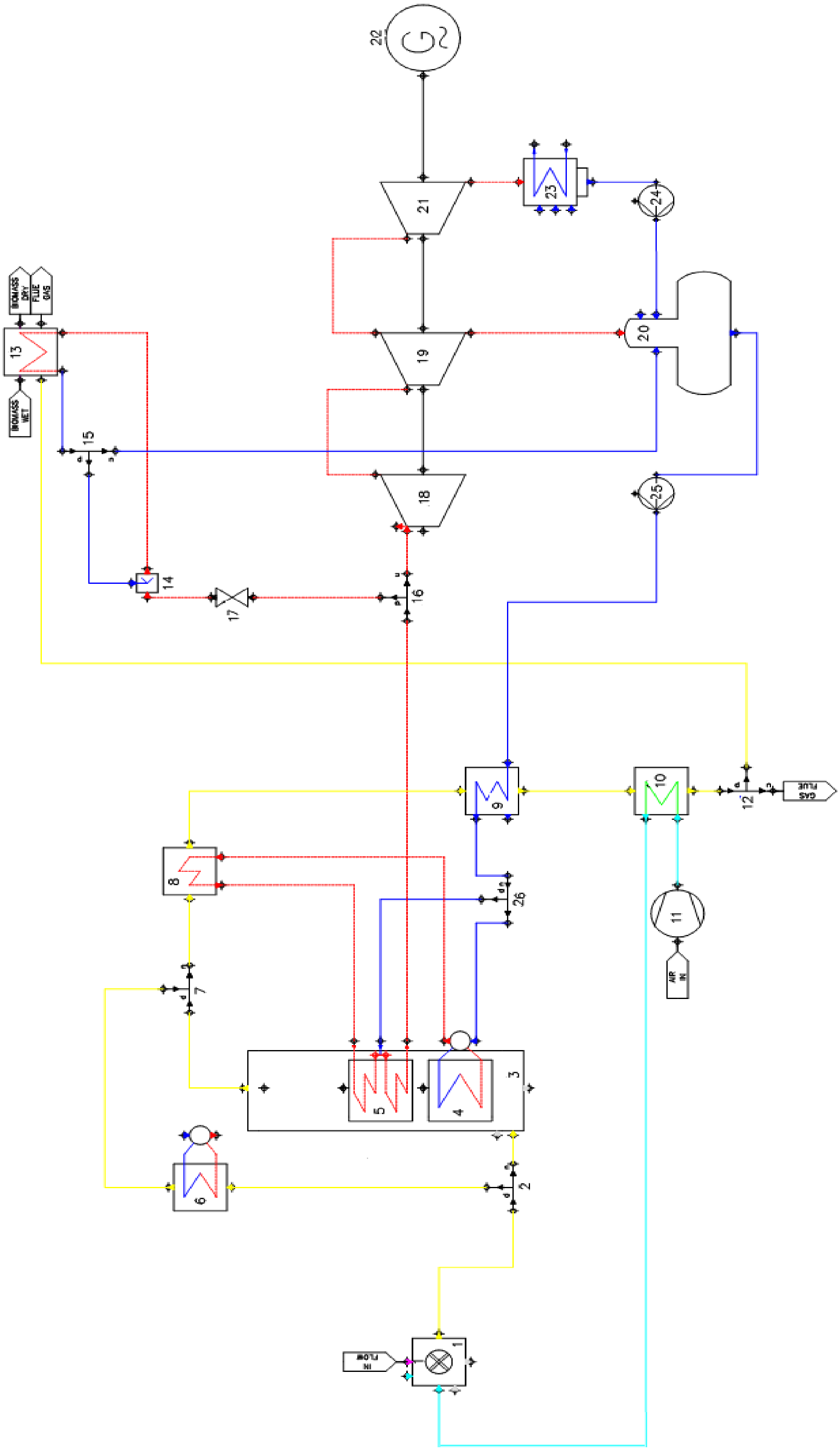


Figure 3.16 Integrated case simulation model with CFB boiler – power cycle

In order to represent the heat extraction from sand circulating within the boiler, flue gases stream representing the heat available within the boiler is split. ProSim calculates the boiler performance by dividing equally the available enthalpy among unit models introduced in the boiler. Therefore splitting the stream before it enters the boiler is the same as a new unit model would be introduced into the boiler (e.g. additional superheater), under the assumption that the amount of heat consumed by new unit in both cases is the same.

The splitting of the hot flue gases stream is done with the splitter unit model. This stream is cooled down by the evaporator unit to the same temperature set for the flue gases leaving the boiler that is 850 °C. Next, the stream is mixed back to the main flue gases stream using a mixer unit module. Then the whole flue gases are sent to the superheater unit model. Summary of the fluidized bed boiler unit module is shown in Table 3.11.

Table 3.11 Fluidized bed boiler unit module parameters

No.	Unit	Stream	Parameters
3	Fluidized bed	Flue gas from superheater 1	temperature 850 °C pressure 1 bar
		Flue gas from boiler	temperature 850 °C pressure 1 bar
		Flue gas in	pressure 1,05 bar
		Flue gas out	pressure 1,05 bar
		Ash in	pressure 1 bar
		Ash out	pressure 1 bar
		Average bed temperature	temperature 850 °C

Other cycle assumptions set are made in similar manner to the radiant furnace boiler integrated case, unless otherwise stated.

Power cycle simulation at part loads

The simulation of part loads is done in similar manner to the radiant furnace integrated case simulation. With the maximization of the pyrolysis products in mind the cycle is kept at full load when decreasing the heat production. This results in similar conditions for the feedwater tank pressure and the steam extraction from the medium-pressure turbine stage. Thus, the extraction is cut-off similarly at loads of 70 % and lower. The arrangement of the model units for this partial load is the same as for the radiant furnace boiler case.

A throttling valve sets the pressure of the condensates entering the tank to 2 bars. Similarly to the radiant furnace case, this pressure is maintained for the loads 50 % and lower.

The dryer simulation procedure used for this case is the same as for the integrated case with radiant furnace, described previously. Energy balance values allowing to match the losses of the dryer unit are presented in Table 3.12.

Table 3.12 Energy flows of input and output streams of the dryer at partial loads for Circulating Fluidized Bed integrated case

Load	90	80	70	60	50	40	30	[%]
Flue gases to the dryer	3210,86	3214,37	3210,86	3283,94	2868,58	2104,08	1407,69	[kJ/s]
Biomass to the dryer	100,69	174,51	253,61	325,80	318,51	246,83	176,76	
Steam to the dryer	1197,85	3123,94	5175,84	6979,76	7053,45	5634,24	4189,54	
Flue gases from the dryer	-2326,21	-2427,03	-2541,46	-2647,54	-2408,58	-1870,25	-1357,83	
Biomass from the dryer	-92,34	-165,23	-246,99	-324,27	-319,4	-247,52	-177,04	
Condensates from the dryer	-326,02	-850,23	-1408,69	-1899,66	-1919,72	-1533,46	-1140,25	

The dryers losses set to control the exhaust flue gases temperature are summarized in the Table 3.13.

Table 3.13 Dryer's losses and wet temperature at partial loads for Circulating Fluidized Bed integrated case

Load	90	80	70	60	50	40	30	[%]
Dryer losses	5	9	12,5	16	18	19	20	%
Wet temp.+	52	49,5	47,5	46	45,5	45	45,5	°C

In order to solve the evaporator representing the pyrolysis a certain amount of flue gases is allowed to flow through it. The mass flow of the gases is dependent on the heat used by the evaporator representing the fast pyrolysis process. This heat in turn is dependent on the amount of the biomass coming out of the dryer unit. Pyrolysis heat flow through the evaporator unit model is shown in Table 3.14.

Table 3.14 Heat flow to the fast pyrolysis process for the Circulating Fluidized Bed integrated case

Load	90	80	70	60	50	40	30	[%]
Heat flow to pyrolysis	1,4997	2,5993	3,7774	4,8527	4,744	3,6764	2,6328	[MW]

At the same time for partial loads the fuel input is decreased. The lowest partial load is 30 %, while the fuel input is reduced to 50 % compared to the maximum fuel load. Therefore the heat duration curve of the multiperiod DH load looks exactly the same as for the integrated cases with radiant furnace and Bubbling Fluidized Bed shown in Figure 3.14.

3.3 Environmental Performance Calculations

The goal and scope of this thesis treats the environmental evaluation of the developed simulation cases of the earlier chapters. In order to make this evaluation comparable with the previous studies on the BFB case integration this has to be done with the help of the EN standards. The energy-related standards used in Kohl's research draw a concept of the Primary Energy Factor and Carbon Dioxide coefficients. These are used in this thesis as a source to evaluate the environmental performance for both base and integrated cases developed in the research part. The following chapter presents the methodology used for environmental calculations.

3.3.1 Primary Energy Factor

For calculations of the Primary Energy Factors of the studied power plant cases the EN 15603 is used. This standard treats the energy performance of a building as a whole. According to the concept all energy carriers involved in the power plant generation process are retraced to their sources (Kohl et al. 2010). Then all energy needed to supply the final products of a power plant is aggregated to the total Primary Energy consumption. Therefore the nature of this approach applies holistic principles of life cycle assessment to an energy rating procedure (Kohl et al. 2010).

According to the general standard EN 15603 the total Primary Energy Factor is the sum of all primary energy inputs to the system divided by the useful energy delivered at the system boarder (Kohl et al. 2010; European Committee for Standardization 2007b). This can be expressed by the mathematical formula:

$$f_{P,dh} = \frac{E_{P,in}}{Q_{DH}} \tag{7}$$

where

$E_{P,in}$ is the primary energy input to the system;

Q_{DH} is the heat delivered at the border of the supplied system;

$f_{P,dh}$ is the Primary Energy Factor of the system in question.

In other words the calculations describe how much Primary Energy is used to give one unit of energy delivered by a studied system. For the Primary Energy Factor calculations of Combined Heat and Power systems and District Heating Networks more detailed information are given in EN 15316-4-5 standard.

In this study, following the assumptions made in Kohl's research the studied system comprises the power plants and the DHN with no losses in the network. As the cogeneration plant produces not only heat, but also electricity the Power Bonus method is applied. This can be used for all base cases with no pyrolysis integration. For better understanding of the approach the general energy balance shown in Figure 3.17 is drawn.

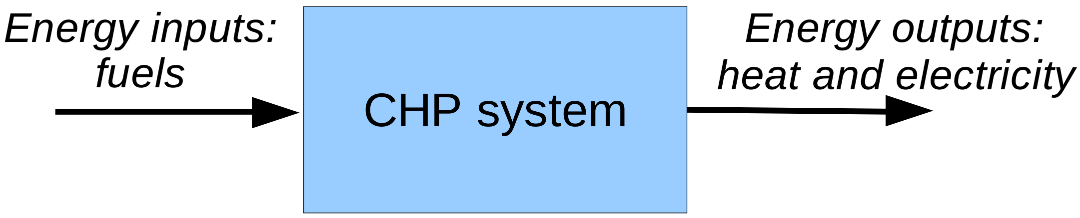


Figure 3.17 Inputs and outputs for environmental calculations – base case

Now, each component of the energy balance has its own Primary Energy Factor. Thus, the energy balance in terms of the Primary Energy can be expressed with following formulas:

$$\sum_i f_{F,i} \cdot E_{F,i} = f_{DH} \cdot Q_{DH} + f_{El} \cdot P \qquad (8)$$

where

$f_{F,i}$ is the Primary Energy Factor of the fuels used;

f_{DH} is the Primary Energy Factor of the system in question;

f_{El} is the Primary Energy Factor of the generated power;

$E_{F,i}$ is the chemical energy of the fuels used;

Q_{DH} is the heat generated by the system in question;

P is the electricity generated by the system in question.

According to the standard, in the power bonus method the Primary Energy Factor (PEF) of the electricity generated is defined as the PEF of the electricity that is thought to be replaced by the studied system. Thus, following Kohl to make the results of the previous research comparable with this thesis, the average power generation efficiency of Finland is used; that is $f_{El} = 3{,}11$.

Solving the equation given above it is possible to determine the Primary Energy Factor of the studied CHP system:

$$f_{DH} = \frac{\sum_i f_{F,i} \cdot E_{F,i} - f_{El} \cdot P}{Q_{DH}} \qquad (9)$$

For the integrated cases additionally to heat and electricity also pyrolysis-product is generated. Therefore this method have to be further modified in order to include the energy of the pyrolysis process. This concept is shown in Figure 3.18.

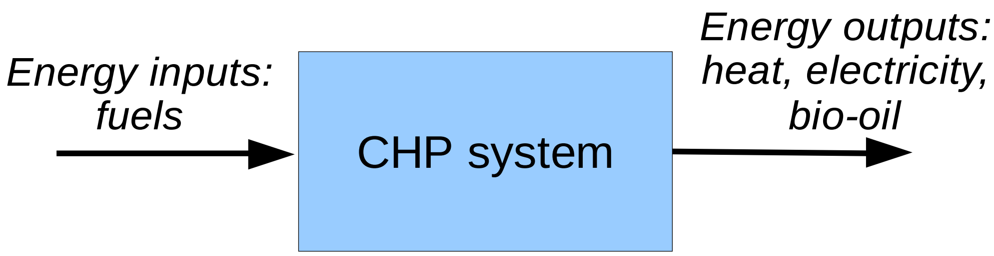


Figure 3.18 Inputs and outputs for environmental calculations – integrated case

Thus following Kohl the modification can be expressed as:

$$f_{DH} = \frac{\sum_i f_{F,i} \cdot E_{F,i} - f_{El} \cdot P - E_{pyro} \cdot f_{pyro}}{Q_{DH}} \qquad (10)$$

where

f_{pyro} is the Primary Energy Factor of the pyrolysis product;

E_{pyro} is the chemical energy of the pyrolysis product.

An important factor in the environmental calculation are the heat-only boiler use for the heat needed to be delivered by the system and not produced by the CHP plant. This situation is expressed in the above described formulas in the fuel input. For the base cases the Primary Energy calculations have to include biomass that is burned in the boiler and oil burned in the heat-only boilers - see Figure 3.19. PEF of the biomass fuel is taken from the EN15603 standard and it is set to f_{BM} = 1,09 same as in Kohl's study. Similarly, for the heavy fuel oil there is a value of f_{Oil} = 1,35 used.

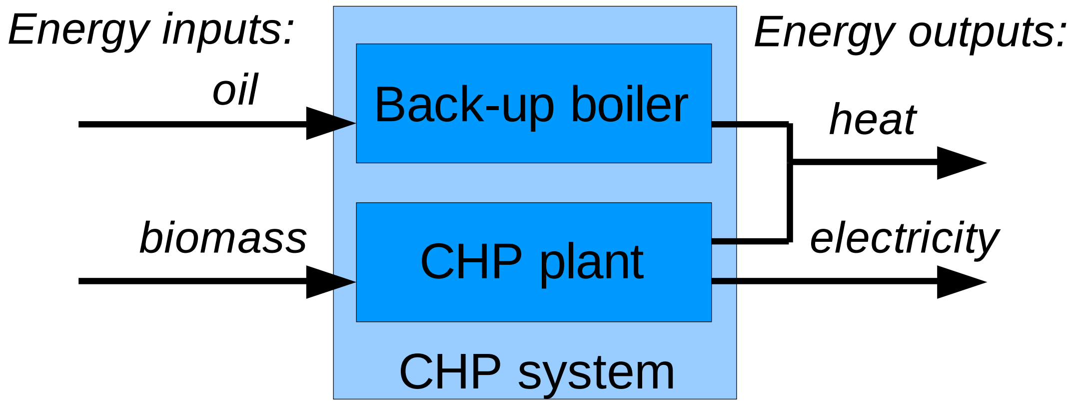


Figure 3.19 Inputs and outputs for environmental calculations – final base case

For the cases with pyrolysis integrated the power plant produces also bio-gases. These gases can be co-fired in the system, thus allowing to substract their energy content from the overall energy input. Therefore, the fuels used in the integrated cases are the biomass burned in the boiler, the energy content of biomass that is fed to the dryer and the heavy oil energy content. Thus, more detailed energy balance of integrated cases for the environmental calculations can be drawn as is shown in Figure 3.20.

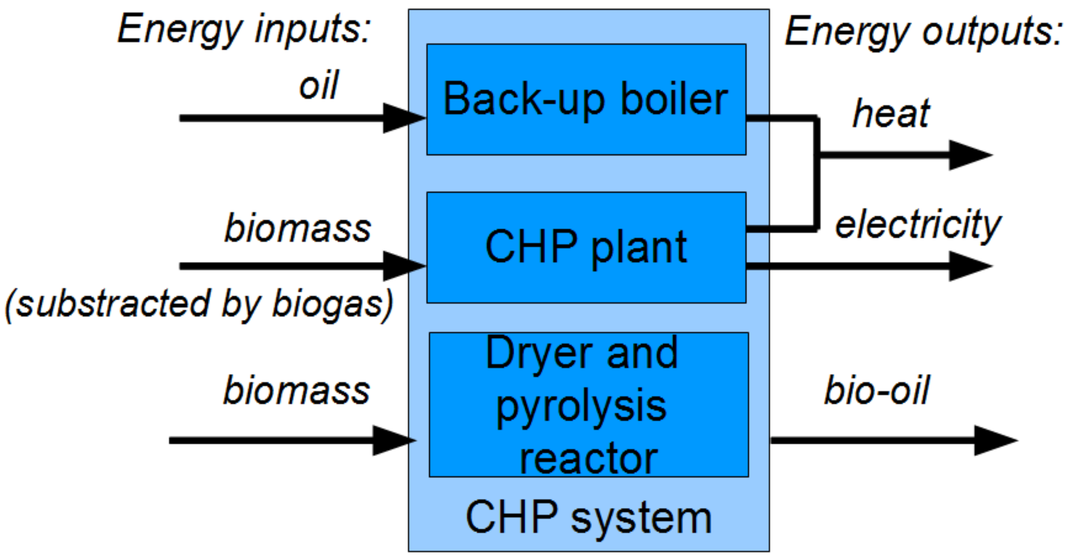


Figure 3.20 Inputs and outputs for environmental calculations – final integrated case

For integration cases another variation of the Primary Energy Factor calculation can be done by investigation a scenario where the produced bio-oil is burned in the heat-only boilers instead of the heavy oil. This allows seeing how the studied system would perform when a part of the in-site derived oil is used and not upgraded further. This idea based on the initial assumptions and previously mentioned energy streams of the CHP system is described in Figure 3.21.

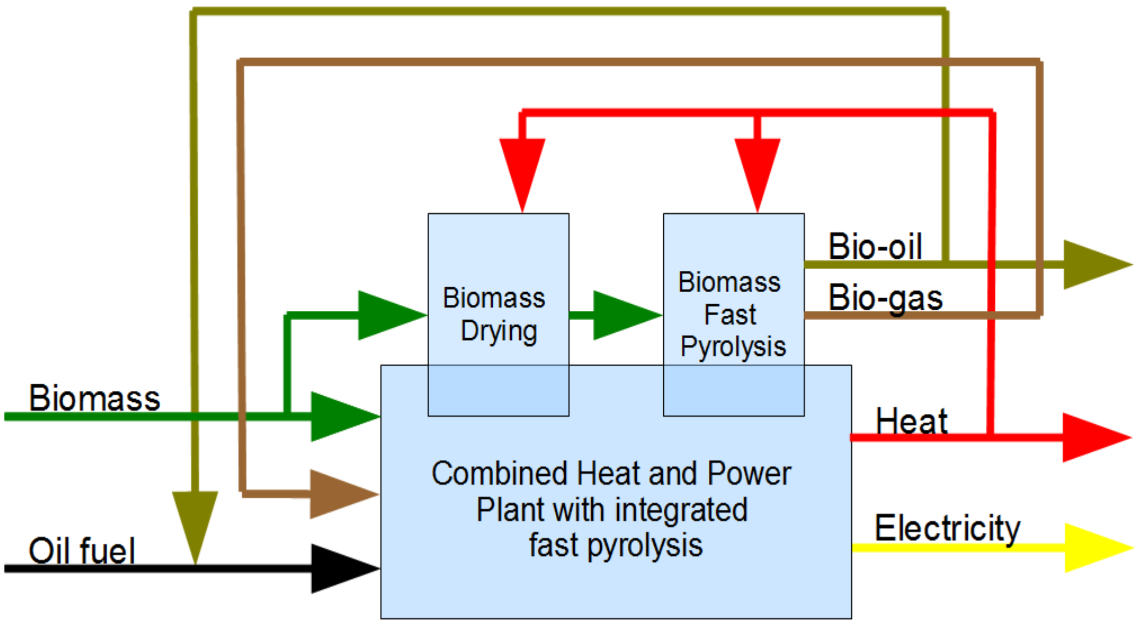


Figure 3.21 Energy streams of the studied integration cases

For these calculations the Primary Energy Factor of the pyrolysis oil is applied f_{pyro} = 1,28. This value is derived from Kohl's study. It has been calculated assuming that the pyrolysis is done in a stand-alone flue gas dryer with energy consumption of 3300 kJ/kg water evaporated and heat of pyrolysis of 1,87 kJ/kg (Kohl et al. 2010).

Implementing all that as described above, a more detailed equation can be applied for the Primary Energy Factor of the studied system. For the cases without the integration:

$$f_{DH} = \frac{Q_{BM} \cdot f_{BM} + Q_{Oil} \cdot f_{Oil} - P \cdot f_{El}}{Q_{DH}} \tag{11}$$

where

f_{BM} is the Primary Energy Factor of the biomass burned;

f_{Oil} is the Primary Energy Factor of heavy oil used in back-up boilers;

Q_{BM} is the chemical energy of the biomass burned;

Q_{Oil} is the chemical energy of the heavy oil burned.

Furthermore, for the integrated cases the final equation is as follows:

$$f_{DH} = \frac{(Q_{BM} + Q_{WetBM} - Q_{Gas}) \cdot f_{BM} + Q_{Oil} \cdot f_{Oil} - (P \cdot f_{El} + E_{Pyro} \cdot f_{Pyro})}{Q_{DH}} \tag{12}$$

where

Q_{WetBM} is the chemical energy of the biomass fed for drying;

Q_{Gas} is the chemical energy of the gases produced by pyrolysis process.

For integrated cases when the pyrolysis oil is assumed to replace the heavy oil the energy contained in the heavy oil burnt has to be subtracted from the energy contained in the bio-oil. Therefore, the equation changes to:

$$f_{DH} = \frac{(Q_{BM} + Q_{WetBM} - Q_{Gas}) \cdot f_{BM} - (P \cdot f_{El} + (E_{Pyro} - Q_{Oil}) \cdot f_{Pyro})}{Q_{DH}} \tag{13}$$

Summary of the Primary Energy Factors used in the environmental performance calculations is shown in the Table 3.15.

Table 3.15 Primary Energy Factors used for environmental performance calculation

PEF	Value
f_{BM}	1,09
f_{Oil}	1,35
f_{El}	3,11
f_{Pyro}	1,28

Based on the annual operation for all studied CHP cases (including prolonged operation hours for the integrated cases) energy inputs and outputs of the CHP system can be calculated. Then, by applying the PEFs from above to final equations the Primary Energy Factors of the DHN is obtained.

The EN standards ask for more detailed analysis that may include the whole energy chain: transportation, DHN losses, transmission losses etc. For the goal and scope of this study those factors has not been implemented to for two reasons. Firstly, they would differ from assumptions of the BFB cases. Secondly, these factors would also not influence the relative result between studied cases since they would have been applied for all of them - integrated and separated production of pyrolysis oil (Kohl et al. 2010).

3.3.2 CO_2 Emission Coefficient

The Carbon Dioxide rating concept applied in this research is derived from the EN 15603. The approach and calculation steps are similar to those presented for the Primary Energy Factors. In this method CO_2 coefficients are used. These coefficients quantify the total amount of fossil fuel derived carbon dioxide that is emitted to the atmosphere for each unit of delivered energy by the studied system (Kohl et al. 2010). To simplify the calculations other Greenhouse Gases are not included in the study. Similarly to the logic for the Primary Energy Factors calculations the system boundary includes studied CHP plants and DH network. Again the Power Bonus method can be applied. Thus, general expression for calculations of the CO_2 coefficient of the studied base case systems can be expressed as:

$$c_{CO_2,DH} = \frac{\sum_i E_{F,i} \cdot c_{CO_2,F,i} - P \cdot c_{CO_2,El}}{Q_{DH}} \qquad (14)$$

where

$E_{F,i}$ is the chemical energy of the fuels used;

Q_{DH} is the heat generated by the system in question;

P is the electricity generated by the system in question;

$c_{CO_2,DH}$ is the carbon dioxide coefficient of the system in question;

$c_{CO_2,F,i}$ is the carbon dioxide coefficient of the fuels;

$c_{CO_2,El}$ is the carbon dioxide coefficient of the electricity.

Modifying the above equation by addition of the “Fuel Bonus” representing the pyrolysis slurry yield in the integrated cases results in the following:

$$c_{CO_2,DH} = \frac{\sum_i E_{F,i} \cdot c_{CO_2,F,i} - P \cdot c_{CO_2,El} - E_{Pyro} \cdot c_{CO_2,Pyro}}{Q_{DH}} \qquad (15)$$

where

E_{Pyro} is the chemical energy of the pyrolysis slurry;

$c_{CO_2,Pyro}$ is the carbon dioxide coefficient of the pyrolysis slurry.

These general equations can be further expanded adding more details concerning fuels used in the simulation cases. Again, the use of the heavy oil in heat only boilers can be included in the equation for the base case resulting in:

$$c_{CO_2,DH} = \frac{Q_{BM} \cdot c_{CO_2,BM} + Q_{Oil} \cdot c_{CO_2,Oil} - P \cdot c_{CO_2,El}}{Q_{DH}} \quad (16)$$

where

Q_{BM} is the chemical energy of the biomass burned;

Q_{Oil} is the chemical energy of the heavy oil burned;

$c_{CO_2,BM}$ is the carbon dioxide coefficient for the biomass burned;

$c_{CO_2,Oil}$ is the carbon dioxide coefficient for the heavy oil burned.

Consequently in the integrated cases yielding the slurry and gas:

$$c_{CO_2,DH} = \frac{(Q_{BM} + Q_{WetBM} - Q_{Gas}) \cdot c_{CO_2,BM} + Q_{Oil} \cdot c_{CO_2,Oil} - (P \cdot c_{CO_2,El} + E_{Pyro} \cdot c_{CO_2,Pyro})}{Q_{DH}} \quad (17)$$

where

Q_{WetBM} is the chemical energy of the biomass fed for drying;

Q_{Gas} is the chemical energy of the gases produced by pyrolysis process.

To investigate the scenario when the pyrolysis oil is assumed to replace the heavy oil used in the back-up boilers:

$$c_{CO_2,DH} = \frac{(Q_{BM} + Q_{WetBM} - Q_{Gas}) \cdot c_{CO_2,BM} - (P \cdot c_{CO_2,El} + (E_{Pyro} - Q_{Oil}) \cdot c_{CO_2,Pyro})}{Q_{DH}} \quad (18)$$

Summary of the coefficient needed to perform the calculation is shown in the table below.

Table 3.16 Carbon Dioxide coefficients used for environmental performance calculation

CO_2 coefficient	Value [kg/MWh]
$c_{CO_2,BM}$	14
$c_{CO_2,Oil}$	330
$c_{CO_2,El}$	270
$c_{CO_2,Pyro}$	14

The coefficient value for the electricity is, as it was in the case of the PEF, taken from national standard - CO_2 coefficient for electricity mix of Finland. Coefficients for the heavy oil and biomass are derived from the EN standard. The pyrolysis slurry CO_2 coefficient is assumed to be equal to the one used in the Kohl's study.

3.4 Concept Implementation in Poland

Poland as a member of the European Union has adopted targets to increase the share of renewable energy to 7,5 % in 2010 (Surma 2009) - already achieved - and 15,5 % in 2020 (Polish Ministry of Economy 2010). This fact has important implications concerning energy sector in the country (Nilsson et al. 2004). Energy Policy for Poland until 2030 sets main areas of improvement (Surma 2009):

- energy efficiency improvement;
- energy security;
- diversification;
- Renewable Energy Sources development;
- increasing market competition;
- minimizing environmental effects.

Cogeneration may to play an important role in overall increase in renewable energy production. Moreover, there is a target to double electricity production in cogeneration until 2030. In Poland, huge production capacity located in heat-only boilers exist, around 16,15 % of the total CHP capacity, as shown in Figure 3.22. Thus, increase of CHP production is possible not only through building new installed capacity, but retrofitting existing heating plants as well.

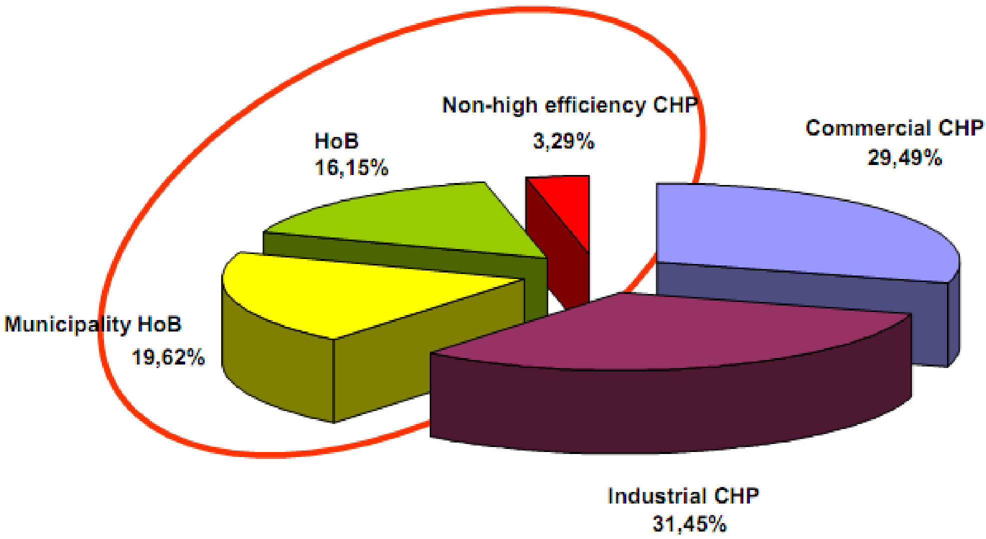


Figure 3.22 Heat production capacity in Poland (Surma 2009)

Commercial CHP consists of 190 boilers with capacity of 18 000 MW and 140 turbines with capacity of 5 300 MW (Surma 2009). Electricity generation from CHP plays a minor, but steadily increasing role in the country. Its share in total electricity production can be seen in Figure 3.23.

Poland has large natural reserves of hard coal. This fuel is therefore the main fuel for CHP and DH plants in Poland. Whereas for small heat production more and more gas, oil and biomass is used (Lensu & Alakangas 2004).

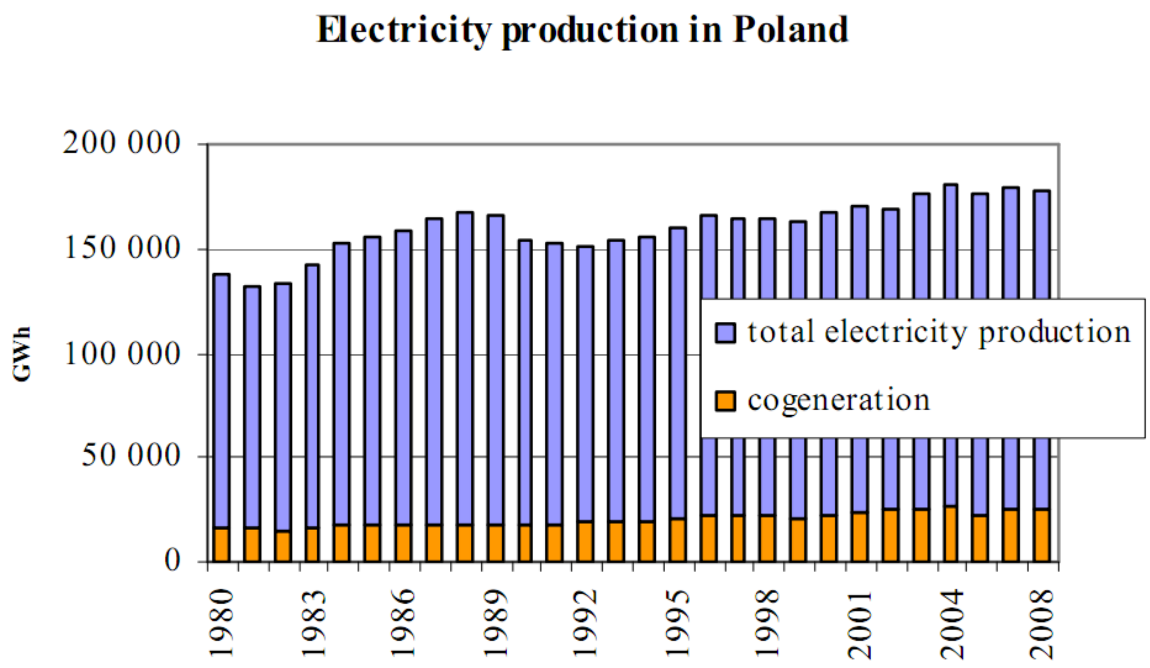


Figure 3.23 Share of cogeneration in electricity production in Poland (Surma 2009)

Poland does not have significant renewable energy resources. As for a relatively flat terrain country the hydro potential is small. The wind power potential is also not favorable unless the off-shore potential is developed on a very large scale (Guła, Mirkowski & Wolszczak 2010). There is a very dynamic development of wind energy observed in Poland, but this can be probably limited in the future due to the grid infrastructure restrictions (Płachecki, P. 2010). If photovoltaics and other emerging technologies such as fuel cells put aside, the only renewable energy source that is promising in the short and medium term is biomass. Especially when one consider it to partly replace coal (Guła, Mirkowski & Wolszczak 2010).

The use of biomass is supported by policies and is expected to grow in the future, as shown in the Figure 3.24. With relatively high long-term bio-energy resource potential in forests (450 PJ of energy stored annually), small- and medium-scale plants for heat and CHP production are seen to be the most promising applications (Nilsson et al. 2004). Some studies show that it might be economically more effective to support the use of biomass for space heating, primarily in rural areas, than to support energy companies through “green certificates” for renewable production (Guła, Mirkowski & Wolszczak 2010).

Another aspect of possible implementation of the pyrolysis into CHP plants in Poland is polish policy concerning biofuels. The integration products include pyrolysis oil that can serve for upgrading into transportation fuels. This might contribute to the future’s fulfillment in Polish bio-fuels share targets in transport fuel market. The targets for the next few years are as follows (Bartoszewicz-Burczy 2009):

- 6,20 % for the year 2011;
- 6,65 % for the year 2012;
- 7,10 % for the year 2013;
- 7,55 % for the year 2014.

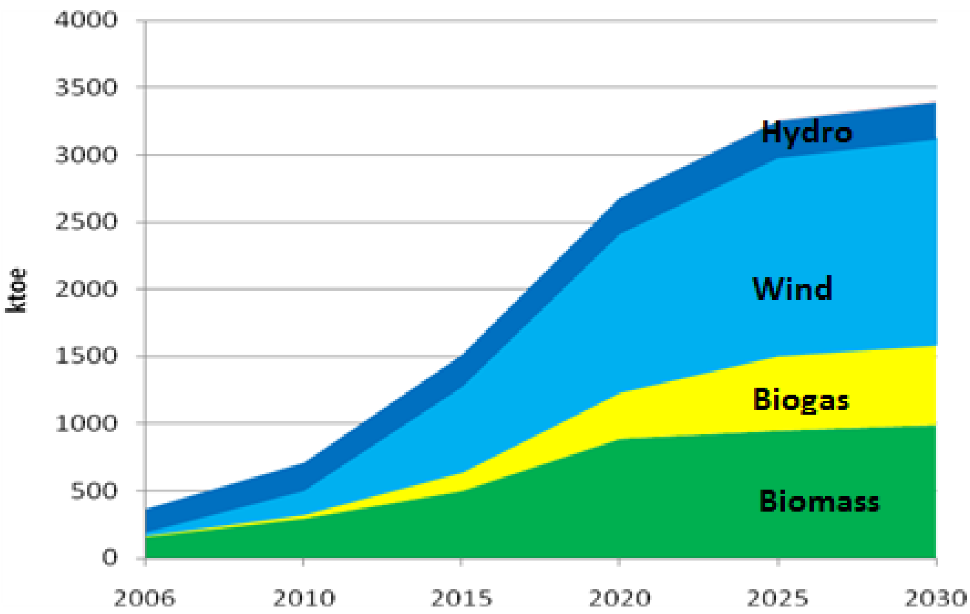


Figure 3.24 Expected growth in biomass utilization in Poland (Guła, Mirkowski & Wolszczak 2010)

The scope of DH systems in Poland is local, but they play an important role in the national economy (Lensu & Alakangas 2004). Therefore special attention has to be paid to policies and technology development in the field. Unfortunately, there are many barriers for implementation of new CHP capacities. Problem of founding and preparation of projects are seen as the most crucial (Lensu & Alakangas 2004). Moreover, very slow decision-making in the case of biomass projects worsen the situation.

In spite of the barriers, there are biomass-based CHP systems in Poland suitable for potential integration with biomass drying and subsequent fast pyrolysis. The integration concept in Poland might be related to two ways of biomass utilization, widely used in Poland:

- biomass combustion in biomass-only systems;
- biomass combustion by co-firing with other fuels.

One of the examples might be a CHP plant in Białystok. There, a Bubbling Fluidized Bed technology is used for biomass combustion. The thermal output of the boiler is 100 MW (Elektrociepłownia Białystok 2011). Another aspect of the potential integration is in the biomass-cofiring installations. An example of this type of the system is a CHP plant in Żerań owned by Vattenfall. Two fluidized beds are used there (Vattenfall 2011).

To sum up, in Poland there is a need of implementation of new CHP installations or retrofitting existing ones. Especially for biomass based projects, due to both high biomass potential and EU-related renewable generation targets. This study can contribute to finding new possibilities and investigation of new paths of modernization for Polish CHP production market. By fast pyrolysis integration CHP plants would get a valuable bio-oil product that could be used in upgrading processes and then further to meet targets related to the total share of bio-fuels in transportation in Poland.

3.5 Results and Discussion

The following chapter presents the results of the simulation models described in the previous section. The chapter discusses the simulations' and environmental calculations results. The discussion order starts with the radiant furnace cases and goes through the circulating fluidized bed cases to arrive at the comparison of these two with the bubbling fluidized bed cases results.

3.5.1 Simulation Results

Operation parameters of the radiant furnace simulations

The simulation of design loads and partial loads gives detailed information on the power plant performance. For the radiant furnace base case (without drying and pyrolysis integration) simulation data derived from the software is shown in Table 3.17 below.

Table 3.17 Radiant furnace base case – multiperiod model results

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Fuel input	[MW]	26,15	23,30	20,39	17,39	14,45	11,75	-	-
Power	[MW]	6,28	5,65	4,92	4,08	3,24	2,55	-	-
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	-	-

The operation time data is calculated using the multiperiod model described earlier. Full load is the level at which the plant is operating for the longest period. The maximum fuel input at this load is resulting in the highest electrical and heat output. The fuel input is the biomass fed to the boiler. Gradually, when the fuel input is decreased in order to match the decreasing heat demand the power output is decreasing as well. This is due to the lower steam parameters, lower mass flow rate and also less favorable steam turbine efficiency that is going down along the efficiency curve for decreasing steam parameters. Total amount of operation days for the base case plant with radiant furnace is 212. The total annual fuel input amounts to 110 GWh. Electrical power produced exceeds 26 GWh and heat supplied to the network corresponds to nearly 71 GWh. Short summary of the most important characteristics for the base case is shown in Table 3.18.

Table 3.18 Radiant furnace base case - annual values of the multiperiod model results

CHP DH Load	Total	
Time	212	[days]
Fuel input	110,05	[GWh]
Power	26,16	[GWh]
District Heat	70,87	[GWh]

Based on the cycle parameters ProSim gives basic data concerning the CHP plant. Electrical efficiency and fuel utilization factor for the base case are presented in Table 3.19.

Table 3.19 Radiant furnace base case – cycle ratios at partial loads

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Electrical efficiency		0,24	0,24	0,24	0,23	0,22	0,22	-	-
Fuel utilization factor		0,87	0,88	0,89	0,90	0,91	0,92	-	-

Electrical efficiency is slowly decreasing in partial loads from 24 to 22 % due to the less favorable steam entering the turbine (due to turbine efficiency curve). The fuel utilization factor is the total amount of energy output divided by the total energy contained in input fuels. The factor can be considered as plant's overall efficiency and is named following the notation used in ProSim. The fuel utilization factor is increasing in partial loads from 87 to 92 %. This might be related to the fact that the fuel input decreases slower than the power and heat output at partial loads. Less and less water is sprayed on the live steam due to the lower, near desired live steam temperature after the superheater. Moreover, flue gas temperature drop decreases heat losses.

The biomass drying and pyrolysis integration results in the prolonged operation hours, as discussed earlier. The plant is operating at loads 40 and 30 % which corresponds to 6,60 and 4,95 MW respectively. This fact and the integration change the plant's annual performance characteristics. Table 3.20 shows the results of the multiperiod model.

Table 3.20 Radiant furnace integrated case - multiperiod model results

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Total fuel input	[MW]	26,15	37,31	44,98	53,34	61,29	50,54	38,45	27,12
Power	[MW]	6,28	5,59	4,78	3,76	2,84	2,14	1,50	0,91
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	6,60	4,95
Pyrolysis slurry	[MW]	-	12,87	21,73	31,38	40,54	33,55	25,36	17,74

In consequence the full load operation period decreased. The fuel input now comprises of the biomass burned in the boiler and biomass dried and subsequently pyrolysed. Therefore, the fuel input is increasing with decreasing thermal load, down to 60 %. The reason for it is that the fuel input to the boiler is kept at 100 % for partial loads at 60 % and higher. From this load the fuel input is decreasing, because the boiler feed is gradually decreased. It is decreased in order to lower steam/water mixture parameters and thus prevent dryer condensate heat flow from bringing the feedwater beyond saturation state. As steam, before it enters the turbine, is extracted for drying, the electrical output gradually decreases with decreasing partial loads. The pyrolysis product yield is increasing with decreasing partial loads for which the fuel fed to the boiler is kept at constant maximum level. For 50 % of the thermal capacity and lower, the pyrolysis yield is decreasing with decreasing fuel feed and steam parameters.

Table 3.21 Radiant furnace integrated case - annual values of the multiperiod model results

CHP DH Load	Total	
Time	279	[days]
Total fuel input	257,34	[GWh]
Power	27,86	[GWh]
District Heat	81,26	[GWh]
Pyrolysis slurry	115,91	[GWh]

The annual performance characteristics are listed in Table 3.21. Total operation time reaches 279 days. The fuel input amounts to 257 GWh. This includes biomass burnt in the boiler and also the biomass dried and subsequently pyrolysed. The heat delivered to the network is around 81 GWh. The pyrolysis slurry yield is equivalent to 116 GWh.

Table 3.22 Radiant furnace integrated case – fuel utilization factor at partial loads

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Fuel utilization factor		0,87	0,89	0,88	0,88	0,87	0,87	0,87	0,87

Electrical efficiency for the integrated cases is problematic to evaluate due to the fact that the fuel input comprises not only the biomass burnt in the boiler. This needs further evaluation and is not included in the results for the integrated cases.

The fuel utilization factor for the integration cases takes the pyrolysis slurry into account. In partial loads the factor is increasing to 88% with lower loads until the 60 % of thermal capacity point is reached. From this level the fuel efficiency of the plant is stable and equal to the initial value of 87 %. The initial increase and further decrease in the fuel utilization factor might be related to the turbine efficiency curve and its decrease for lower than design loads. Some other inefficiency related to - for example fixed heat exchange areas designed for maximum load - might influence the factor as well.

Operation parameters of the Circulating Fluidized Bed simulations

The results of the base case for both Fluidized Beds were presented earlier in *3.2.3 Base case with Circulating Fluidized Bed Boiler*. This case is determined by the fuel fed to the boiler, similarly as in the base case for the radiant furnace. The thermal output is depended on the fuel input, the lower the input the lower the heat supplied to the District Heating network. Additionally, the decreasing fuel input lowers the steam parameters resulting in decreased electrical output.

For this simulation the total operation time according to the multiperiod model is 212 days. Total fuel input amounts to nearly 110 GWh. Total electrical production reaches 26 GWh and heat delivered to the network only by the CHP plant is nearly 71 GWh. The summary of the above mentioned data is presented in Table 3.23.

Table 3.23 BFB and CFB base case - annual values of the multiperiod model results

CHP DH Load	Total	
Time	212	[days]
Fuel input	109,56	[GWh]
Power	26,13	[GWh]
District Heat	70,85	[GWh]

The plant's efficiency is increasing successively from 88 to 91 % - as shown in Table 3.24 – due to the same reasons as explained earlier for the base case with radiant furnace boiler.

Table 3.24 BFB and CFB base case – fuel utilization factor at partial loads

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Fuel utilization factor		0,88	0,88	0,89	0,89	0,90	0,91	-	-

The integration of the drying and pyrolysis in CHP plant with Circulating Fluidized Bed delivers similar characteristics as in the radiant furnace case with integration. The simulation give parameters listed in Table 3.25.

Table 3.25 Circulating Fluidized Bed integrated case - multiperiod model results

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Total fuel input	[MW]	25,90	36,33	43,98	52,17	59,65	56,15	43,66	31,43
Power	[MW]	6,29	5,60	4,79	3,82	3,06	2,42	1,81	1,24
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	6,60	4,95
Pyrolysis slurry	[MW]	-	12,03	20,86	30,31	38,94	38,07	29,50	21,13

Also here, the multiperiod model is extending the operation hours of the plant. Lower partial loads of 40 and 30 % are possible. The total fuel input to the model increases with decreasing thermal load, down until the biomass fed to the boiler is decreased. Then, the fuel input decreases with decreasing partial loads with having a maximum at 60 % load level being the tip point. Electrical power is decreasing gradually with partial loads. Again, the same as it is in the integrated case for the radiant furnace, the pyrolysis slurry yield is increasing while the fuel input to the boiler is kept at the constant level. Then, for lower partial loads the pyrolysis produce less bio-oil and less char. The total annual CHP outputs are presented in Table 3.26.

Table 3.26 Circulating Fluidized Bed integrated case - annual values of the multiperiod model results

CHP DH Load	Total	
Time	279	[days]
Total fuel input	263,33	[GWh]
Power	28,64	[GWh]
District Heat	81,26	[GWh]
Pyrolysis slurry	120,76	[GWh]

The total operation time is equal to the radiant furnace and BFB integrated cases. The total energy content of fuels used exceeds 263 GWh supplying around 29 and 81 GWh of the electrical and thermal power, respectively. The pyrolysis slurry energy content is calculated to 121 GWh.

In this integrated case the fuel efficiency is following the path of the integrated case for the radiant furnace. Variations of 1 % - in both directions can be observed due to the same factors as in the radiant furnace boiler simulation results. The summary of the ratios is shown in Table 3.27.

Table 3.27 Circulating Fluidized Bed integrated case – fuel utilization factor at partial loads

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Fuel utilization factor		0,88	0,89	0,88	0,88	0,87	0,87	0,87	0,87

With details described above, comparison with Bubbling Fluidized Bed integrated case developed by Kohl can be made.

Comparison of simulated cases and Bubbling Fluidized Bed case

The results of the integration simulation for the BFB case follow the general path previously described for other integration cases. Key results are shown in the table below.

Table 3.28 Bubbling Fluidized Bed integrated case – multiperiod model results (Kohl et al. 2010)

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Time	[h]	2266	633	633	633	633	633	633	633
Total fuel input	[MW]	25,90	36,49	44,24	52,42	60,21	50,97	39,56	28,88
Power	[MW]	6,29	5,54	4,69	3,71	2,88	2,27	1,71	1,18
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	6,60	4,95
Pyrolysis slurry	[MW]	-	12,21	21,16	30,60	39,58	33,79	26,11	19,00

The summary data for the annual power plant performance are presented in Table 3.29. The total annual fuel input amounts to 257 GWh. Power and heat production is around 28 and 81 GWh, respectively. Pyrolysis slurry yield is calculated to 115 GWh.

Table 3.29 Bubbling Fluidized Bed integrated case – annual values of the multiperiod model results (Kohl et al. 2010)

CHP DH Load	Total	
Time	279	[days]
Total fuel input	256,62	[GWh]
Power	28,17	[GWh]
District Heat	81,26	[GWh]
Pyrolysis slurry	115,46	[GWh]

The BFB case results show similarity to the other integrated cases explained previously. The fuel utilization factor for different loads is presented in Table 3.30.

Table 3.30 Bubbling Fluidized Bed integrated case – fuel utilization factor at partial loads

CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Fuel utilization factor		0,88	0,89	0,88	0,87	0,87	0,87	0,87	0,87

Integration of the biomass drying and pyrolysis for all cases studied resulted in prolonged operating hours of the power plant. The full load total operating hours have decreased in the integrated cases by nearly 7 % from 2440 to 2266 hours per annum due to the initial assumptions on the multiperiod model. In contrast, partial loads have been extended by 20 % in the model from 530 to 633 hours. Lower partial loads not possible to reach without integration are now producing additional electricity, heat and pyrolysis slurry. Total amount of operating days is extended with integration as can be seen in Figure 3.25. Additional 67 days are estimated. This fact has important implications for the plant's economics. The plant gains additional electricity and heat to sell. Less money on operation and maintenance of the plant during shut-off period are spent. Moreover, the pyrolysis oil can be sold or used to replace heavy oil in the heat-only boilers.

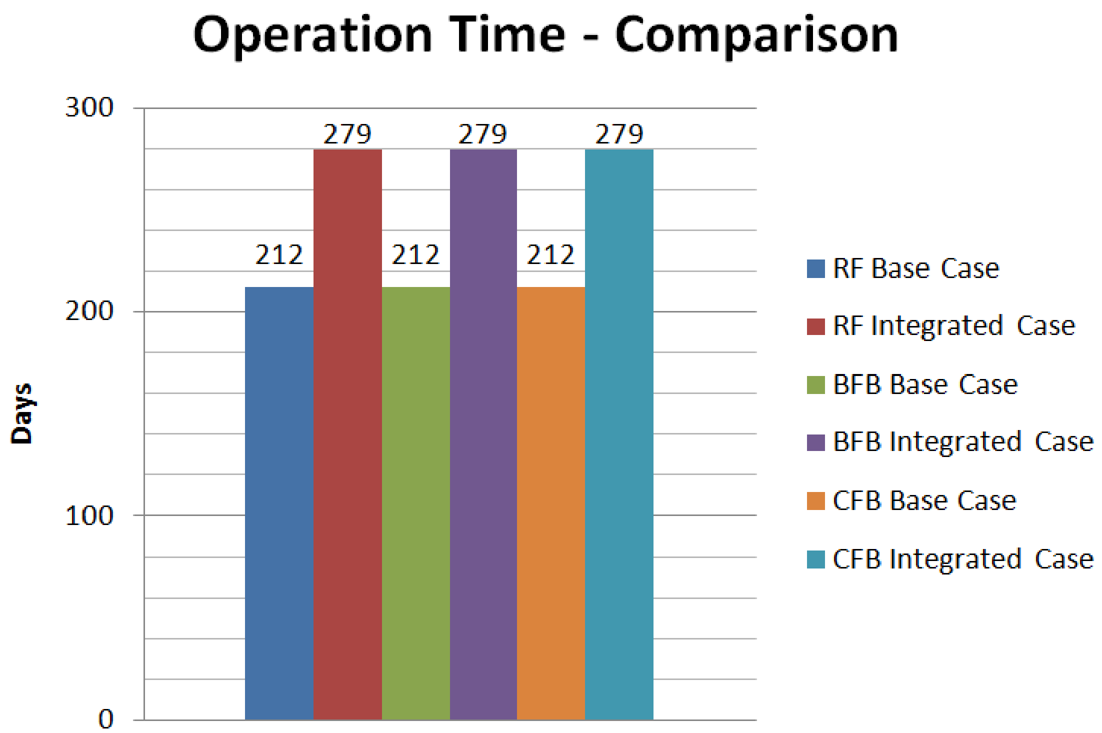


Figure 3.25 Total CHP plant operation time - comparison

The number of additional days comes from the multiperiod model created earlier in the chapter *3.1.2 DH Load Characteristics.* The simulation results clearly show that the heat supplied to the District Heating network has increased due to the integration. Figure 3.26 shows both multiperiod curves and the real heat needed to be supply.

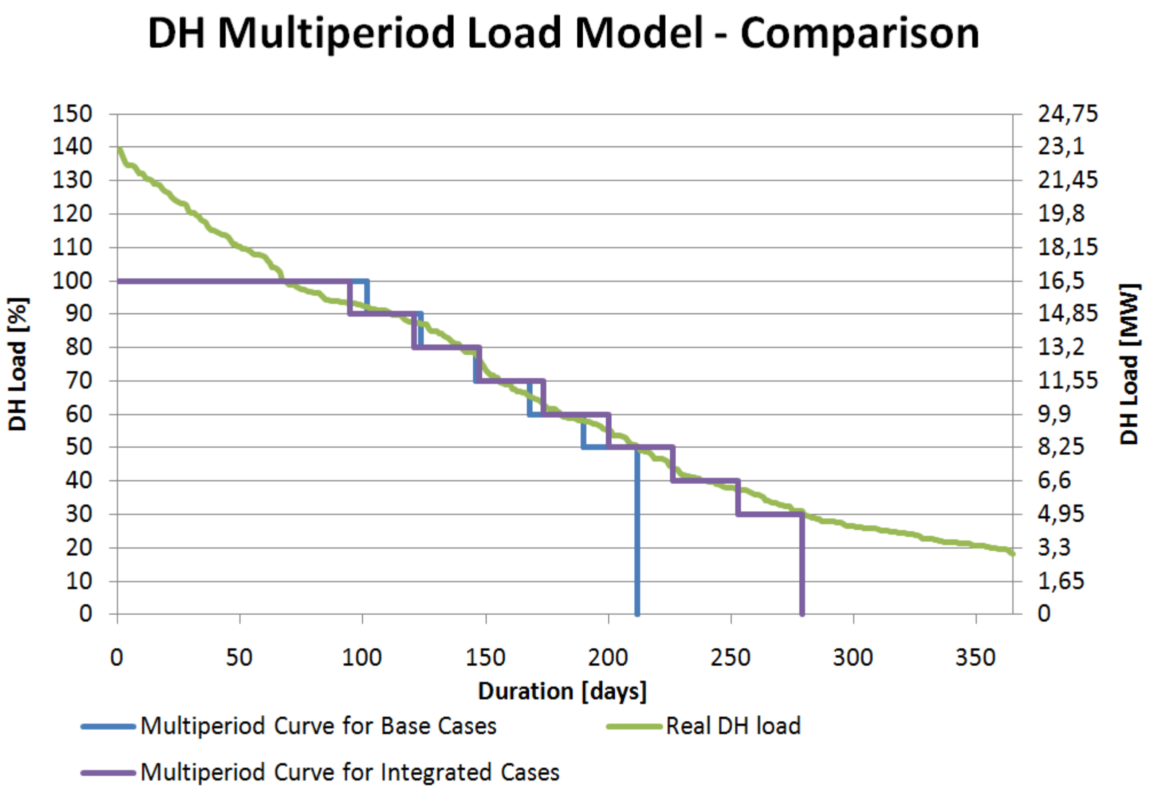


Figure 3.26 Multiperiod curves and DHN - comparison

As stated in Table 3.31 the total annual heat demand amounts to 94,5 GWh. Without integration all cases delivered around 75 % of this value. With the integration introduced and enhanced thermal output all cases produced the same 81 GWh due to the same operation hours coming from the multiperiod model.

Table 3.31 Heat delivered to the DHN in different cases

Total amount of heat to delivered	[GWh] 94,46	[%] 100
RF Base Case	70,87	75
RF Integrated Case	81,26	86
BFB Base Case	70,85	75
BFB Integrated Case	81,26	86
CFB Base Case	70,85	75
CFB Integrated Case	81,26	86

Clearly, as it can be seen in Figure 3.27, integration has increased CHP plant's thermal output by more than 10 % of the heat needed to be delivered to the District Heating Network.

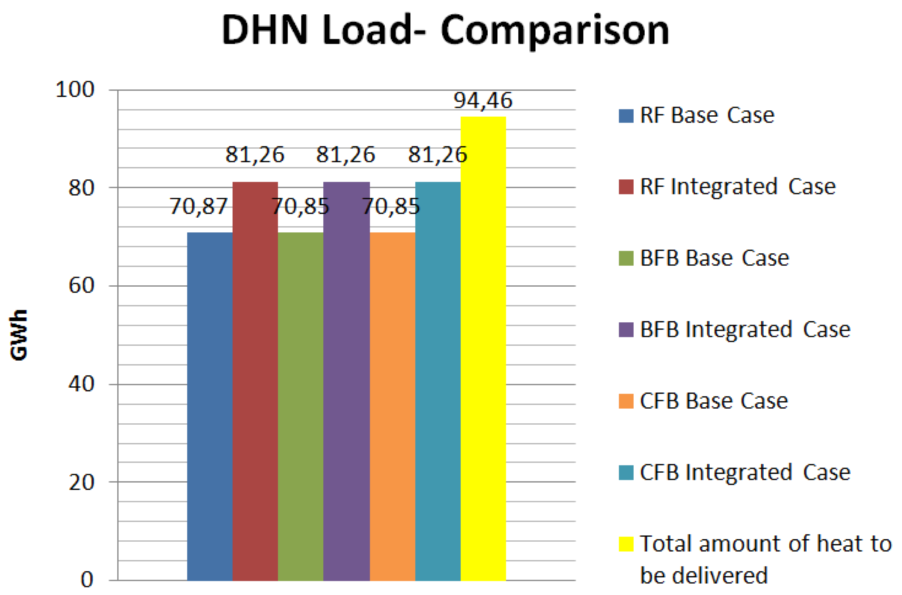


Figure 3.27 Total CHP plant heat delivered to the Districts Heating Network - comparison

In return, this influences the heat needed to be delivered by the heat-only boilers. More heat generated by the integration results in less back-up boiler heat requirements. This is shown in Figure 3.28 below.

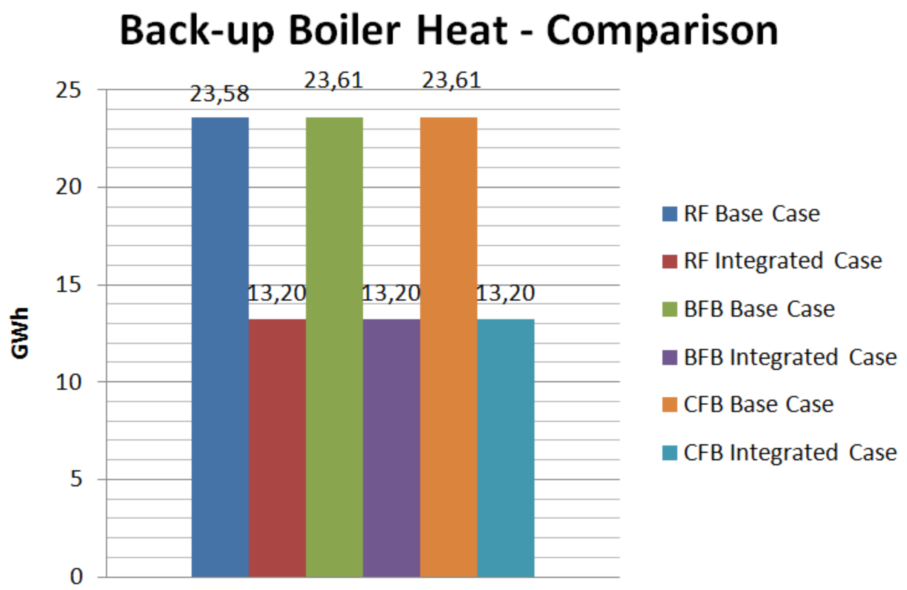


Figure 3.28 Total back-up boiler heat delivered to the District Heating Network - comparison

Only around 56 % of the heat needed to be delivered by the back-up boiler in each base case has to be supplied by the boiler when the drying and pyrolysis are integrated. Thus heavy oil usage will drop by around 12,2 GWh annually in the integration cases considering boiler's efficiency of 0,85. This can contribute to cost savings and lower plant's dependence on the uncertain future of the liquid fuel market.

Biomass total input to the plant is almost the same for base cases. As can be seen in Figure 3.29 this usage is steadily declining with lower partial loads for integrated cases, and steadily declining for all partial loads in base cases.

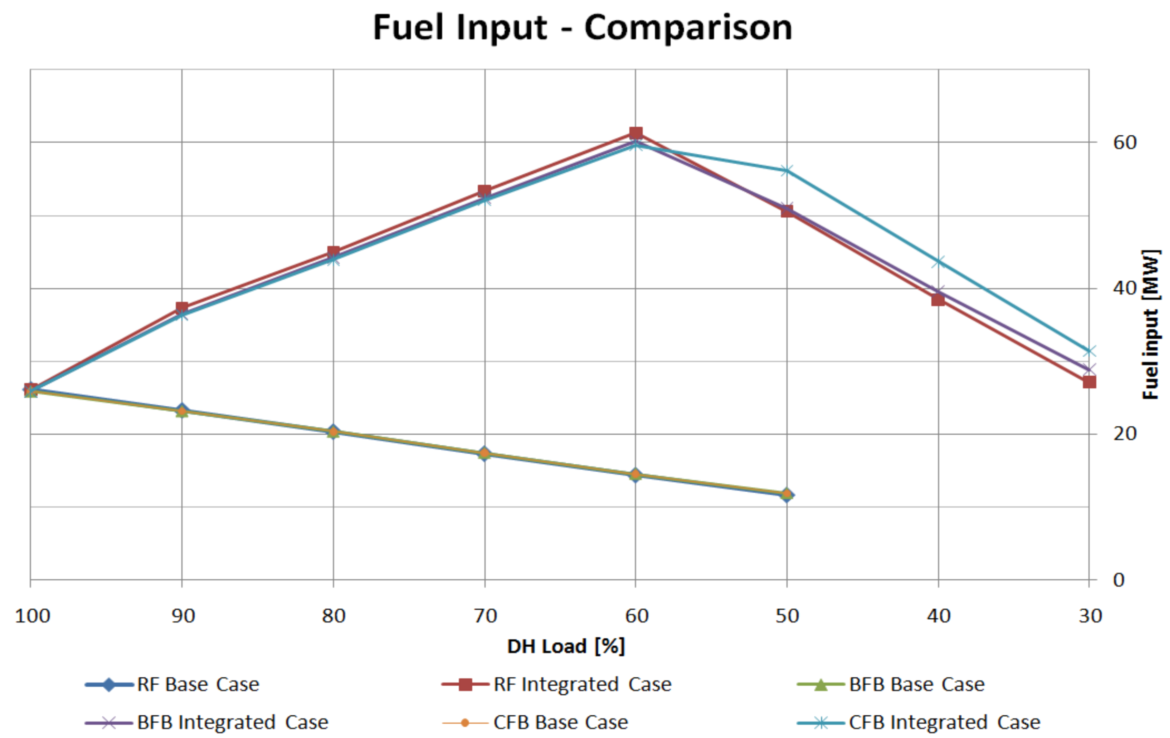


Figure 3.29 Fuel input at partial loads - comparison

The steady increase in the biomass input for integration cases is due to two reasons: firstly, the biomass fed to the boiler is kept constant to 60 % heat load level while secondly, the amount of biomass that can be dried and pyrolysed is increasing. Then after the maximum biomass usage for all integration cases at the peak of 60 MW the fuel input is decreasing due to the decrease in the boiler fuel load. For this decrease the Circulating Fluidized Bed integration case seems to have slightly higher fuel input requirements of around 3,5 MW comparing to other cases. This is related to the higher pyrolysis slurry production that can be achieved. The largest gap between the fuel feed of base cases and integration cases is as big as 45 MW. Figure 3.30 shows the total annual fuel delivered to the plant for different cases.

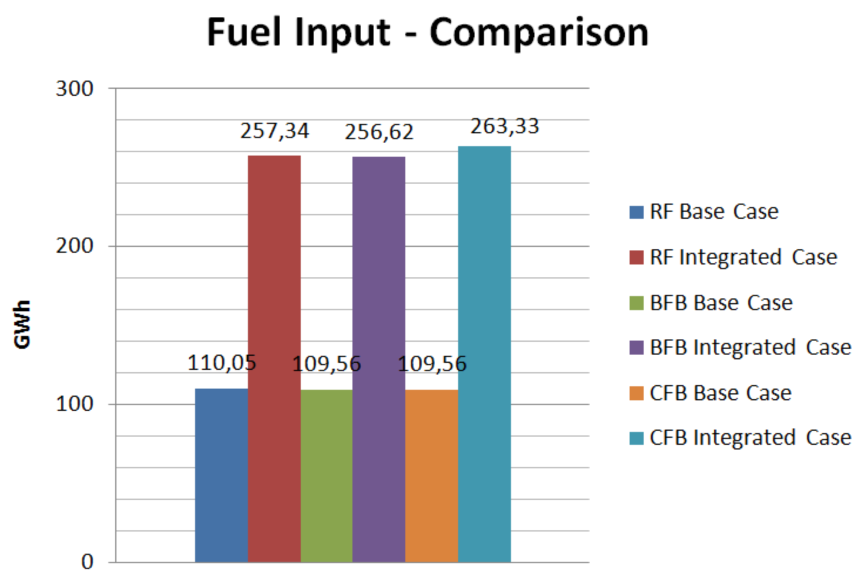


Figure 3.30 Total CHP plant fuel input – comparison

Nearly 150 % more biomass is used in the integration cases due to the biomass fed for drying and pyrolysis. Total fuel usage differ between the cases with integration from 256,62 GWh in the BFB and 257,34 GWh in the radiant furnace case to 263,33 GWh in the CFB case. Total biomass input in both base cases amounts to around 110 GWh.

The electricity production at different part load levels is shown in Figure 3.31.

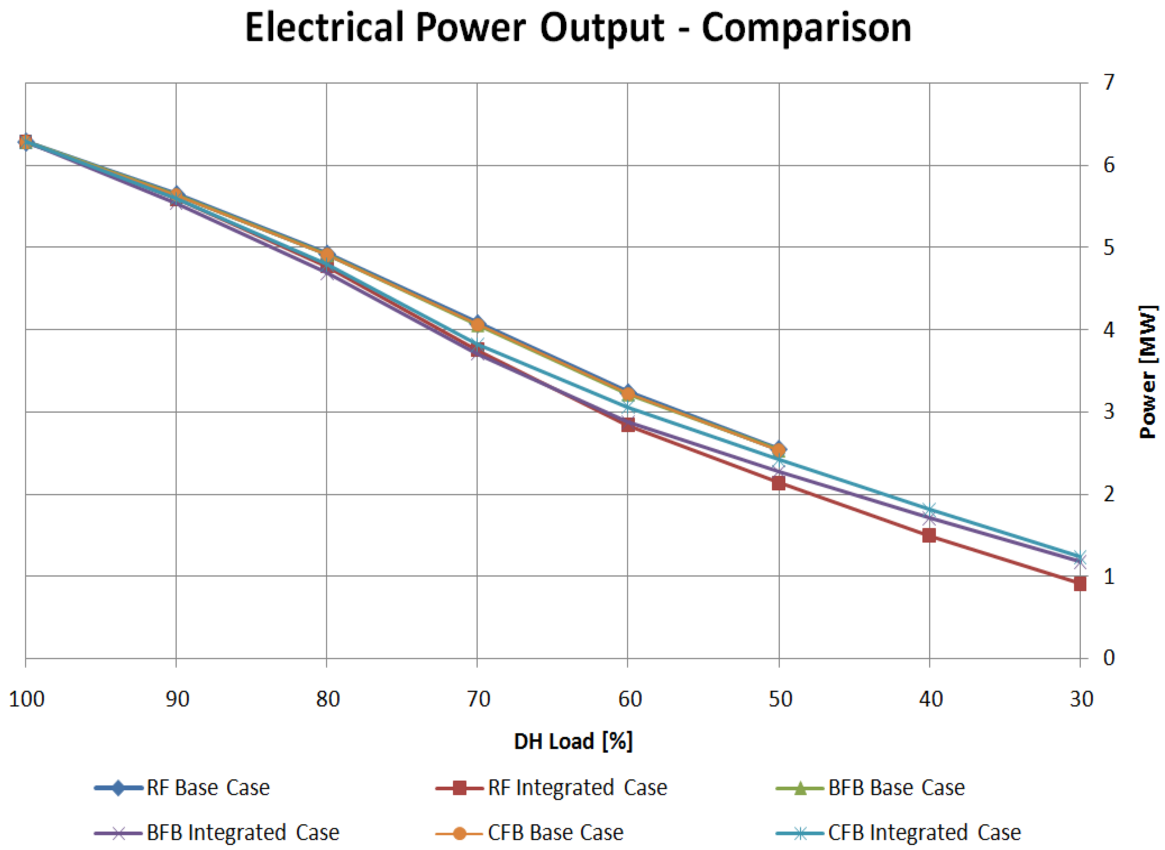


Figure 3.31 Electrical production at partial loads – comparison

From the design point to 80 % of the thermal load the electrical output is similar for all cases. For lower loads down until 50 % it can be observed that base cases are producing more power. The difference is even up to around 0,5 MW. This might be explained with the fact that for the integration cases the steam has lower parameters, some of the live steam is directed to the dryer. The radiant furnace case with integration has the lowest production level followed by BFB and CFB. This is again due to the lower live steam temperature in the radiant furnace case. On the other hand, as can be seen in Figure 3.32, due to prolonged operation hours in the integration cases the total annual electrical output is higher.

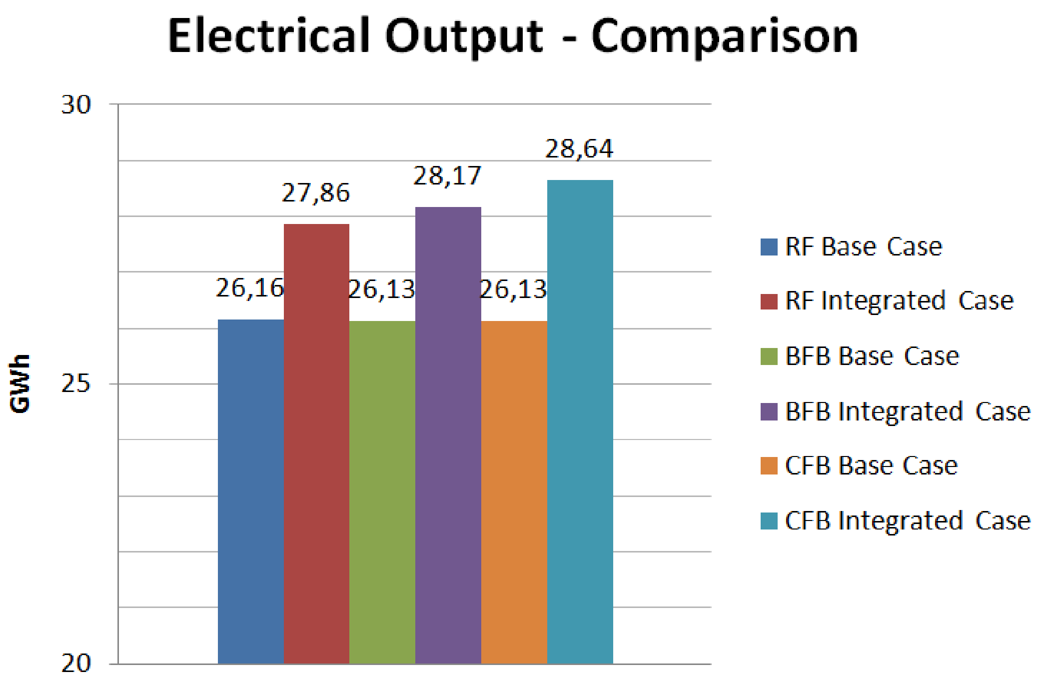


Figure 3.32 Total electrical power output - comparison

The difference reaches around 10 % for the integration of fluidized beds and 6,5 % in the case of integration with radiant furnace. The radiant furnace case is producing the lowest amount of electricity comparing to other integrated cases. This might be explained with the fact that the grate fired boiler is controlled with the amount of water evaporated. Therefore a certain amount of steam is produced to maintain the given boiler temperature. Then, especially at lower partial loads, this steam is superheated by the decreased flue gases flow due to the pyrolysis. This results in having the higher mass flow rate compared to both fluidized beds and the lowest temperature of the live steam. Therefore the electrical output is lower. Additionally, the BFB boiler case has lower power output than the CFB case due to the fact that at partial loads the steam temperature of 510 °C is not achieved. This is because part of the hot flue gases flow that is meant to superheat the steam is directed to the pyrolysis. Hence the electrical output is lower. The summary of electrical production results is presented in Table 3.32.

Table 3.32 Summary of the total electrical output

Electricity delivered	[GWh]	[%]
RF Base Case	26,16	100
RF Integrated Case	27,86	106,5
BFB/CFB Base Case	26,13	100
BFB Integrated Case	28,17	107,8
CFB Integrated Case	28,64	109,6

The pyrolysis product is yielded only in the integration cases. As it was explained earlier in this chapter, the pyrolysis process has increasing amount of biomass in partial loads up to the 60 % peak point. This is due to the fact that more steam or flue gases can be extracted from the cycle for pyrolysis and drying at constant fuel input. Maximum slurry production reaches around 40 MW for all studied boilers. As can be seen from Figure 3.33, the bio-product yield is decreasing for lower partial loads.

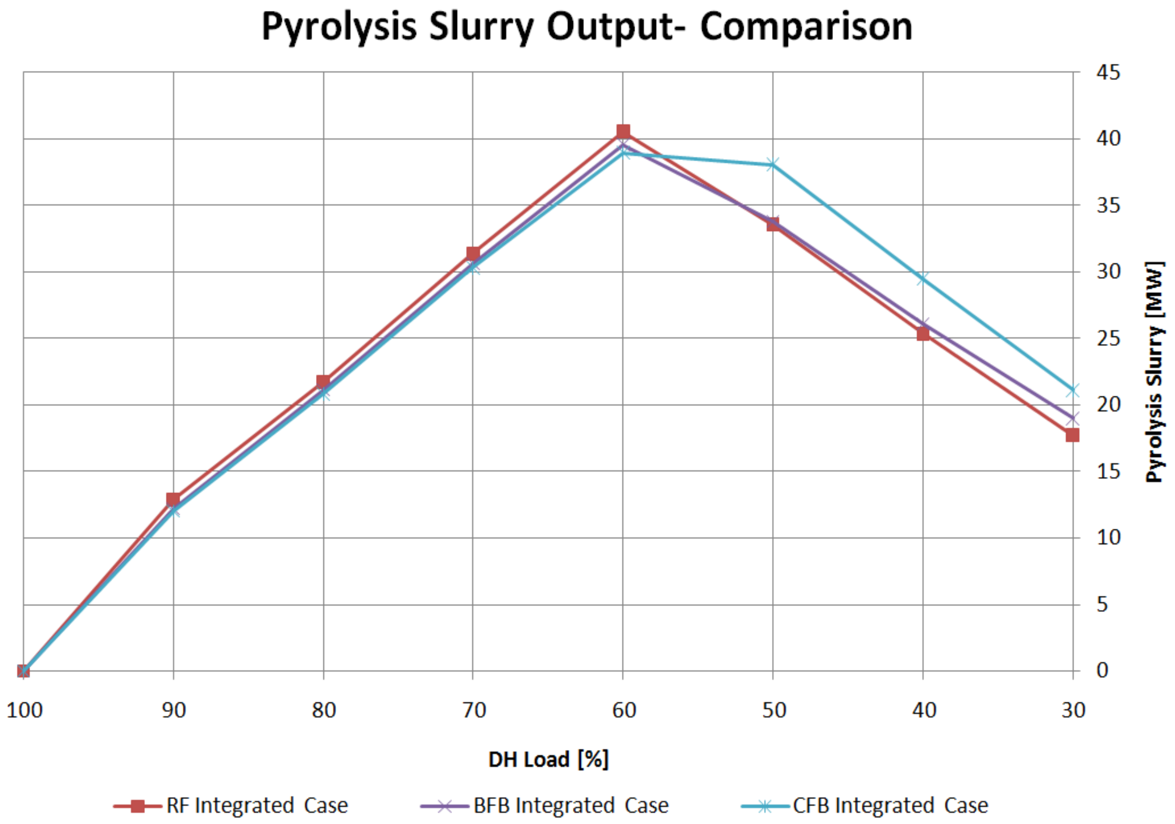


Figure 3.33 Pyrolysis slurry production at partial loads – comparison

The Circulating Fluidized Bed yields relatively more compared to similar result of radiant furnace and BFB cases. The difference is up to 4,5 MW of the slurry production at partial loads. At 30 % bio-product generation amounts to 17,74 MW and 19 MW for the radiant furnace and BFB case respectively, and 21,13 MW for the CFB. The total energy in the slurry yielded from the radiant and BFB case is almost 116 GWh. The CFB integrated case production is 3 % more and amounts to around 121 GWh. The differences are dictated by the flows to the dryer unit. In CFB case, more steam is directed to drying and also the flue gases entering the unit are at higher temperature and have higher mass flow compared to two other cases. This on the other hand is a result of the higher amount of the fuel that can be burnt in the boiler, producing more heat that can be used.

When taking all energy outputs into consideration the integration concept gives even up to 240 % more energy contained in final products comparing to the base situation. As it is in Figure 3.34 heat and power produced in the radiant furnace and fluidized bed base cases is similar and rounds to 97 GWh.

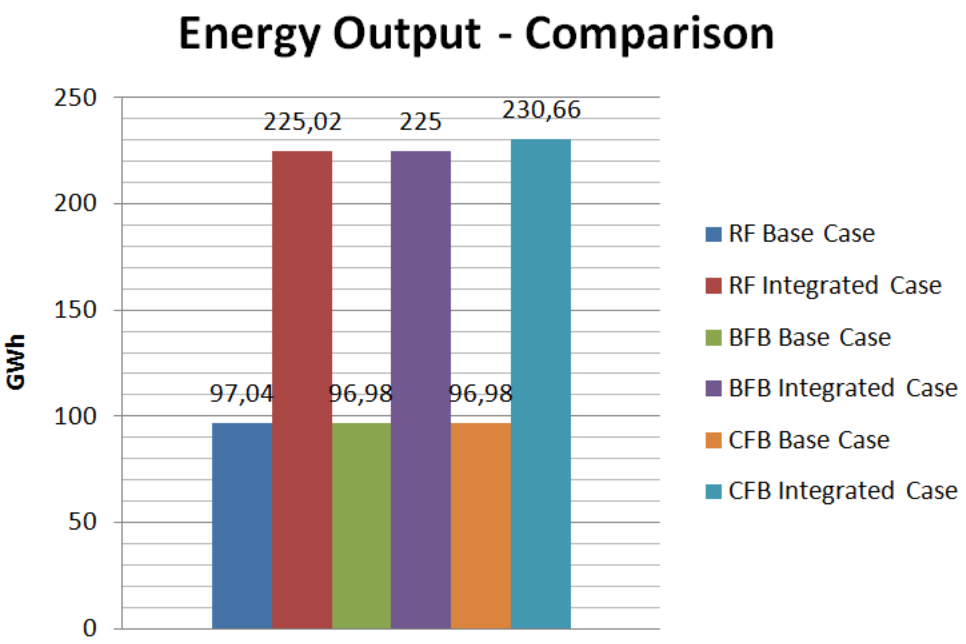


Figure 3.34 Total energy in products – comparison

In the integration the total embodied energy in final products reach 225 GWh in case of radiant furnace and BFB. The CFB case gives around 6 GWh more.

The fuel utilization factor that is including also the pyrolysis yield is similar for all cases at the design and down to 80 % level. As shown in Figure 3.35 from this point the efficiency is stable in cases with pyrolysis integration.

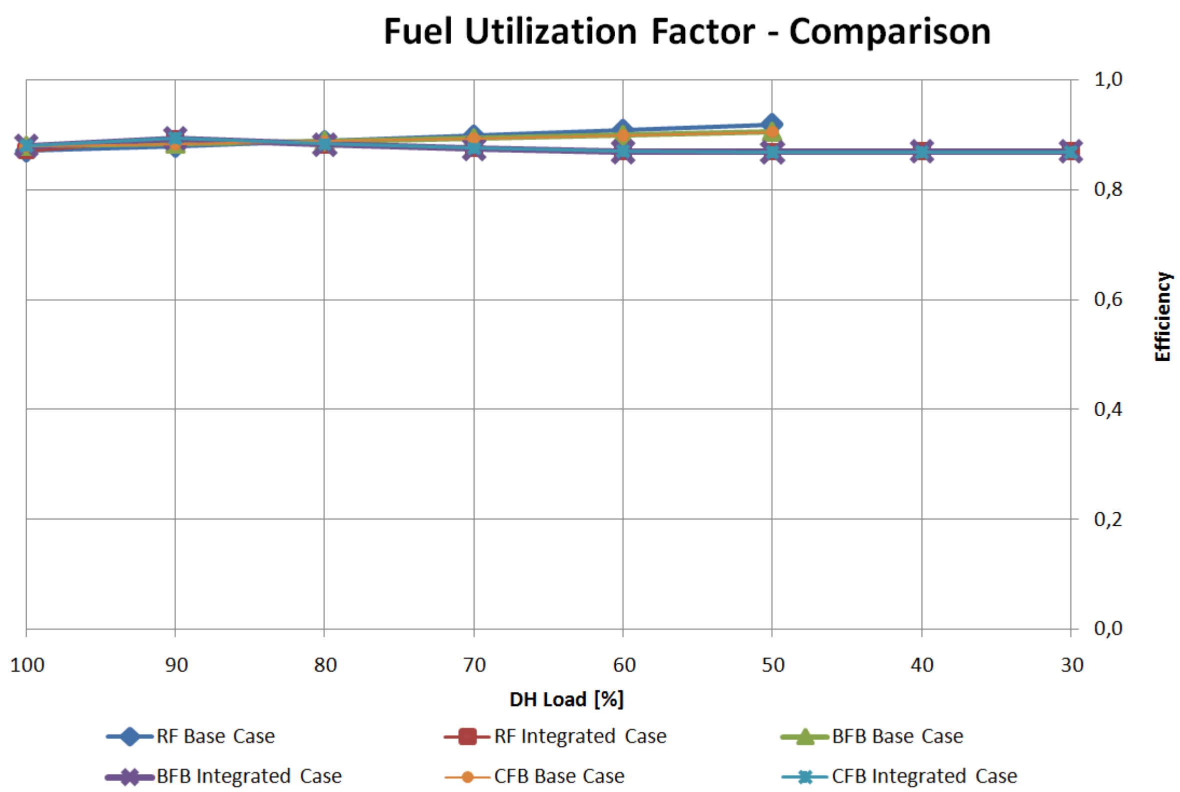


Figure 3.35 Fuel utilization factor at partial loads – comparison

In contrast, the efficiency in base cases is steadily increasing with radiant furnace case having the highest value at the lowest 50 % level. This might be related to the fact that for the partial loads the steam parameters decrease with the decrease of the fuel fed to the boiler. Therefore, the steam reaches the desired temperature value and there is no need for spraying before the turbine. This could be one of the reasons, but the final explanation is not clear yet and is planned to be further investigated.

3.5.2 Environmental Performance Results

Radiant Furnace calculations

Environmental performance evaluation aims to calculate the Primary Energy Factor and CO_2 coefficient for each of the studied CHP systems. For each study case both factors can be calculated. Additionally, in integration cases these factors can be calculated considering the situation where the pyrolysis oil is used instead of the heavy oil in the heat-only boilers. Thus, as described earlier, this fact is resulting in having three different sets of both factors for each type of the boiler.

For the fuel input needed for the final equation *(11)* on the Primary Energy Factor for a base case cycle, has been mentioned earlier. The energy content of the fuel oil can be calculated taking into account the assumed boiler efficiency (85 %) and the total heat needed to be delivered by the boiler. The total heat and power produced is also known. Therefore by applying the Primary Energy Factors from Table 3.15 to the final equation *(11)* the PEF of the DH network can be calculated to 0,81.

In the calculation for the integration case with radiant furnace the pyrolysis process needs to be implemented. Separately from the heat and electricity the system is also yielding the slurry and the gas. The energy content of the gas is subtracted from the fuel input. Thus, the total fuel input in this case is around 244,5 GWh. Another value needed according to the equation *(12)* is the heat provided by the back-up boiler. This is calculated in the same way as for the base case and results in 15,5 GWh. The heat supplied by the CHP plant together with the electrical power and energy content of the pyrolysis slurry is known. Hereby, by applying all the data into the final equation the Primary Energy Factor for the integrated case with radiant furnace is 0,70.

From the above, the heavy oil can be replaced by the bio-oil from the pyrolysis process under the assumption that the back-up boiler can burn the bio-product as well. As it is in the equation *(13)*, the PEF for the oil used is changed to 1,28. This in consequence is decreasing the final result to 0,69.

Similar procedure is applied in the calculations of the CO_2 coefficients. From the equation *(16)* by applying the same data as in the PEF calculations and also using the coefficients listed in

Table 3.16 it can be calculated that the CO_2 coefficient for the CHP plant using radiant furnace without integration is 38,47 kg/MWh.

Following the logic in the PEF calculations, by applying all data in the equation *(17)* it can be calculated that the CO_2 coefficient for the integration case with radiant furnace is negative: -4,39 kg/MWh.

When the oil is replaced with the bio-oil this result can be decreased even further to -56,37 kg/MWh. This is due to the fact that the heavy oil has a much higher CO_2 coefficient. Thus burning the pyrolysis oil is much more environmentally friendly.

Circulating Fluidized Bed calculations

The Primary Energy Factor for the base CHP system with CFB is derived from Kohl's study. According to this research the PEF value is 0,8 (Kohl et al. 2010). Following the procedure and equations used in the radiant furnace case the PEF for the CFB case with pyrolysis integration amounts to 0,68. When the heavy oil is replaced by the bio-oil this value is decreasing to 0,67.

In the emission calculations the base case has performed 38,6 kg/MWh (Kohl et al. 2010). The integration lowers this value to -6,47 kg/MWh and further to around -58,5 kg/MWh when the heavy oil is replaced with the pyrolysis product.

Comparison of modeled cases and Bubbling Fluidized Bed case

The integration case with the BFB boiler gives the Primary Energy Factor of 0,68 (Kohl et al. 2010). The carbon dioxide coefficient is estimated to -5,3 kg/MWh (Kohl et al. 2010). Both of these values are calculated for the scenario when heavy oil is used in the back-up boiler. Therefore, an additional scenario can be calculated when heavy oil is replaced with the pyrolysis oil. This gives the Primary Energy Factor of 0,67 and CO_2 coefficient of -57,3 kg/MWh.

The Primary Energy Factor comparison for all calculated cases and scenarios is shown in Figure 3.36.

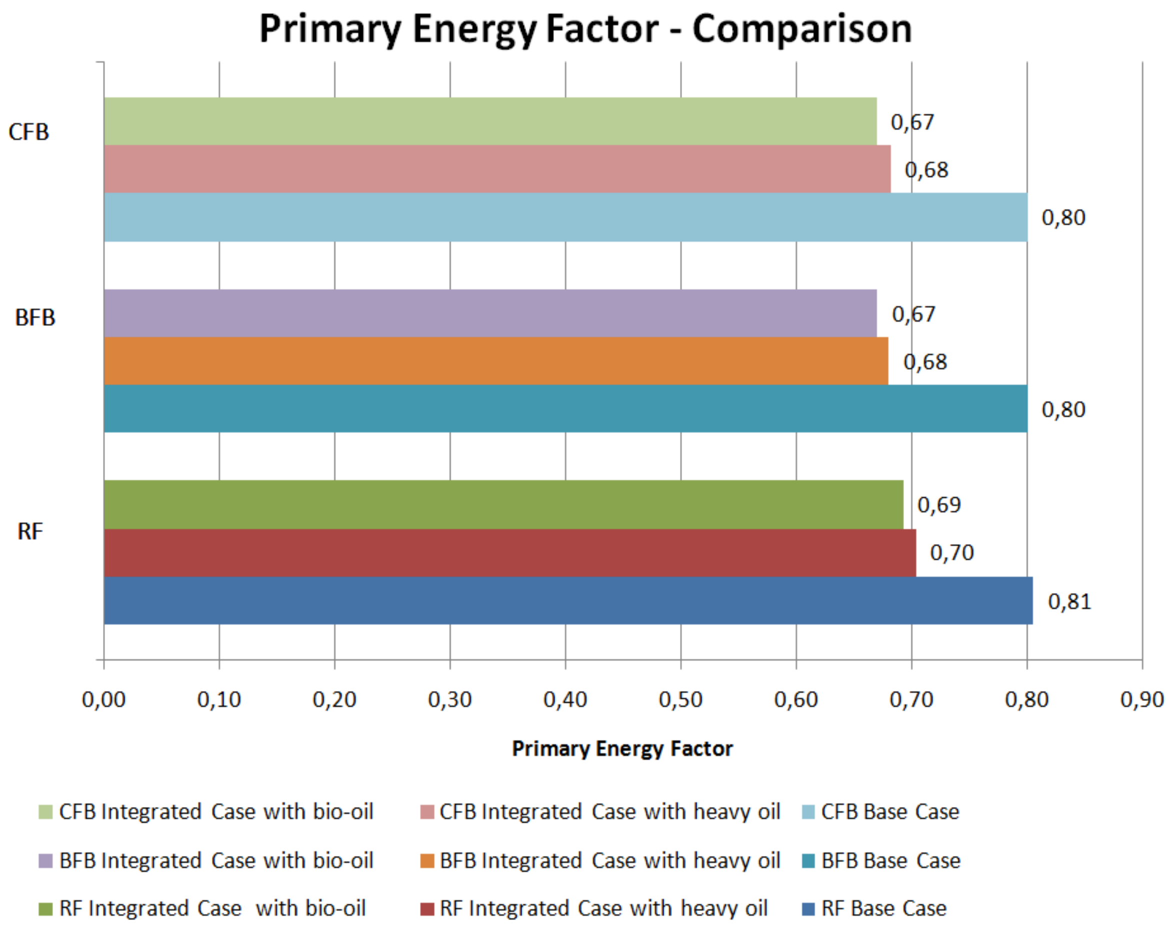


Figure 3.36 Primary Energy Factor calculation results – comparison

Primary Energy usage has improved for all integration cases compared to their respective base cases. For the radiant furnace CHP plant the factor has decreased by 13 %. The Fluidized Beds have both improved by 15 %. The difference between radiant furnace case and fluidized beds is a result of a different electricity production. The radiant furnace case is producing less electricity in total. The power bonus then is stronger for the Fluidized Bed cases which in consequence is lowering the final primary energy factor. For all studied cases there is a decrease of approximately 1 % observed when the heavy oil is replaced in calculations with the bio-oil from the pyrolysis.

The Primary Energy Factor is strongly influenced by the assumption on the PEF of the electricity thought to be replaced by the electricity produced from studied CHP system. For this research the PEF of electricity mix of Finland is used. Thus, the better the PEF of electricity the higher the PEF of the studied system.

Even more significant environmental improvements can be observed in the carbon dioxide emission coefficient – Figure 3.37.

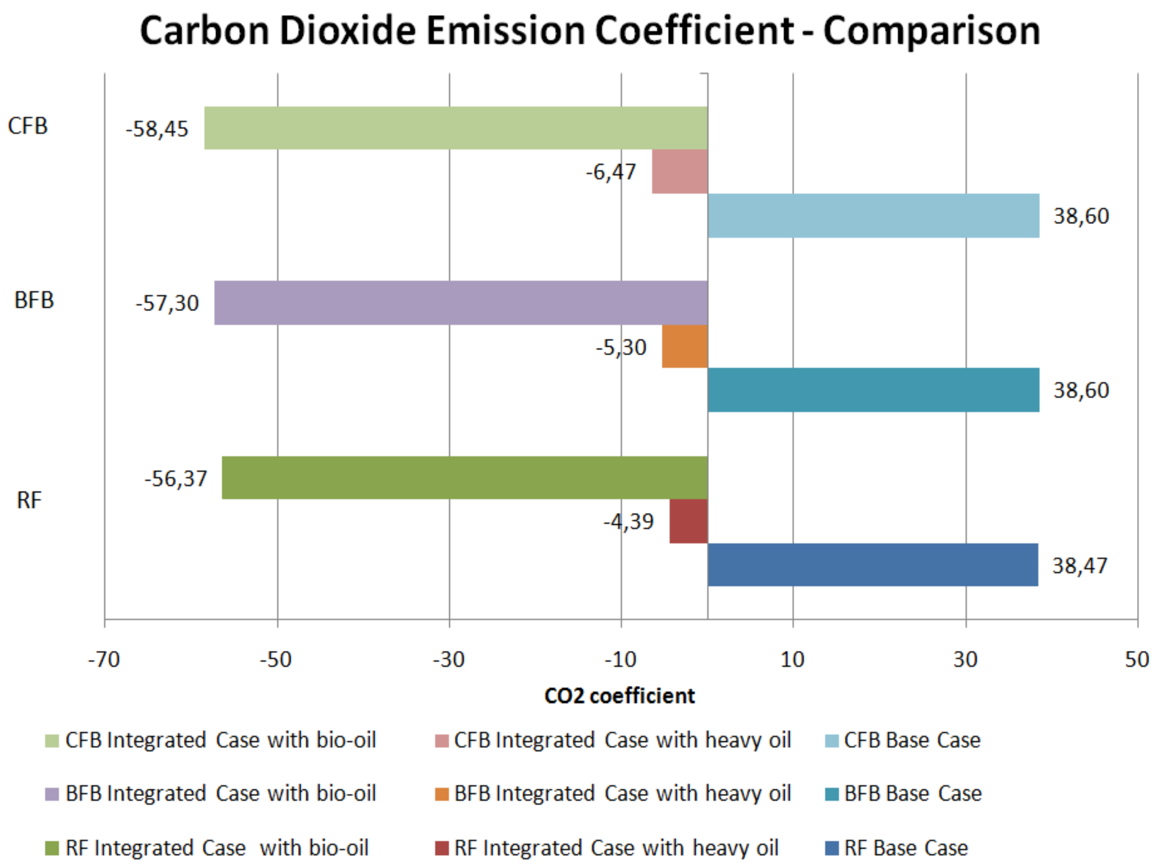


Figure 3.37 Carbon Dioxide emission coefficient calculation results - comparison

The integration improved the CO_2 coefficient by 111 % in the radiant furnace case with heavy oil burned in the back-up boilers. The change in fluidized beds is 114 and 117 % for the BFB and CFB case respectively. This means that the integration positively influences the CO2 emissions. Furthermore, when the heavy oil is replaced by the renewable bio-oil the coefficient goes down by around 250 % reaching very low values. These negative values are very unlikely to reach. In this study they are a result of the system boundary not including transmission, transportation, distribution and other factors that may strongly influence the final result.

The differences between studied cases are relatively small and dictated again, as it was in the case of Primary Energy Factors, by the electrical output. The higher the total annual electricity delivered the higher the power bonus which is lowering the final value – the case is producing more “green” energy from renewable biomass therefore this is rewarded in lowering the CO_2 coefficient.

Short summary of the environmental calculation results for all cases mentioned above is shown in Table 3.33 below.

Table 3.33 Environmental performance calculations results

	RF Base Case	RF Integrated Case with heavy oil	RF Integrated Case with bio-oil	BFB Base Case	BFB Integrated Case with heavy oil	BFB Integrated Case with bio-oil	CFB Base Case	CFB Integrated Case with heavy oil	CFB Integrated Case with bio-oil
Primary Energy Factor	0,81	0,70	0,69	0,80	0,68	0,67	0,80	0,68	0,67
CO_2 Coefficient	38,47	-4,39	-56,37	38,60	-5,30	-57,30	38,60	-6,47	-58,45

Following the EN standard, the Primary Energy Factor of a value below 1 should be set to be equal to 1. However, in this study the aim of the calculation is to compare the studied cases. Therefore the values calculated are not changed. The results obtained here are comparable between cases since in each of them have the same system boundary - what is outside of the system boundary is assumed not to change between cases.

4 CONCLUSION AND REMARKS

This chapter summarizes all the work done and described earlier. It presents the main conclusions that can be drawn from the results described on the previous pages. These are remarks related to the goal and scope of the work and also directly connected with anticipated research outcomes explained in the introduction section. Limitations of the study are briefly analyzed. The challenges encountered during research are shortly mentioned as well. Finally, recommendations for future work are presented to complete the picture.

4.1 Conclusions

The integration of biomass drying and subsequent pyrolysis into a Combined Heat and Power plant cycle has been analyzed in the study. According to the research and results discussed earlier, the following final conclusions can be drawn:

- thanks to integration there is a potential to increase the plant's operation hours – in the studied cases the plant with radiant furnace boiler can increase its operational hours by 30%, the Fluidized Bed boiler plants can provide lower DH loads by shifting excess heat to the pyrolysis and drying process extending their operation hours;
- integration may improve the environmental performance of CHP systems significantly– for the studied cases the Primary Energy Factors and Carbon Dioxide Emission coefficients have decreased to negative values due to the modified "bonus" method for a pyrolysis slurry that is not included in the EN standards;
- integration does not considerably depend on the type of the boiler used – for all studied boiler types the annual outputs were similar, all power cycles reacted in a similar way; also the environmental calculations show that the integration equally improves their performance.

It can also be concluded that Poland might have a considerable potential for the pyrolysis integration in biomass-based CHP installations connected to DH networks. This applies especially to high biomass resources and maturity of the CHP technology in this country.

4.2 Limitations of the Study

It is important to mention that there are many uncertainties concerning the potential integration of biomass pyrolysis. The work is not a detailed technical research thus many of the assumptions made are to simplify the complexity of the problem. Some of the important remarks and limitations of this study include:

- shut-off point of the CFB mode is not clear, therefore there is a question if load level of 50% will provide enough heat carrier (hot sand) for the pyrolysis process, at a certain point of a low load the CFB becomes a BFB;
- as CFB boilers become BFBs they can reach lower partial loads, therefore the advantage of the integration and reaching lower loads may be less favorable;

- influence of the pyrolyis gas on the combustion processes has not yet been taken into account in this study;
- for the integration cases more biomass is used compared to their base cases, thus the collection radius of biomass is higher; consequences of this fact are not taken into account in this study;
- biomass assumed for the study is pine wood; use of different biomass could result in different drying and pyrolysis requirements and combustion properties;
- bio-oil's influence on the backup boilers is not taken into account;
- environmental performance calculations are simplified and for instance are not taking into account losses in the DH network, therefore the calculations can be used in the comparison of the studied cases, but not as reference to the values in the EN standard which include a broader system boundary;
- assumptions made on the multiperiod model use certain time periods for partial loads, thus may influence the final results in some way.

In consequence, many variables not taken into account could lead to challenges and counter-weighting of the potential advantages of integration. On the other hand they should not change the main conclusion stating that biomass drying and subsequent fast pyrolysis have the potential to be beneficial for the Combined Heat and Power systems connected to District Heating Networks.

4.3 Challenges Encountered

The main challenges encountered during the work were related to the simulation. At the beginning of the work, non-experienced user behavior resulted in time consuming problems with the simulation models. Another difficulty in simulating the power plant was in the assumptions that had to be made in the cycle model units. Finally, the biggest challenge for this work was the simulation of the cycle itself. This was done only by iteration, therefore the amount of time spent on adjusting so many variables for each case was tremendous.

4.4 Recommendations for Future Work

The pyrolysis integration into a Combined Heat and Power production is still mostly in a research stage of development, therefore there is a lot that can be done in this field. The research and findings drawn from this thesis make this work a potential base for future investigations of the main concepts studied here. In general, further work could expand the simple frames of steady-state simulations.

Therefore, further investigations could be related to the following issues:

- detailed chemical and energy analysis of the fast pyrolysis process could be performed for the integration options described;
- detailed chemical and energy analysis of the fast pyrolysis products could be done to investigate among others its influence on the combustion parameters in co-firing;
- simulation of different boilers and fuel inputs could be done to investigate the possibility and feasibility of larger plants and further influences of the boiler type;

- additionally, a more detailed investigation of the three boilers' deployment and their performance in the integration could be studied;
- further integration of other technologies could be investigated, for instance absorption chilling during the time when the plant is not producing;
- extra improvements of the process integration can be investigated, particularly use of the heat available after fast pyrolysis when the bio-oil needs to be cooled from high temperature;
- there could also be a study to determine how many power plants are suitable for pyrolysis integration and what the factors determining this possibility of integration are; also an investigation of how many new boilers with integrated CFB pyrolysis could be installed within a specific country;
- further work may include an investigation of other consequences of the integration in the cogeneration cycle to see if they do not counterweight potential benefits, this may include economical analysis;
- shut-off point of the CFB boiler could be investigated to see if all partial loads can provide enough sand for the pyrolysis;
- size variation of the plant with different steam parameters at design point;
- more detailed environmental evaluation could be performed on a basis of life cycle frames in order to make the integration comparable to other technologies.

There are a lot of different aspects involved in the idea of biomass drying and subsequent pyrolysis integration into Combined Heat and Power production. More detailed studies could result in a faster market introduction of this promising concept.

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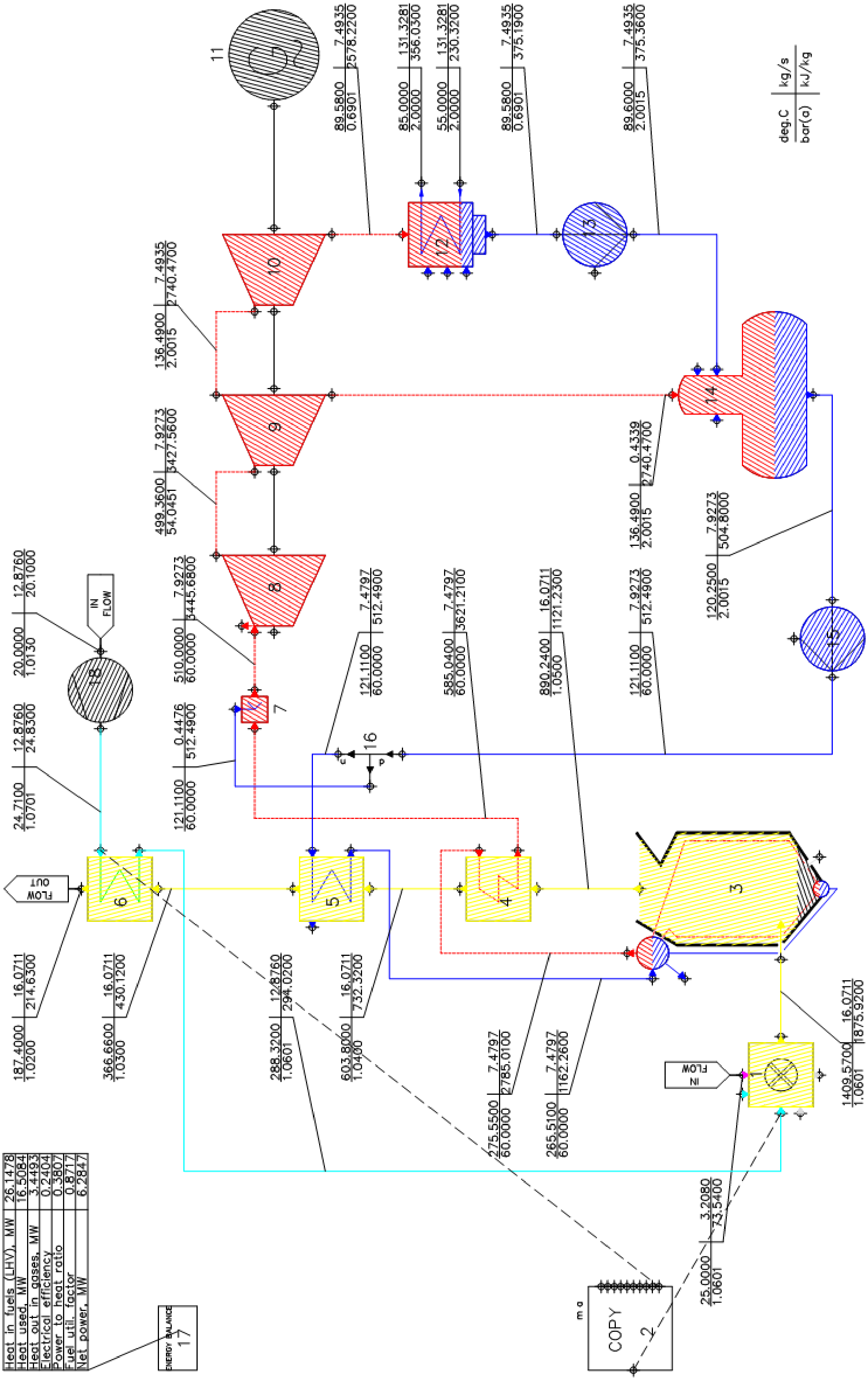
APPENDIX A

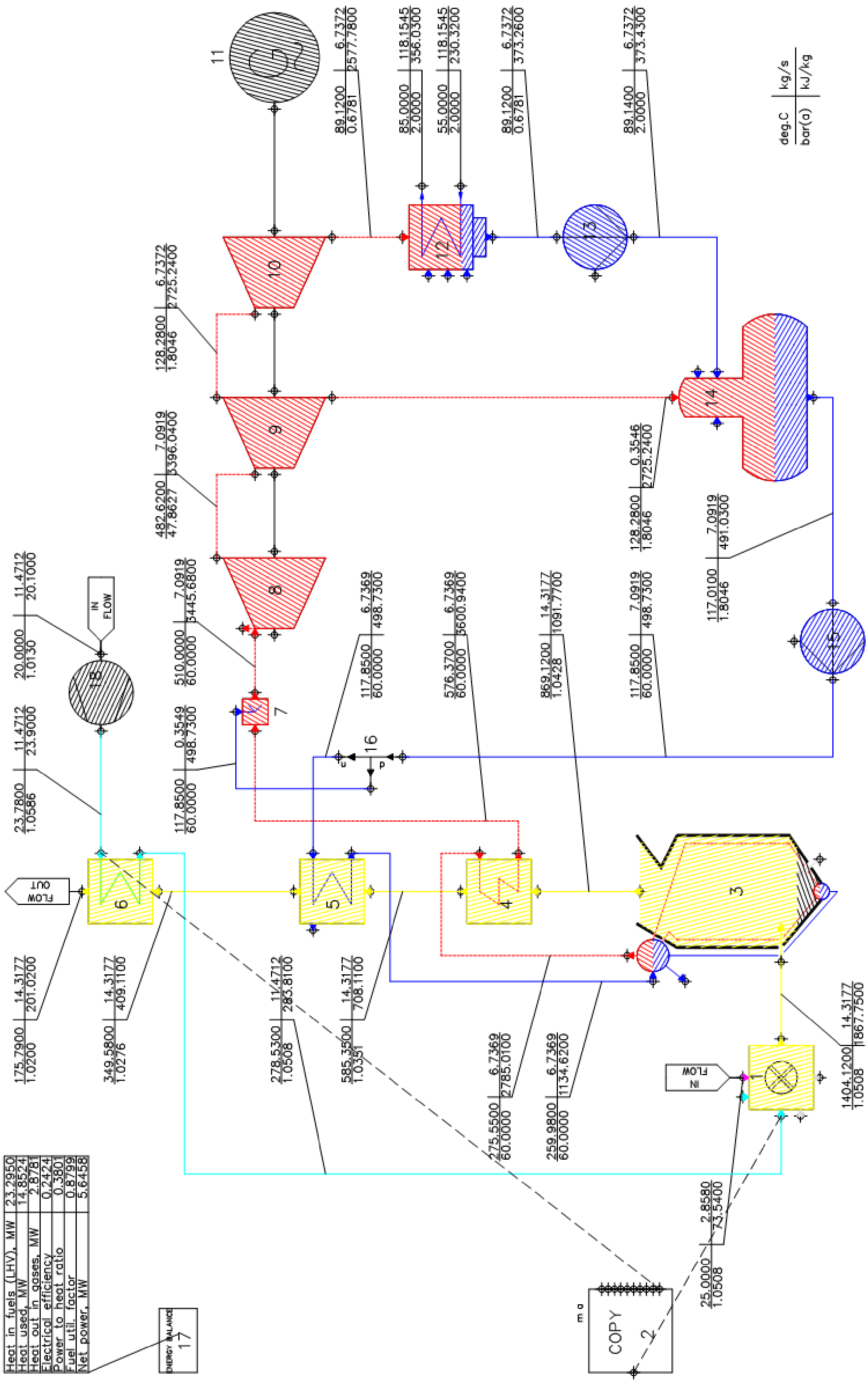
Simulation flowsheets wit cycle parameters for all developed models:

- Radianct furnace base case;
  - 100 % thermal load level;
  - 90 % thermal load level;
  - 80 % thermal load level;
  - 70 % thermal loadlevel;
  - 60 % thermal load level;
  - 50 % thermal load level;
- Radianct furnace integrated case;
  - 100 % thermal load level;
  - 90 % thermal load level;
  - 80 % thermal load level;
  - 70 % thermal loadlevel;
  - 60 % thermal load level;
  - 50 % thermal load level;
  - 40 % thermal load level;
  - 30 % thermal load level;
- Circulatt Radianct furnace integrated case;
  - 100 % thermal load level;
  - 90 % thermal load level;
  - 80 % thermal load level;
  - 70 % thermal loadlevel;
  - 60 % thermal load level;
  - 50 % thermal load level;
  - 40 % thermal load level;
  - 30 % thermal load level.

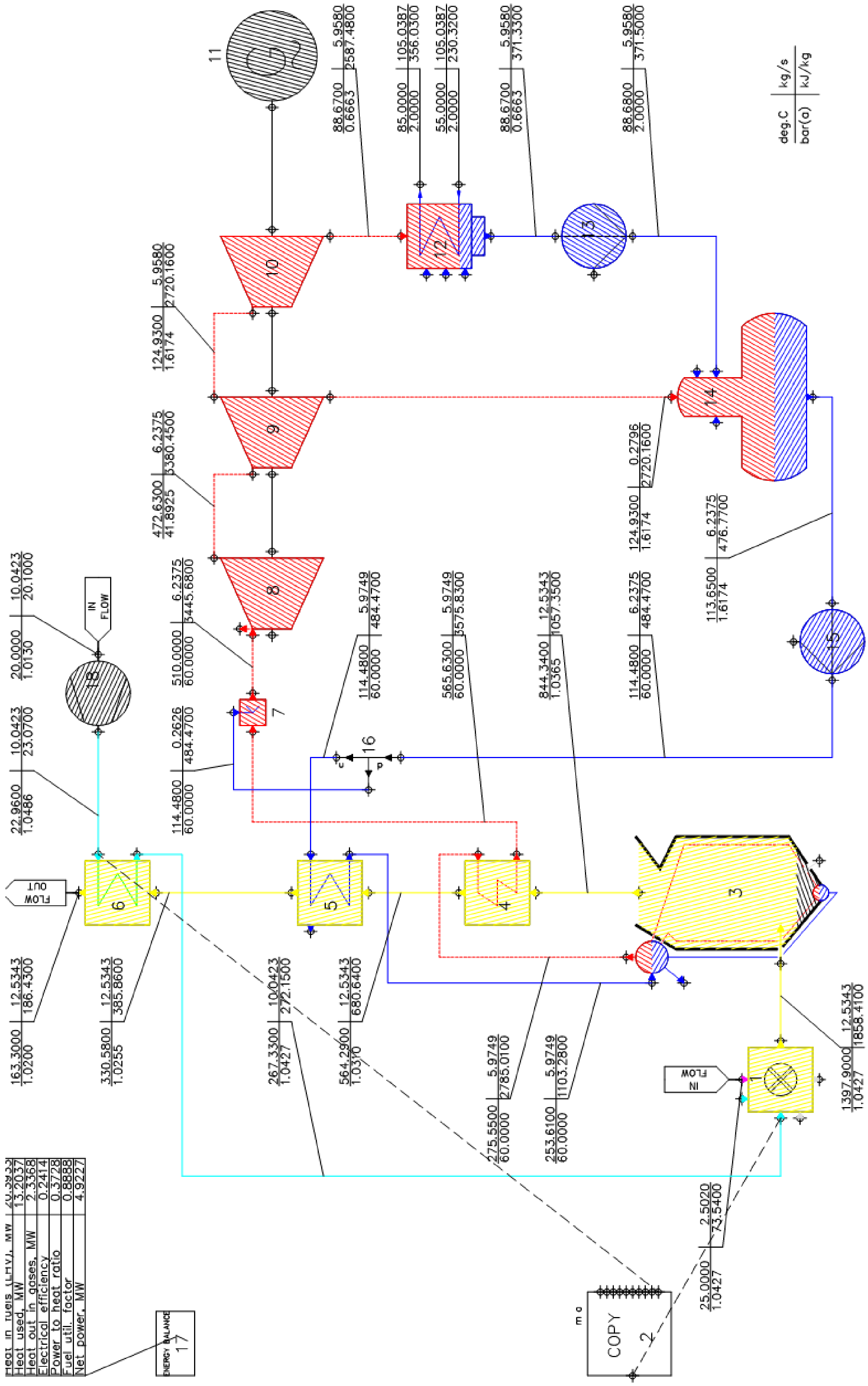
Simulation flowsheet – Radiant furnace base case 100 % thermal load



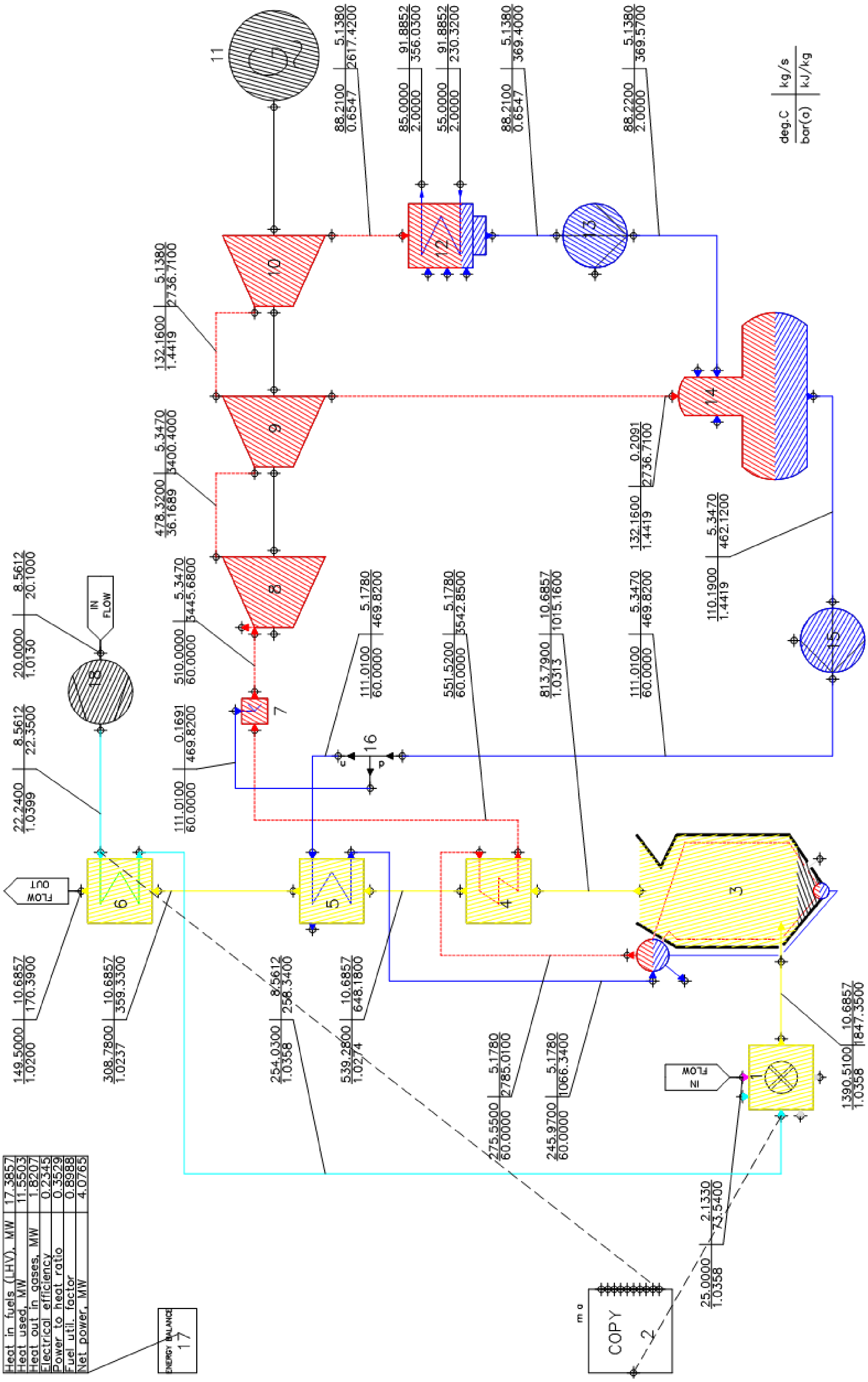
Simulation flowsheet – Radiant furnace base case 90 % thermal load



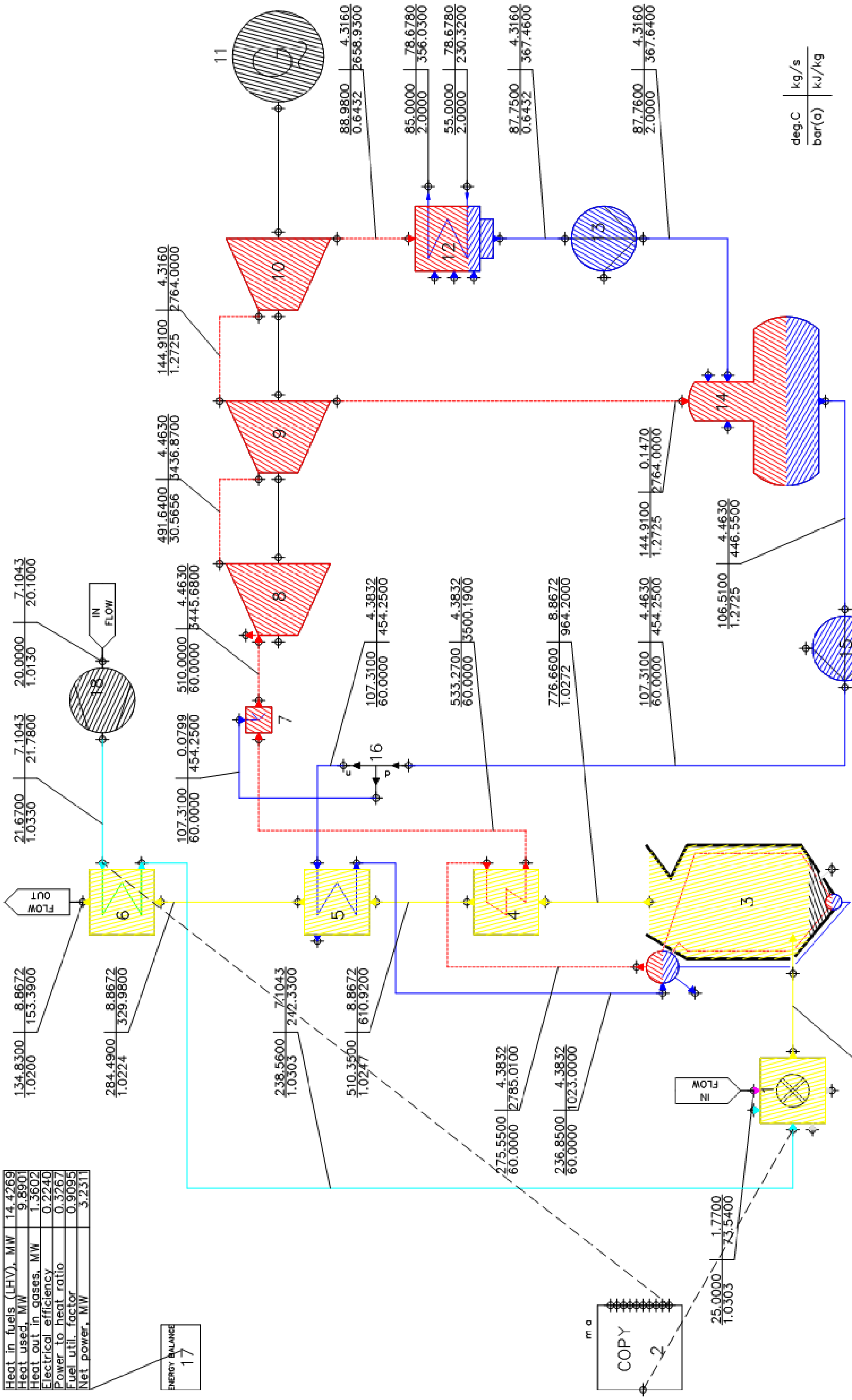
Simulation flowsheet – Radiant furnace base case 80 % thermal load



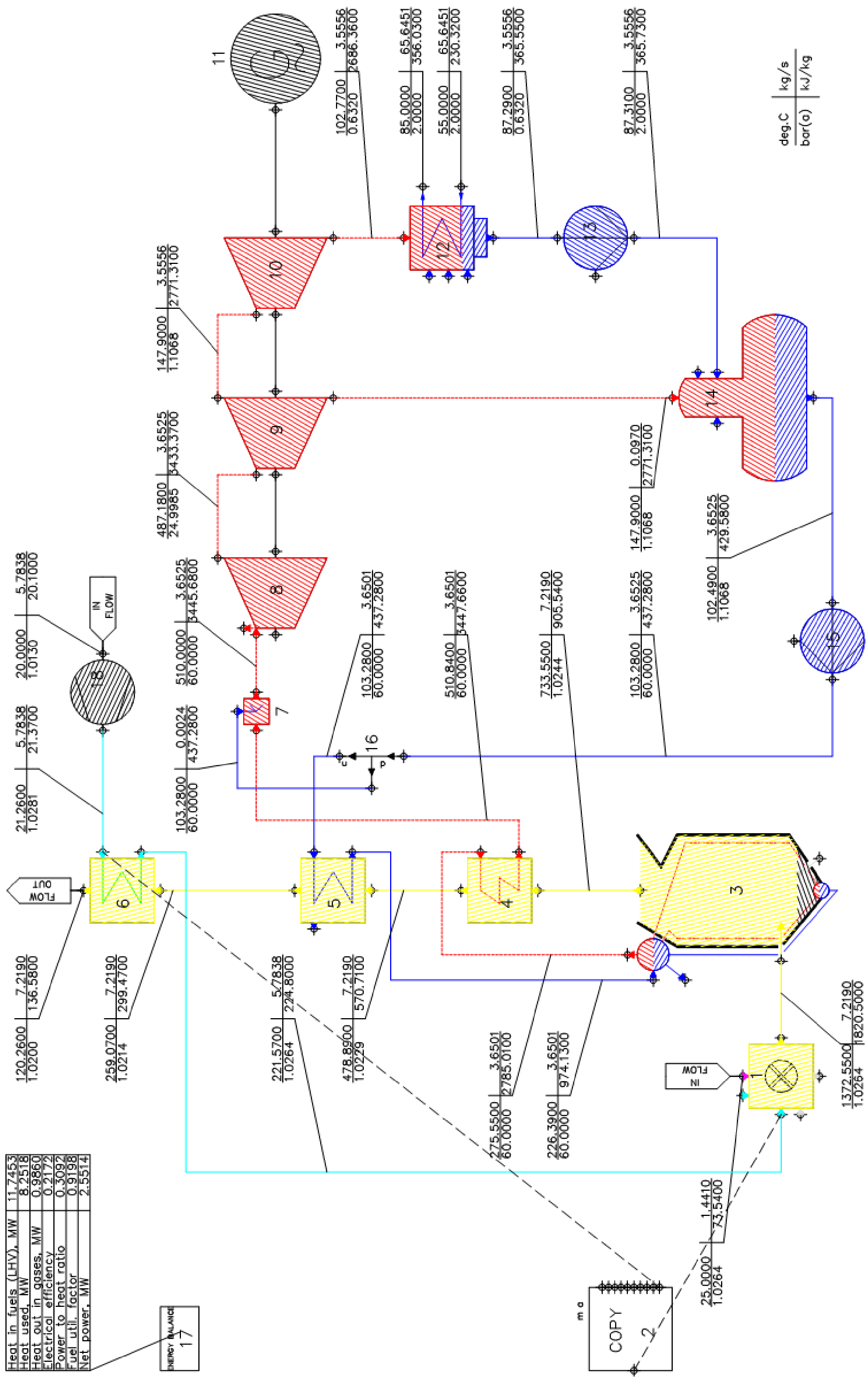
Simulation flowsheet – Radiant furnace base case 70 % thermal load



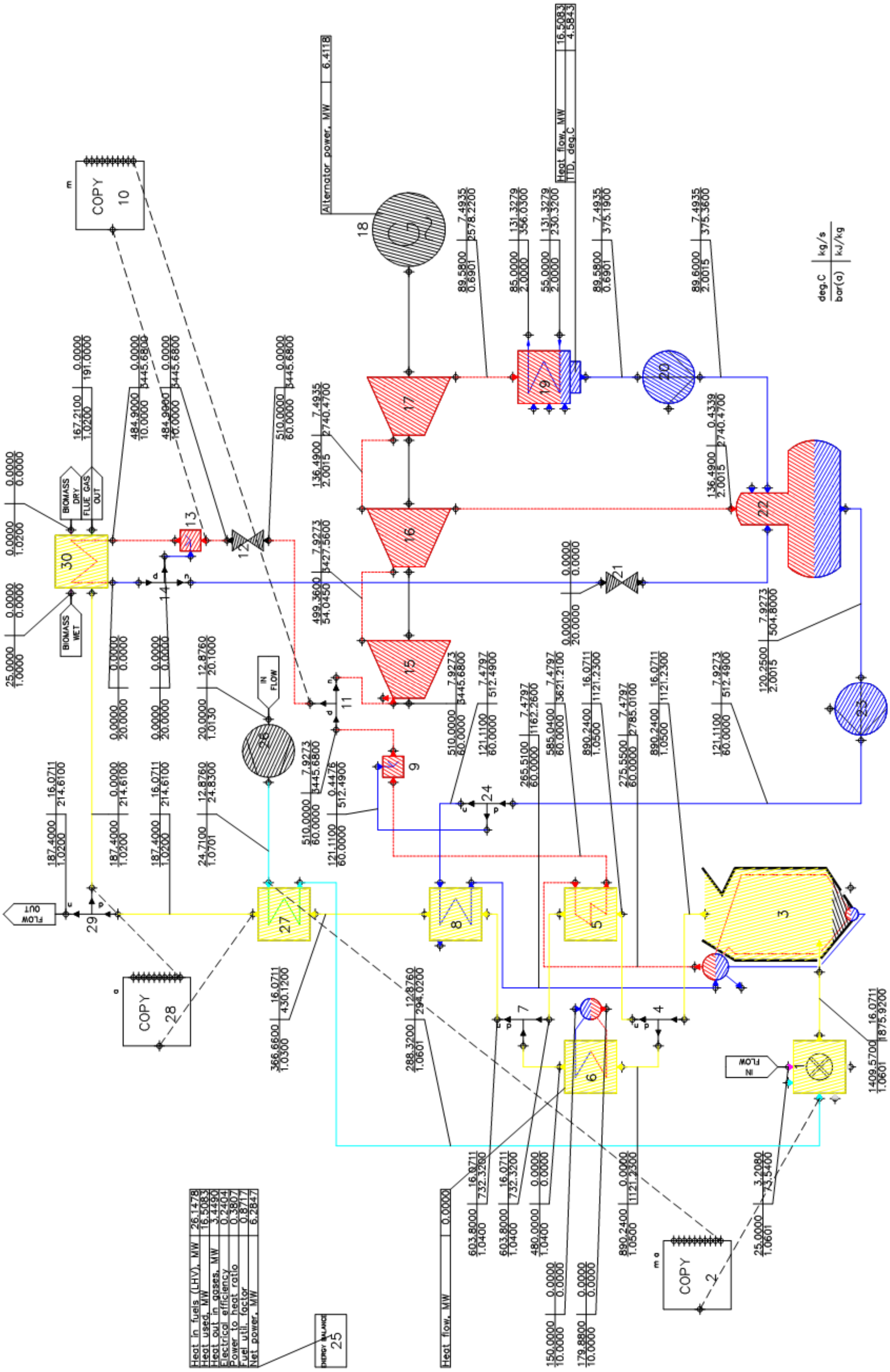
Simulation flowsheet – Radiant furnace base case 60 % thermal load



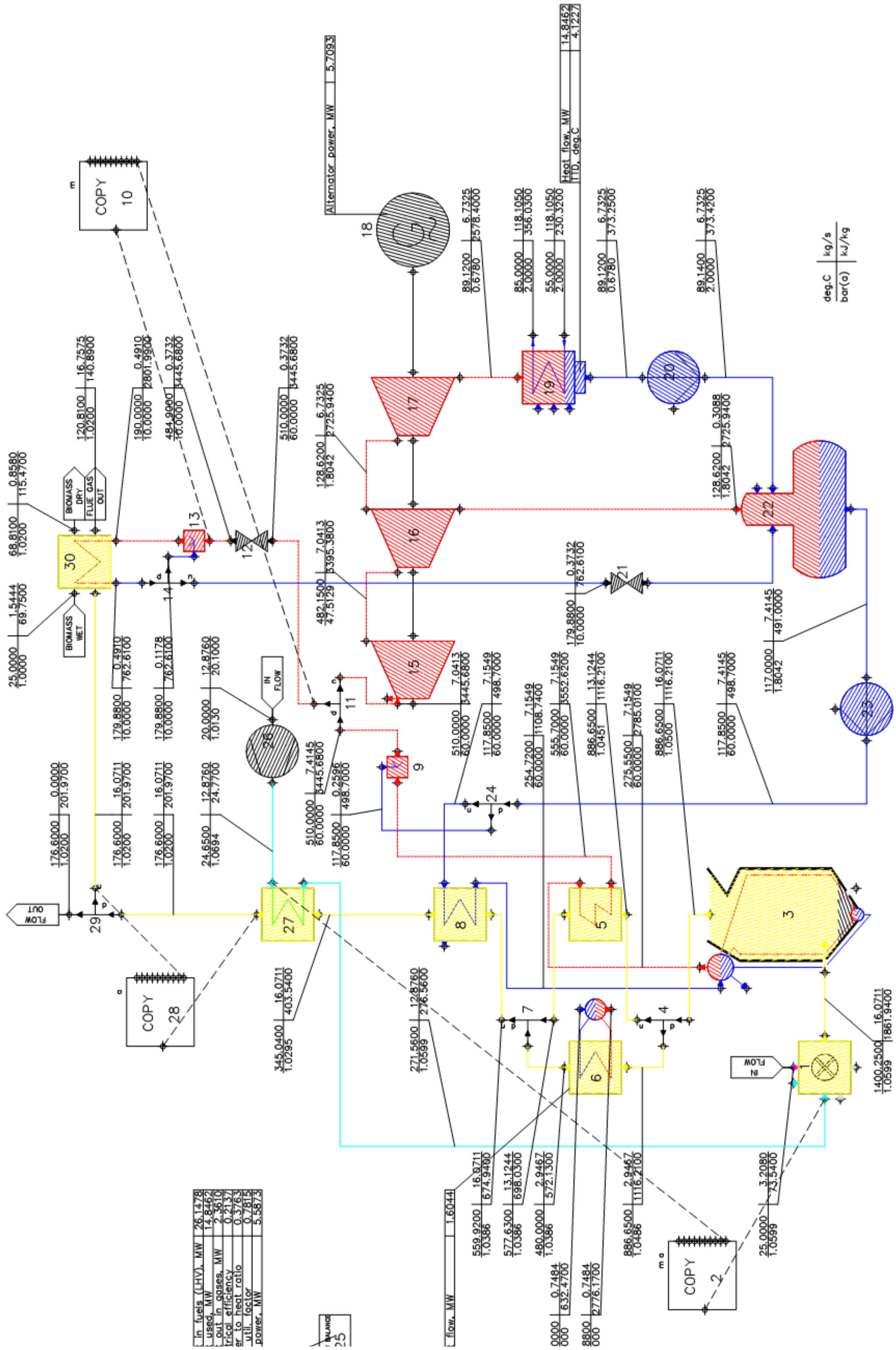
Simulation flowsheet – Radiant furnace base case 50 % thermal load



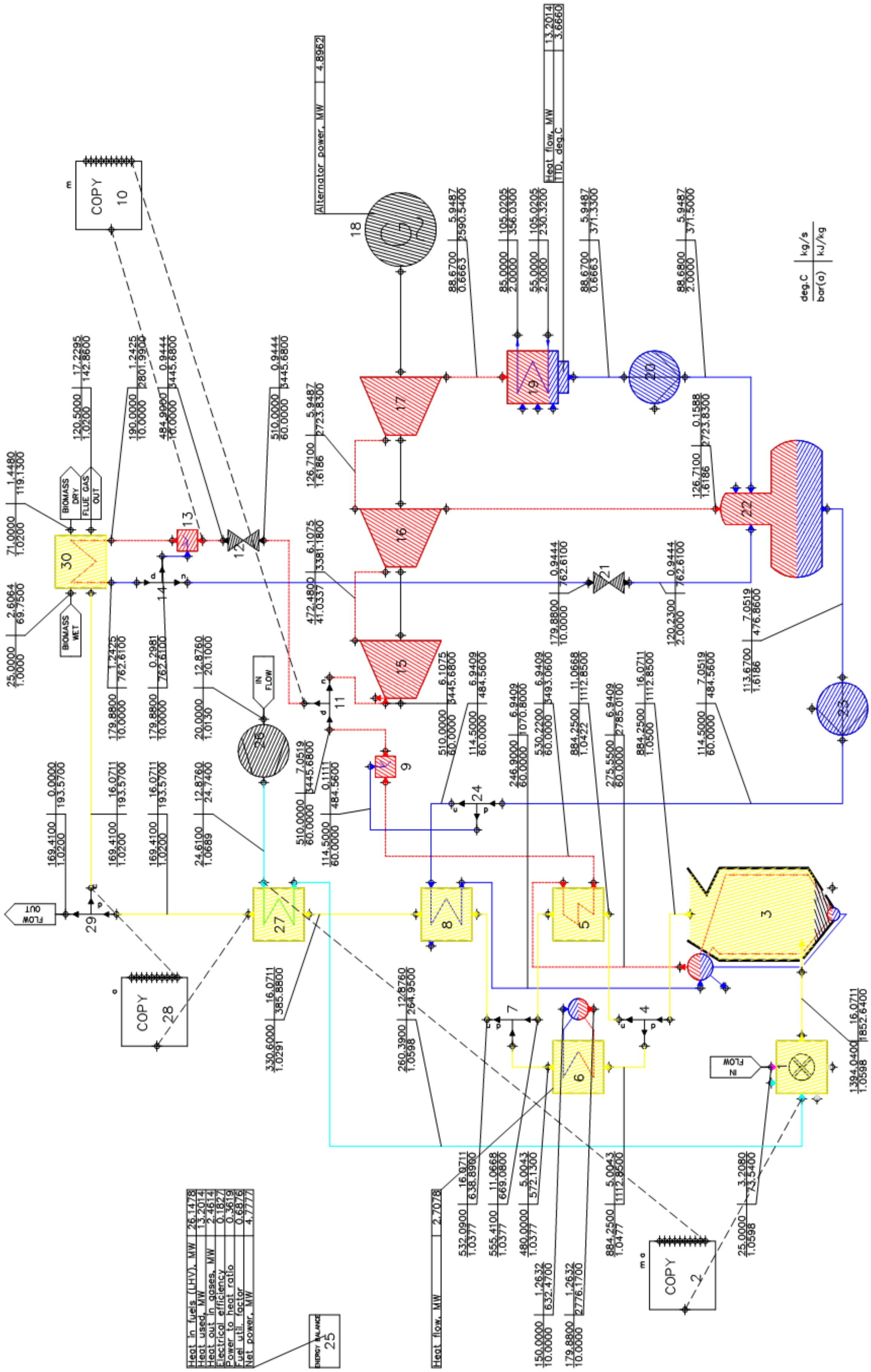
Simulation flowsheet – Radiant furnace integrated case 100 % thermal load



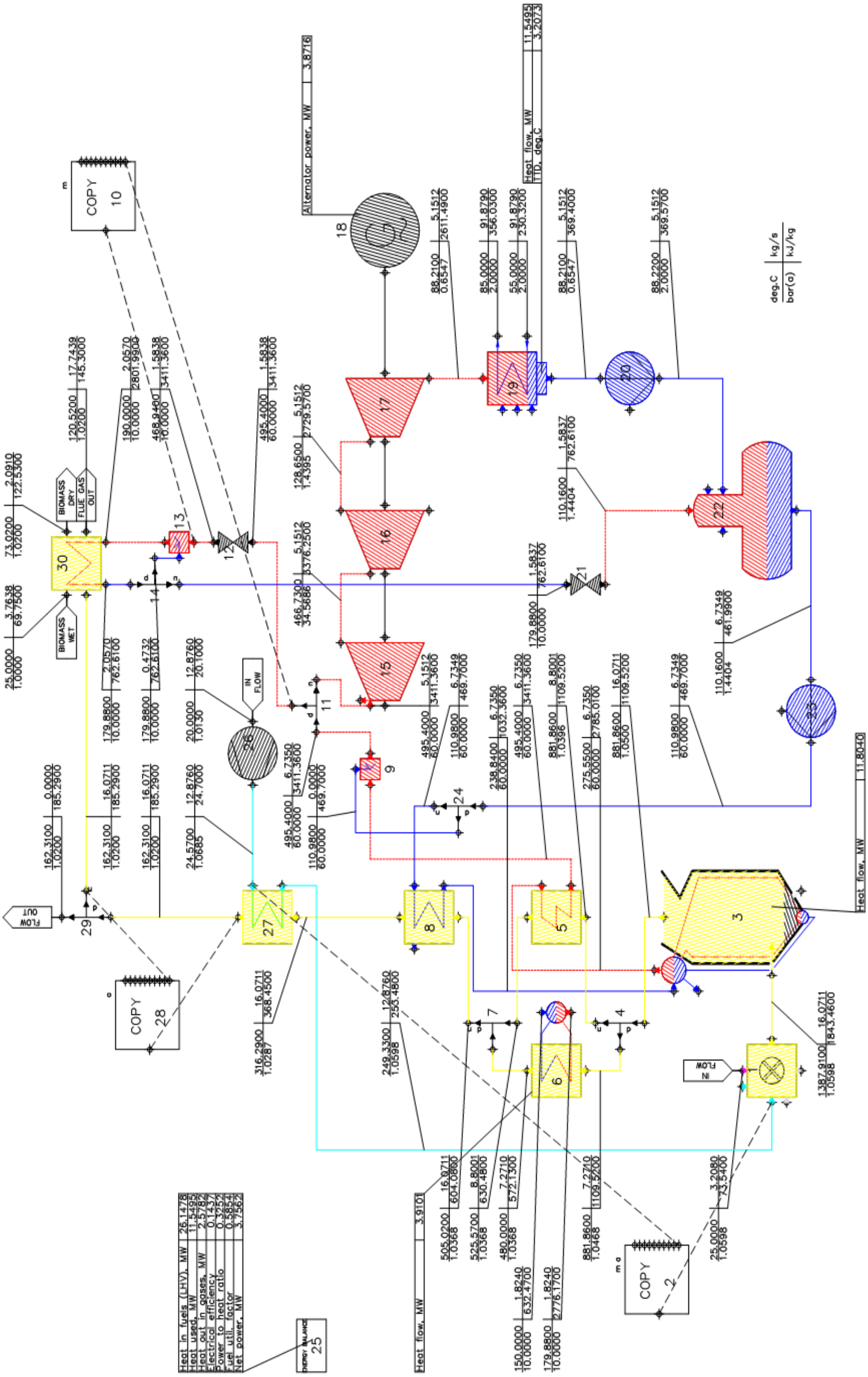
Simulation flowsheet – Radiant furnace integrated case 90 % thermal load



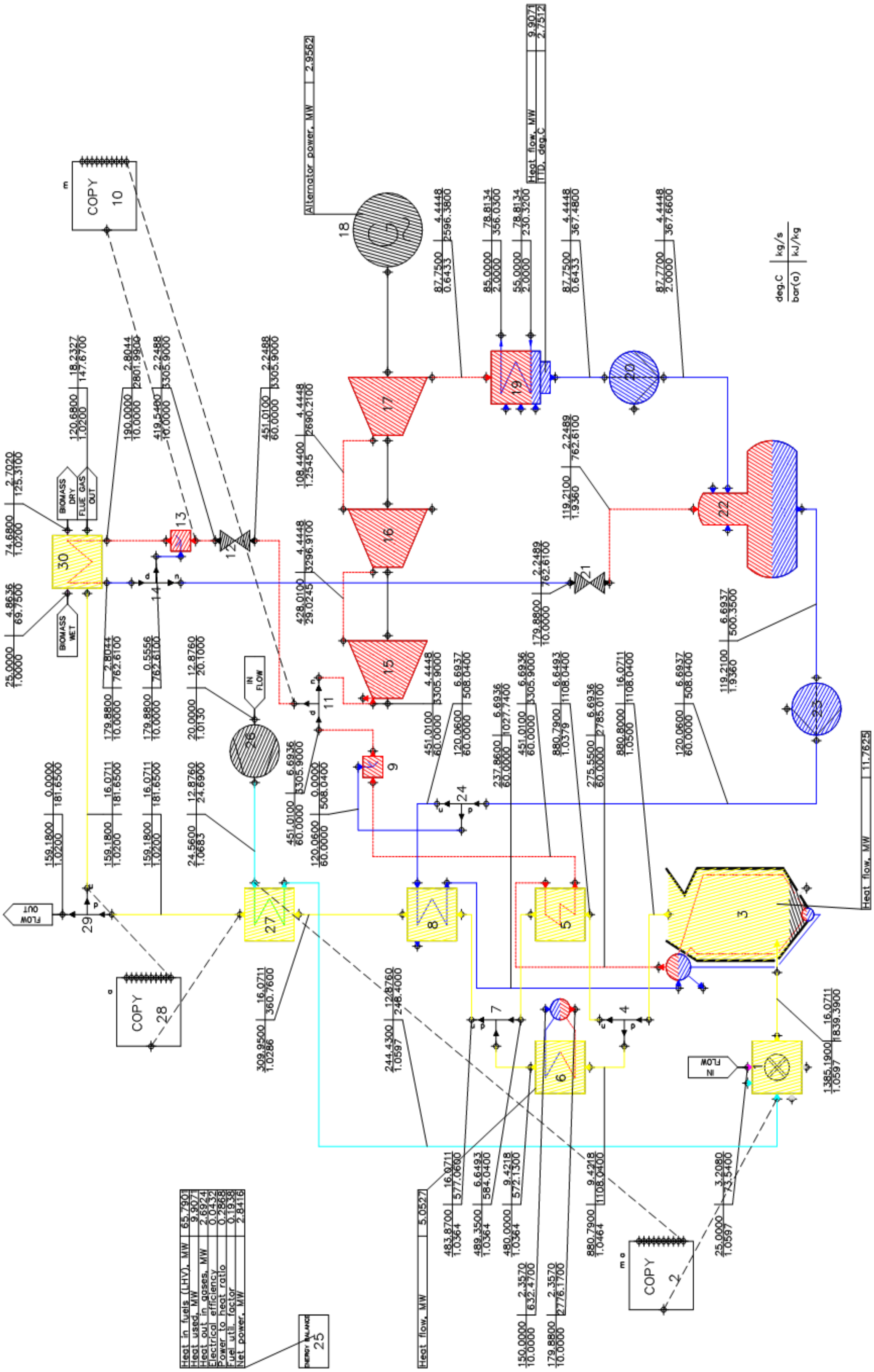
Simulation flowsheet – Radiant furnace integrated case 80 % thermal load



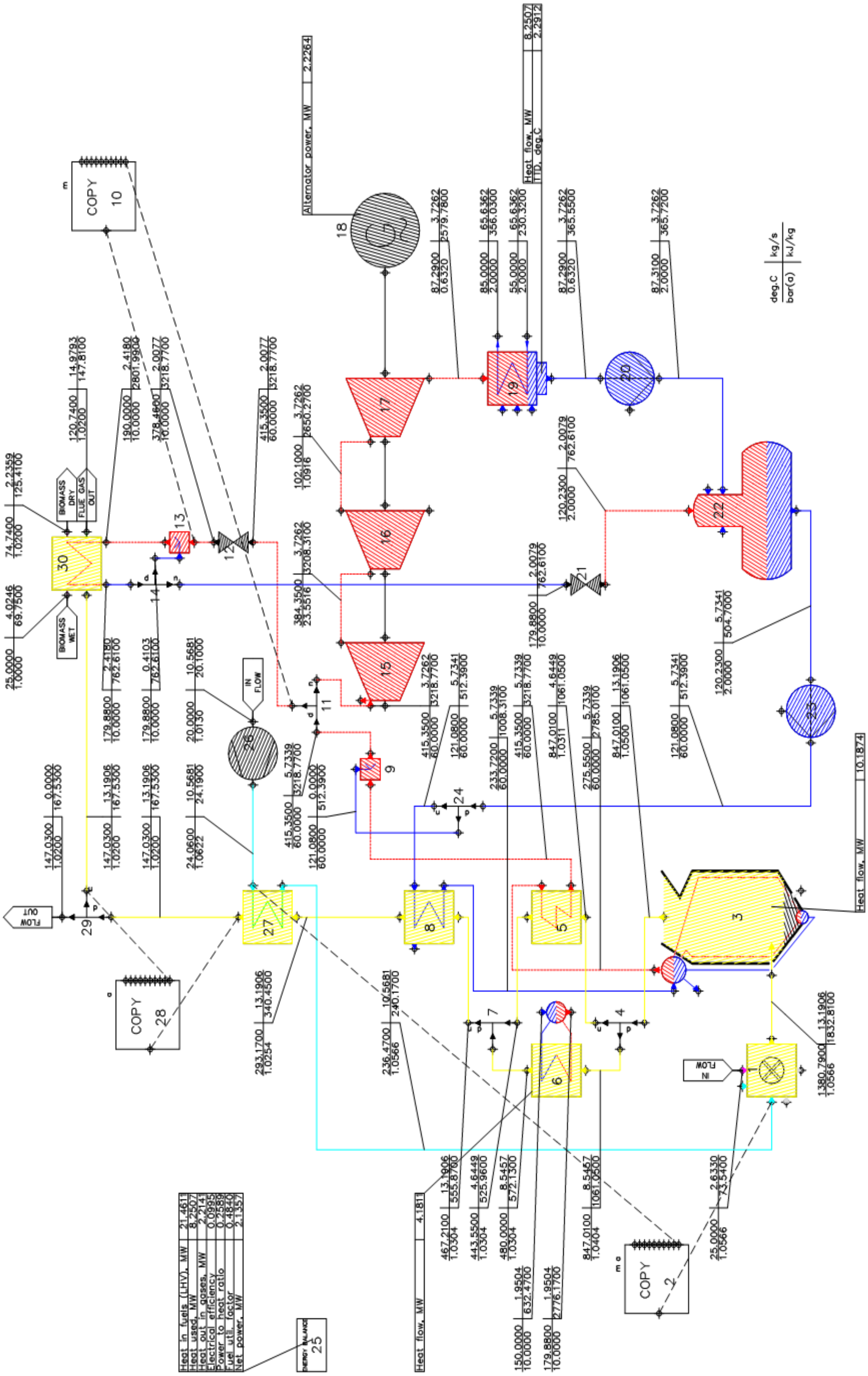
Simulation flowsheet – Radiant furnace integrated case 70 % thermal load



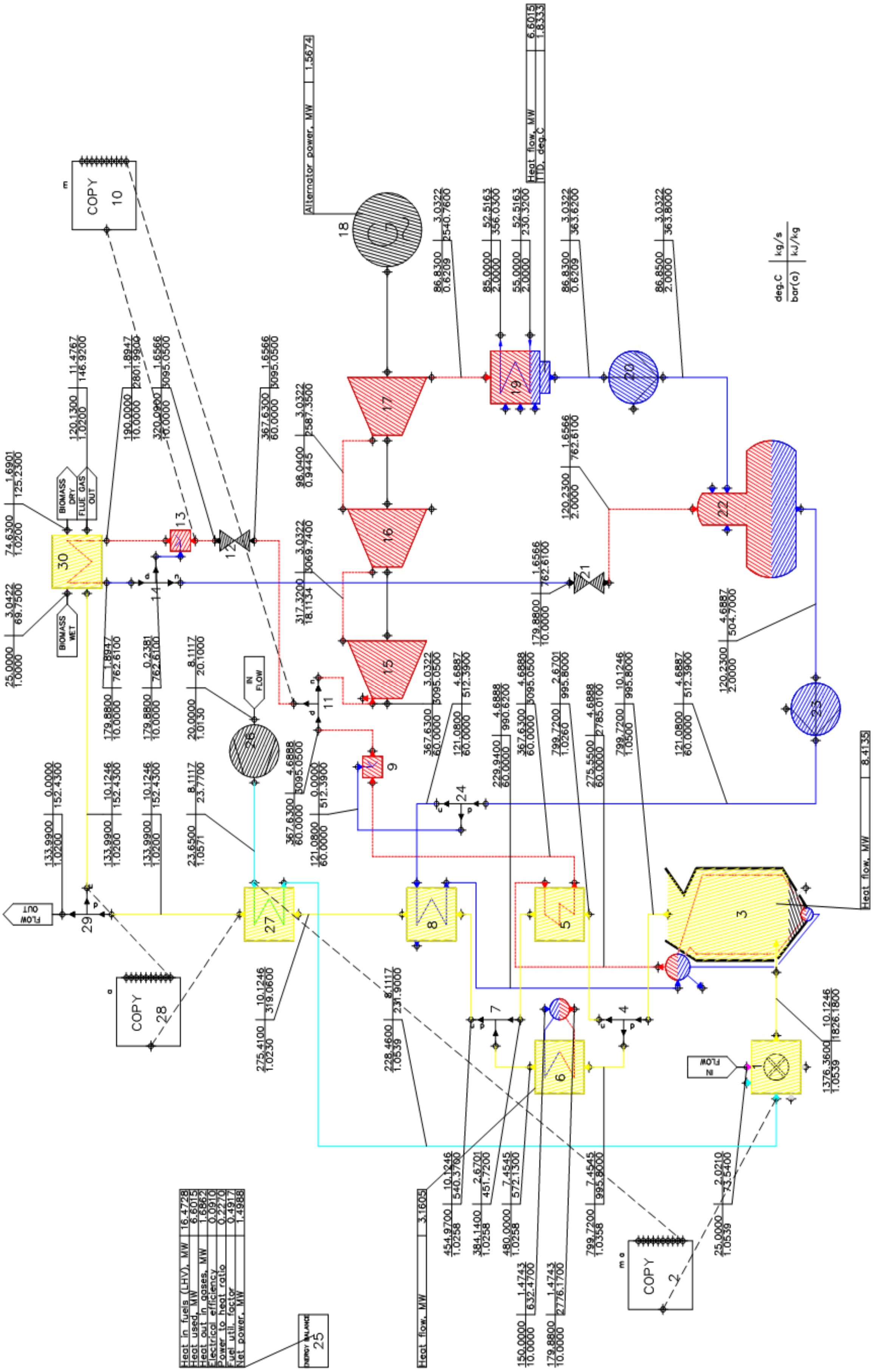
Simulation flowsheet – Radiant furnace integrated case 60 % thermal load



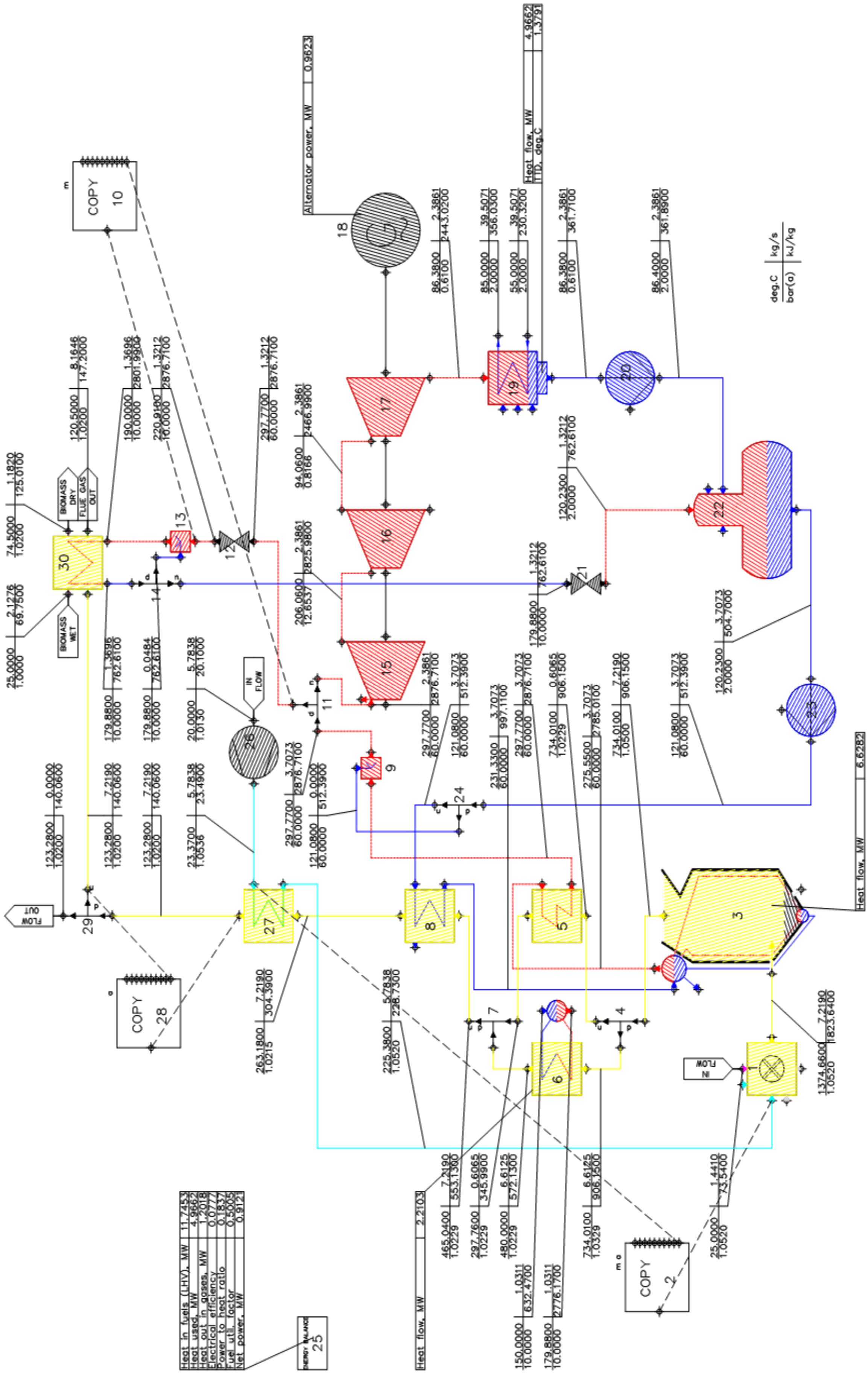
Simulation flowsheet – Radiant furnace integrated case 50 % thermal load



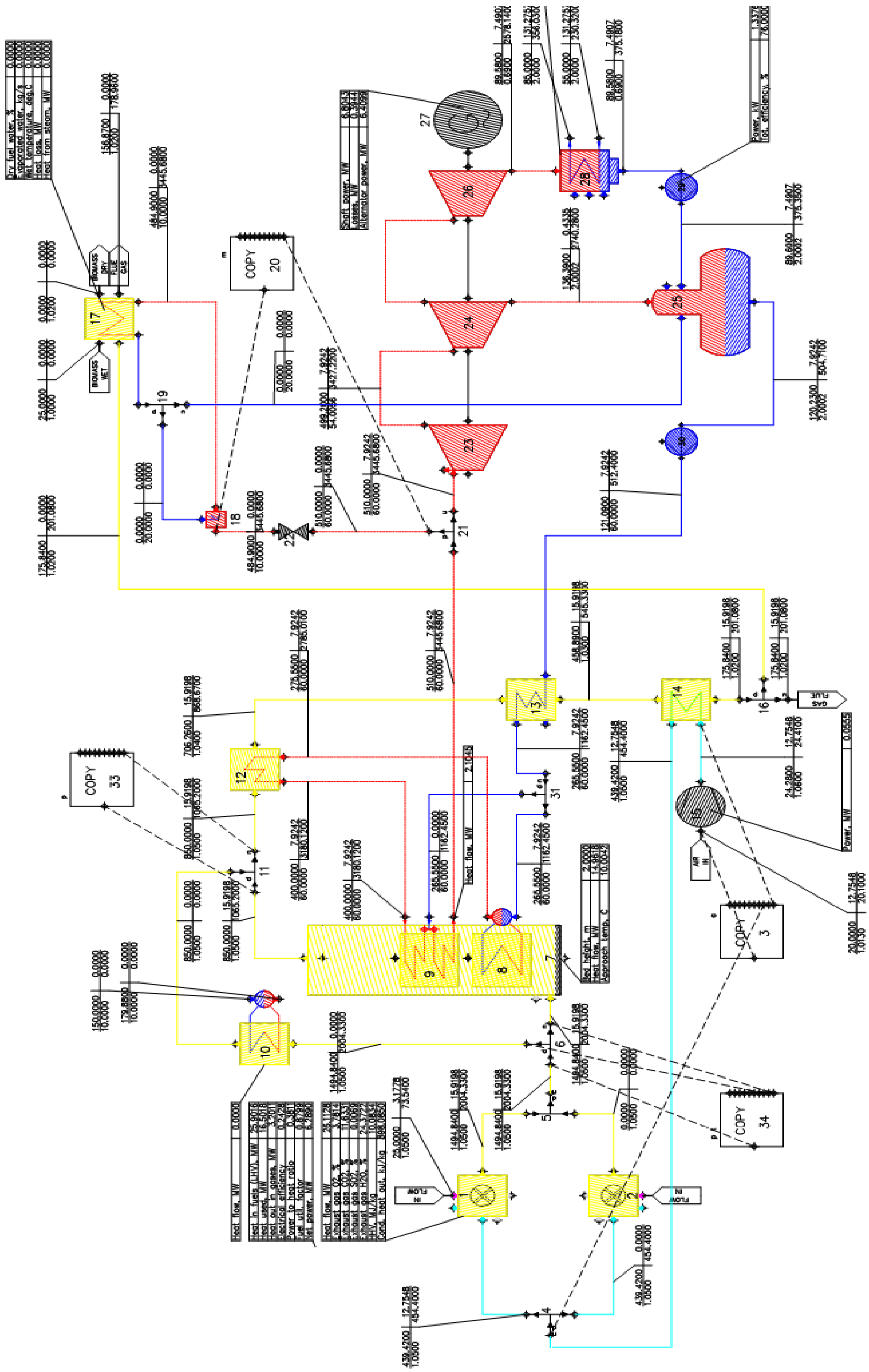
Simulation flowsheet – Radiant furnace integrated case 40 % thermal load



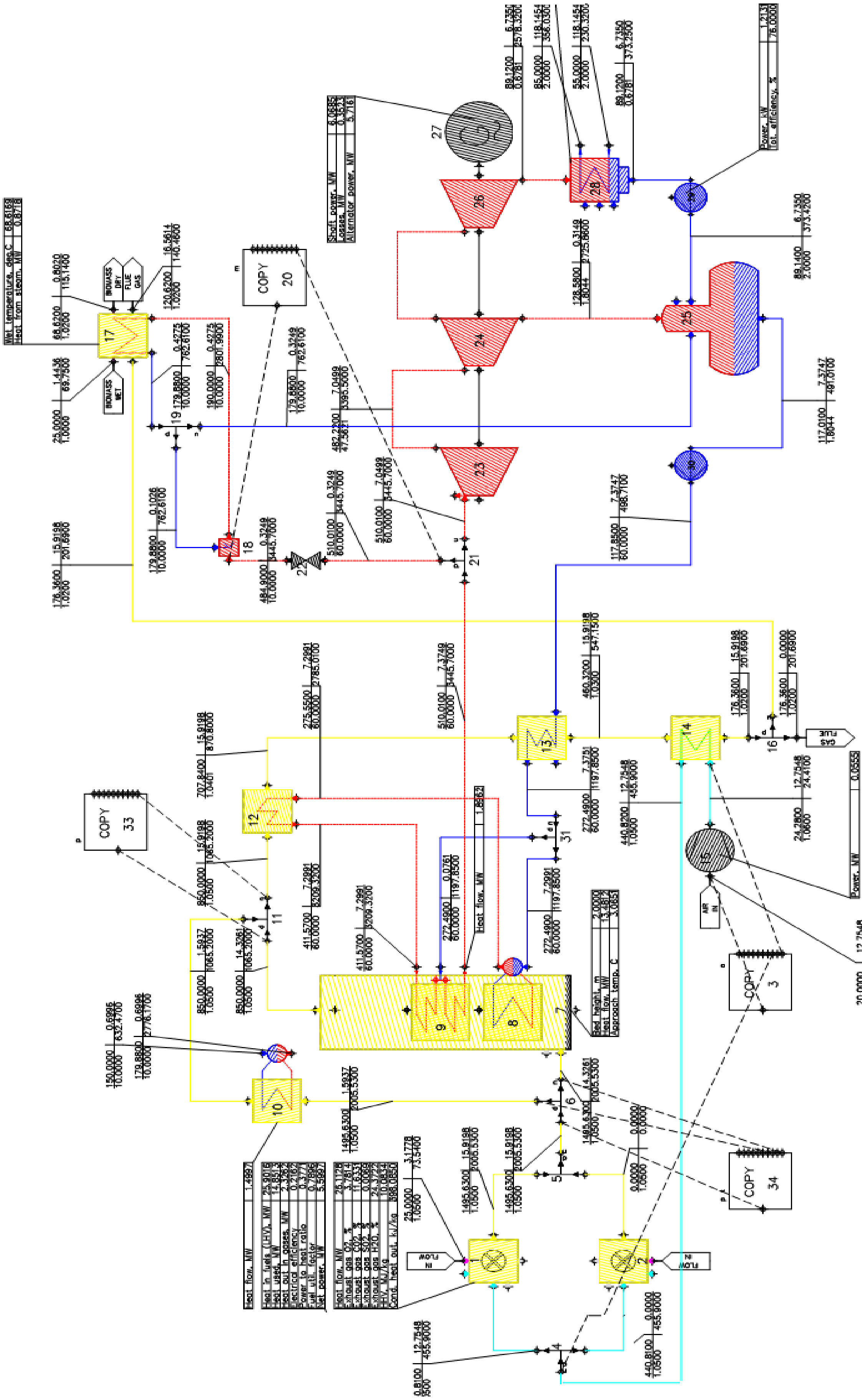
Simulation flowsheet – Radiant furnace integrated case 30 % thermal load



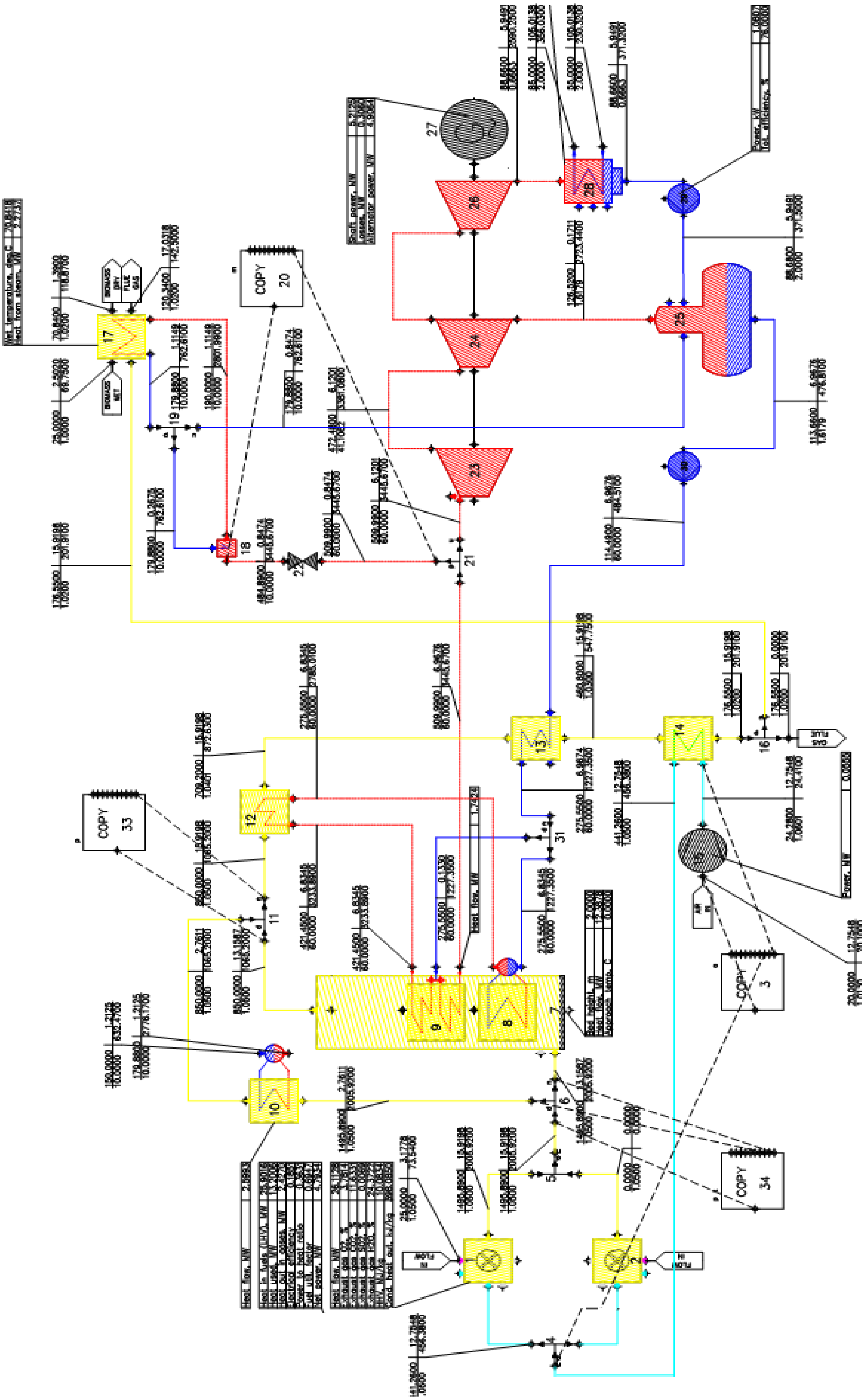
Simulation flowsheet – Circullating Fluidized Bed integrated case 100 % thermal load



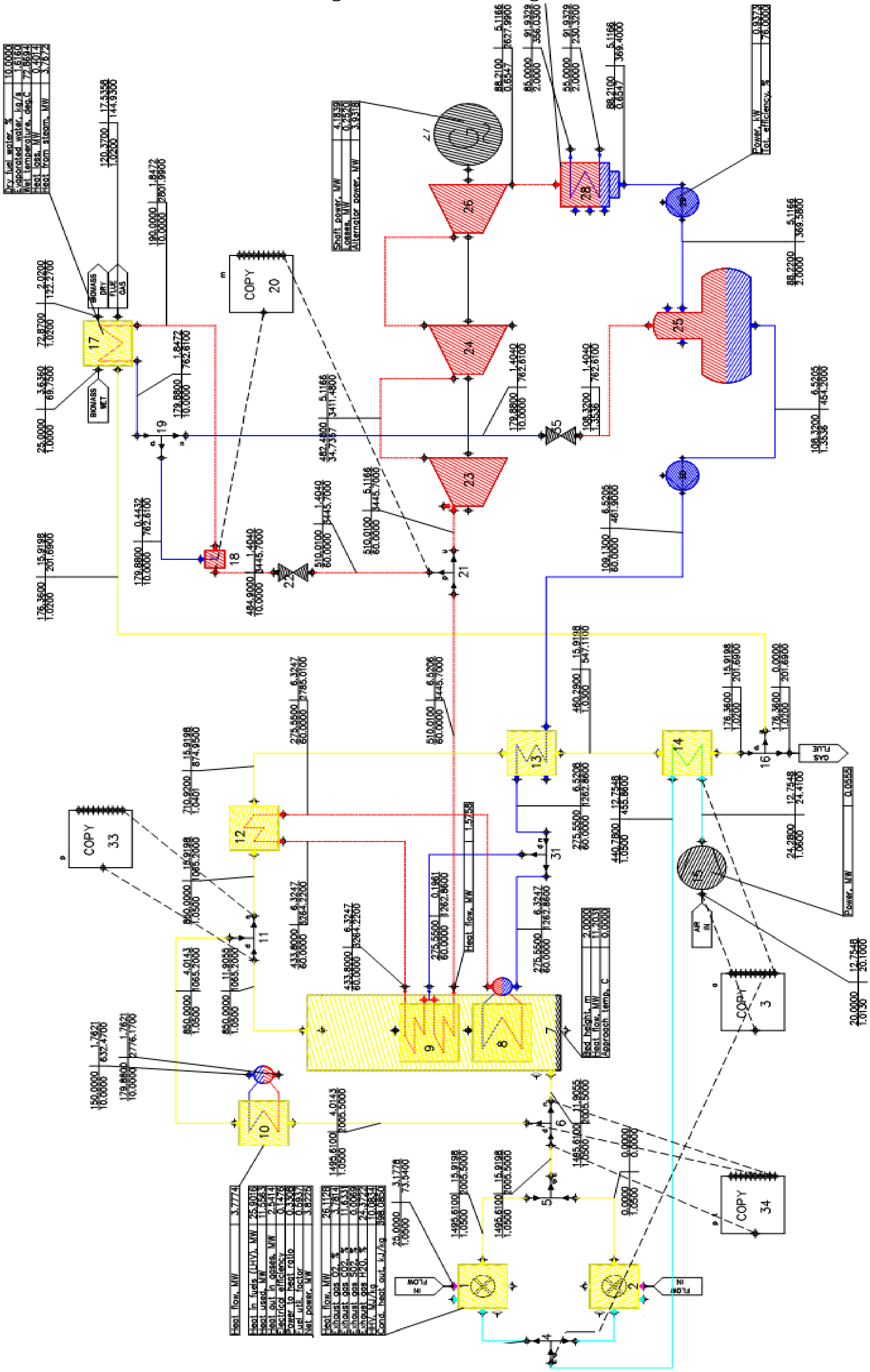
Simulation flowsheet – Circullating Fluidized Bed integrated case 90 % thermal load



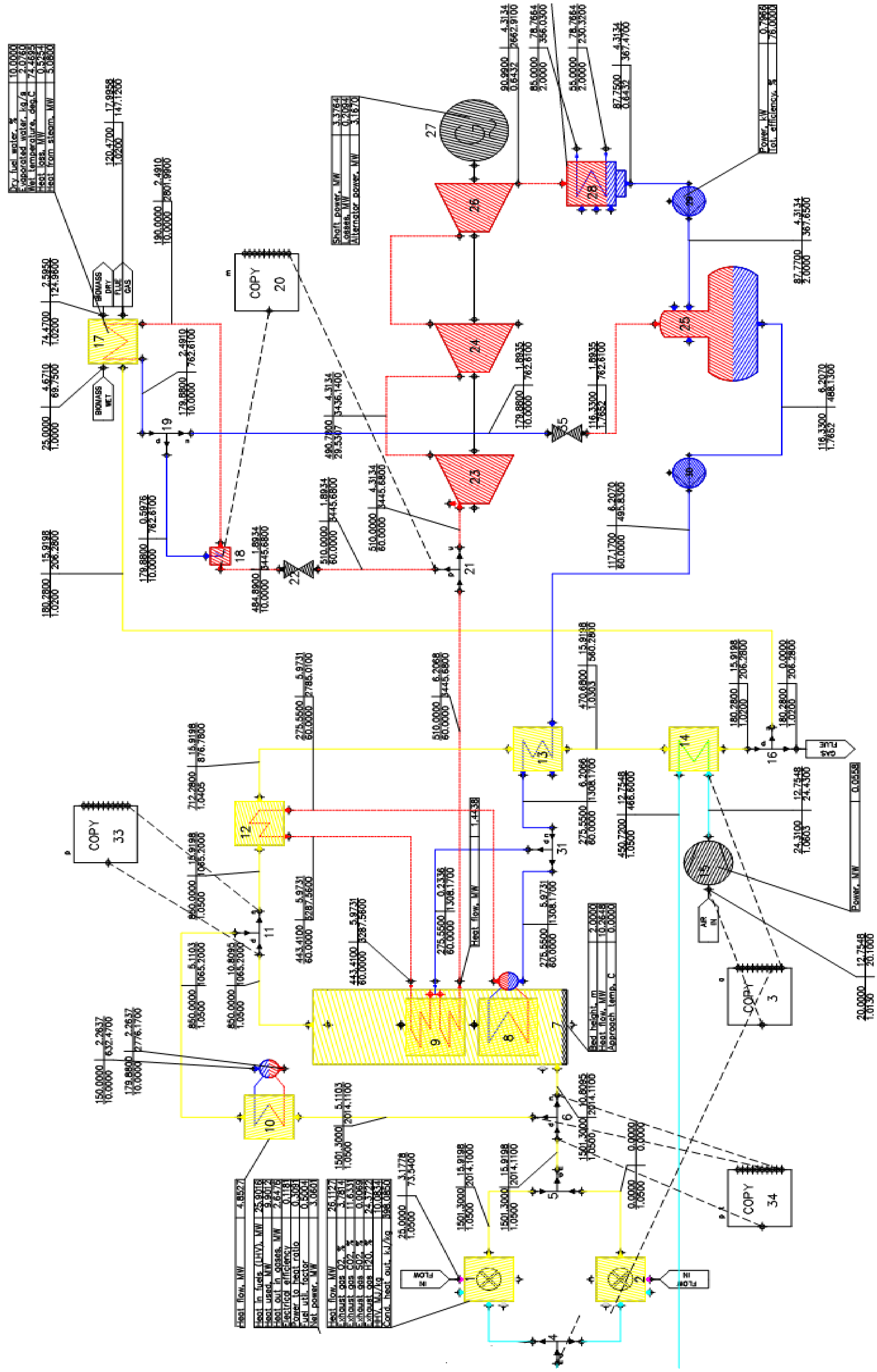
Simulation flowsheet – Circullating Fluidized Bed integrated case 80 % thermal load



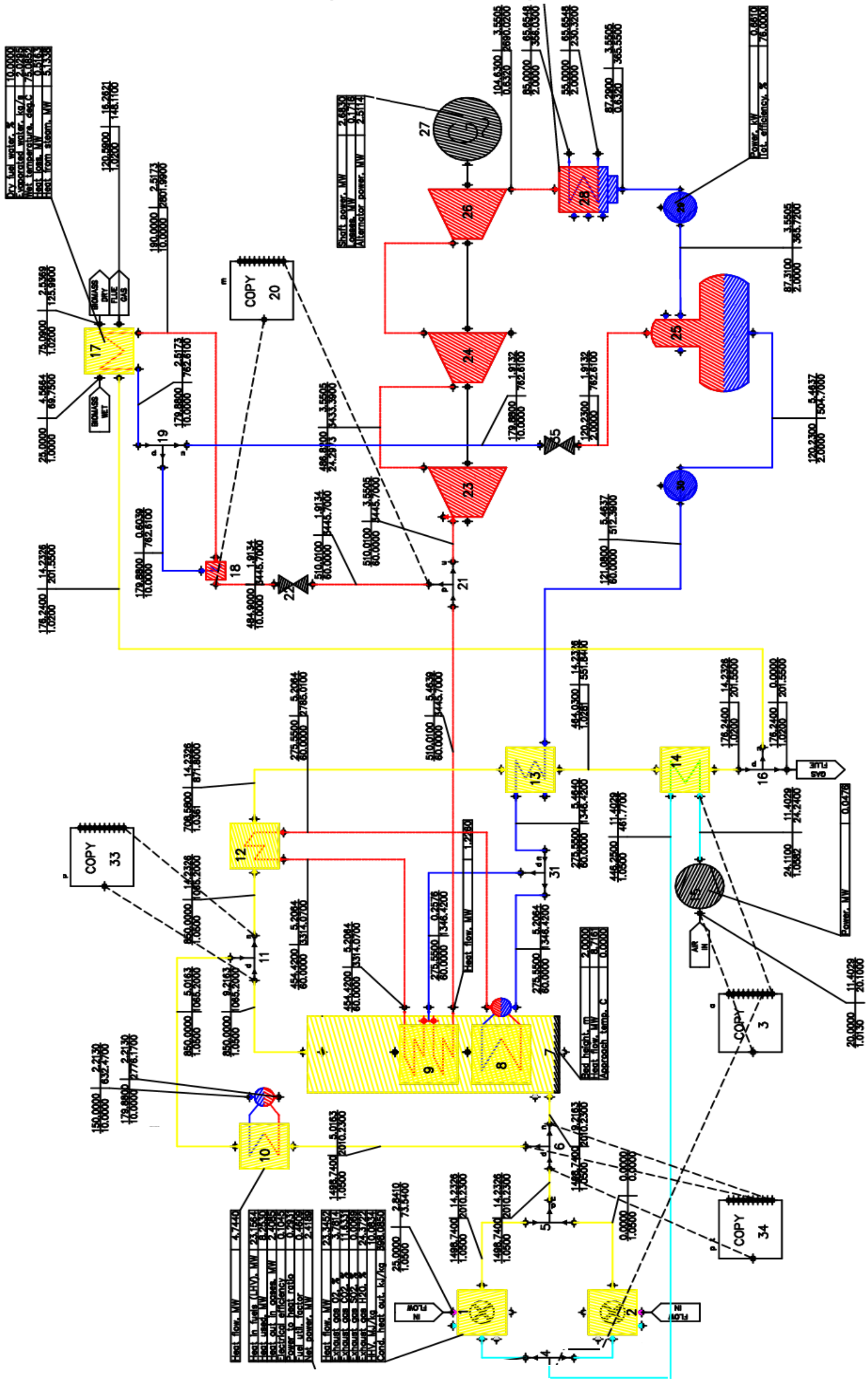
Simulation flowsheet – Circullating Fluidized Bed integrated case 70 % thermal load



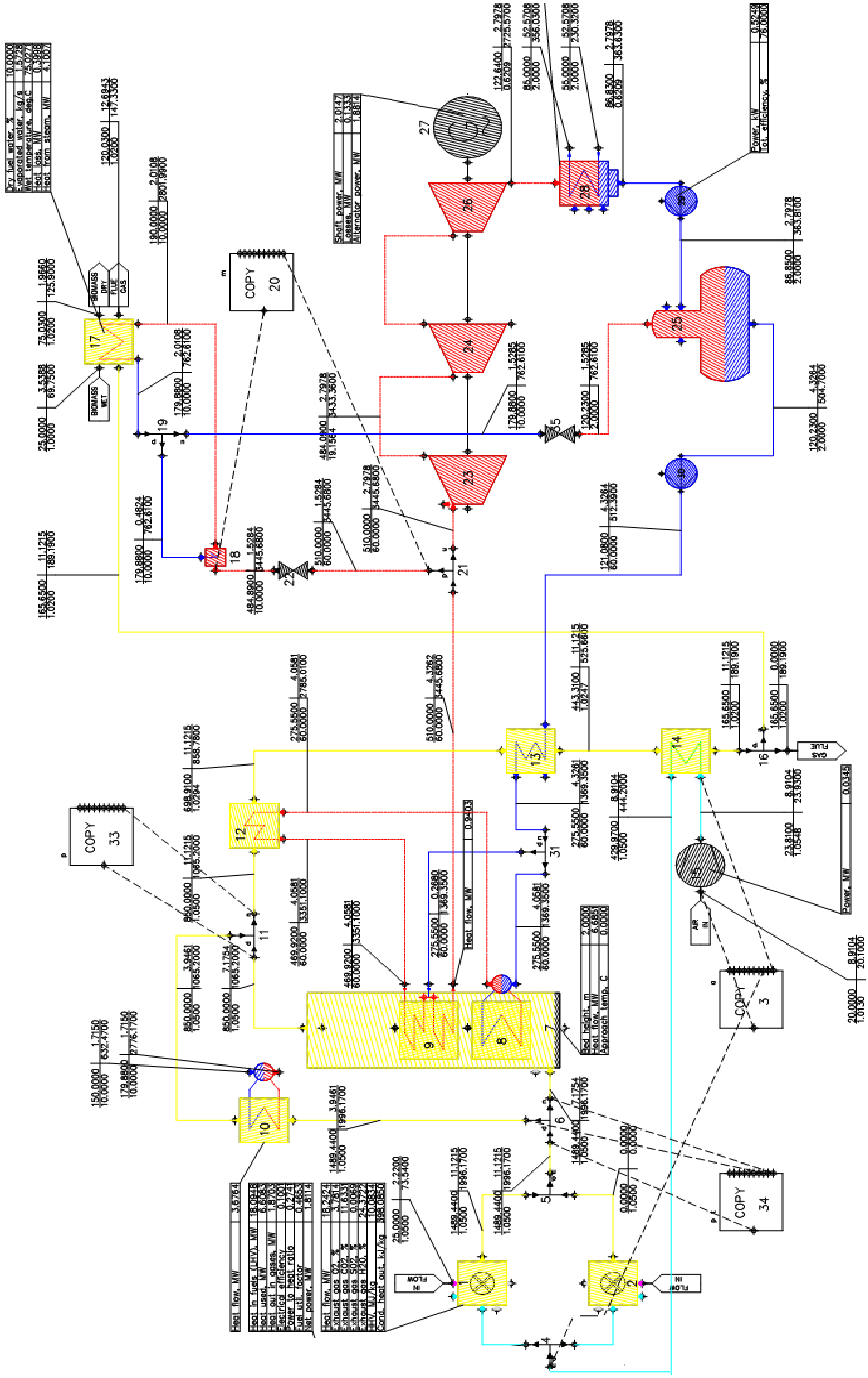
Simulation flowsheet – Circullating Fluidized Bed integrated case 60 % thermal load



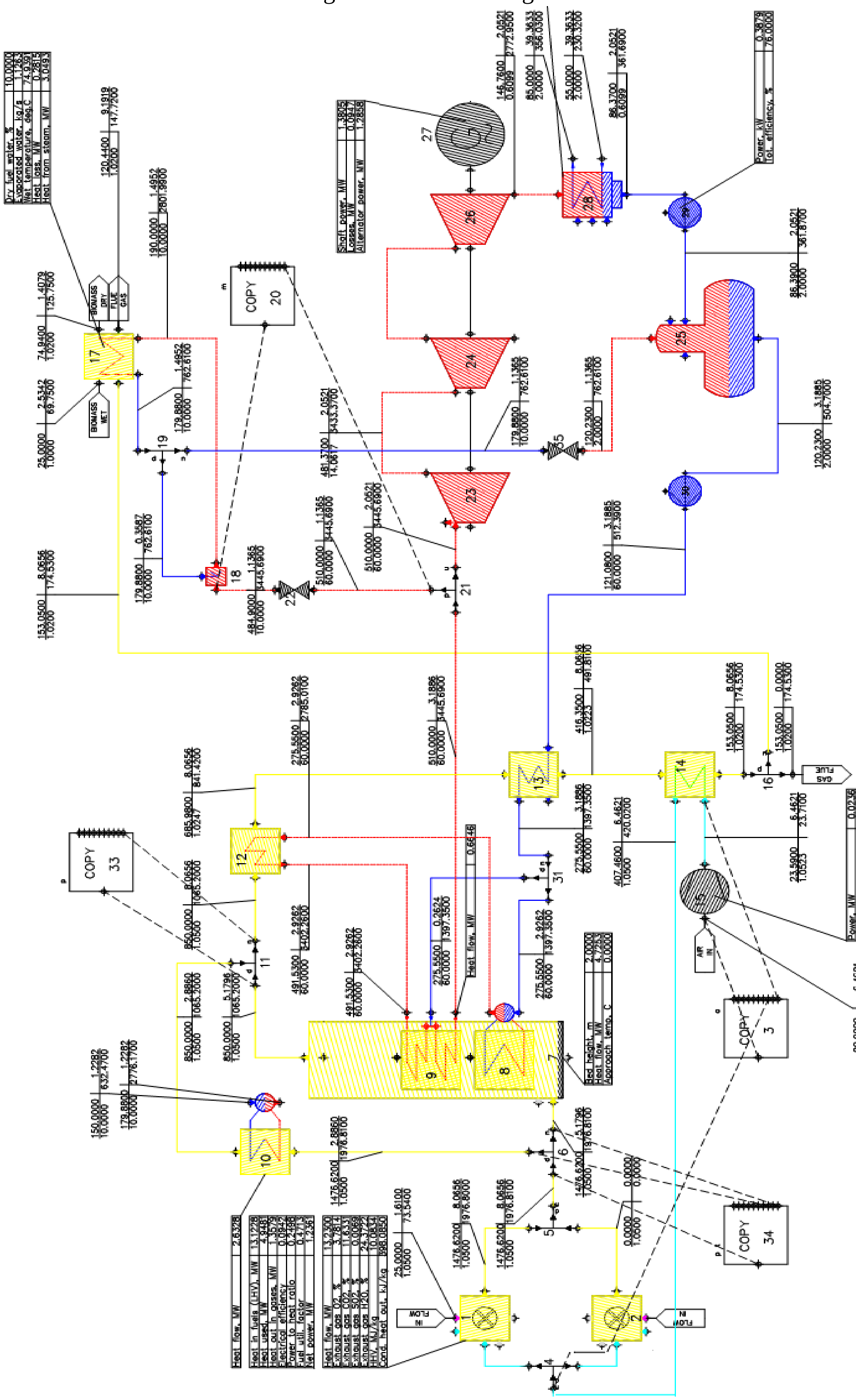
Simulation flowsheet – Circullating Fluidized Bed integrated case 50 % thermal load



Simulation flowsheet – Circullating Fluidized Bed integrated case 40 % thermal load



Simulation flowsheet – Circullating Fluidized Bed integrated case 30 % thermal load



APPENDIX B

Comparison of the simulation results

		RF Base Case									
CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**	Total	
Time	[h]	2440	530	530	530	530	530	-	-	212	days
Fuel input	[MW]	26,15	23,30	20,39	17,39	14,45	11,75	-	-	110,05	GWh
Power	[MW]	6,28	5,65	4,92	4,08	3,24	2,55	-	-	26,16	GWh
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	-	-	70,87	GWh
		RF Integrated Case									
CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**	Total	
Time	[h]	2266	633	633	633	633	633	633	633	279	days
Fuel input	[MW]	26,15	37,31	44,98	53,34	61,29	50,54	38,45	27,12	257,34	GWh
Power	[MW]	6,28	5,59	4,78	3,76	2,84	2,14	1,50	0,91	27,86	GWh
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	6,60	4,95	81,26	GWh
Pyrolysis Slurry	[MW]	-	12,87	21,73	31,38	40,54	33,55	25,36	17,74	115,91	GWh
		BFB/CFB Base Case									
CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**	Total	
Time	[h]	2440	530	530	530	530	530	-	-	212	days
Fuel input	[MW]	25,90	23,19	20,39	17,47	14,58	11,91	-	-	109,56	GWh
Power	[MW]	6,29	5,64	4,91	4,06	3,22	2,54	-	-	26,13	GWh
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	-	-	70,85	GWh
		BFB Integrated Case									
CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**	Total	
Time	[h]	2266	633	633	633	633	633	633	633	279	days
Fuel input	[MW]	25,90	36,49	44,24	52,42	60,21	50,97	39,56	28,88	256,62	GWh
Power	[MW]	6,29	5,54	4,69	3,71	2,88	2,27	1,71	1,18	28,17	GWh
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	6,60	4,95	81,26	GWh
Pyrolysis Slurry	[MW]	-	12,21	21,16	30,60	39,58	33,79	26,11	19,00	115,46	GWh
		CFB Integrated Case									
CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**	Total	
Time	[h]	2266	633	633	633	633	633	633	633	279	days
Fuel input	[MW]	25,90	36,33	43,98	52,17	59,65	56,15	43,66	31,43	263,33	GWh
Power	[MW]	6,29	5,60	4,79	3,82	3,06	2,42	1,81	1,24	28,64	GWh
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	6,60	4,95	81,26	GWh
Pyrolysis Slurry	[MW]	-	12,03	20,86	30,31	38,94	38,07	29,50	21,13	120,76	GWh