MASTER’S THESIS

Gasification of alternative biomass feedstock in a dual fluidized bed gasification

written at the Vienna University of Technology, supervised by

Prof. Hermann Hofbauer

Matthias Kuba

Katharina Wagner

E166 Institute of Chemical Engineering

Monica Martin

01638163

Vienna, July 17th, 2017

Monica Martin

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

MÁSTER EN INGENIERÍA INDUSTRIAL

GASIFICATION OF ALTERNATIVE BIOMASS FEEDSTOCK IN A DUAL FLUIDIZED BED GASIFICATION

Autor: Mónica Martín Garijo
Director: Hermann Hofbauer

Madrid
Agosto 2017

ABSTRACT

Reducing greenhouse gas emissions, cutting the dependency on non-renewable energy sources characterized by fluctuating prices and usually located in countries with a non-stable political situation, as well as promoting the locally available energy sources are objectives that could mean a boost in the development of renewable energy sources. Wind, solar power, or hydropower are nowadays well known and widely implemented with the aim of replacing a significant share of fossil fuels as primary energy; however, seasonality and intermittency characterize these renewable sources, being the biomass the only renewable carbon carrier with the possibility of being stored. Biomass, as produced, is solid and difficult to be used without conversion into gaseous and liquid energy carriers. Hence, biomass gasification and specifically the dual fluidized bed (DFB) steam gasification is a promising technology that converts a wide range of feedstocks into a medium calorific product gas to produce electricity, heat, fuels, and chemicals.

Even though biomass is considered to be the only alternative to fossil fuels, it is difficult to compete against the plummeting prices of fossil fuels. It is true that harmful long-term effects of fossil fuels are insufficiently included in the economic analysis and for that reason, governments should promote the research and investment in biomass plants by awarding incentives in return for taking risks.

This thesis proves the economic disadvantages of using biomass to supply the heat demand of a kiln or boiler instead of using fossil fuels. The industrial gasification plant which is chosen to carry out the economic study is Güssing (Austria), as Vienna University of Technology (TU Wien) initially demonstrated there the DFB technology, several researches have been completed at this plant and moreover, the data are of sufficient quality to carry out an economic analysis. This analysis leads to the conclusion that even increasing the capacity of the plant and taking advantages from economies of scale, would not be enough to overthrow fossil fuel prices. However, a glimmer of hope comes linked to the fuel flexibility of the novel DFB steam gasification pilot plant at TU Wien that allows alternative biogenic feedstocks to be gasified. These alternative feedstocks such as chicken manure or exhausted olive pomace mean a waste stream and gasification could be a solution for getting rid of them.

Three test runs were successfully carried out at TU Wien, which proves the technical feasibility of gasifying alternative feedstocks such as bark and chicken manure with K-feldspar (potassium feldspar) as bed material that has not been used so far at the pilot plant. In particular, the gasification of softwood pellets, a mixture of chicken manure/bark pellets, and pure chicken manure pellets with K-feldspar as bed material represents the core of the experimental part of the present work. Additionally, these tests are compared to the traditional gasification of softwood and olivine.

The alternative feedstocks analysed in this thesis are characterized by high ash content with components that can cause fouling, slagging, and bed material agglomeration, causing unscheduled downtimes and damages in downstream equipment. Despite the diversity in fuel composition, the product gas composition is not strongly affected. Furthermore, inorganic matter is related not only to the dust content, but also to their catalytic activity allowing tar content in the product gas to be reduced. Therefore, softwood is the biomass feedstock with the lowest ash content among the ones studied but also its product gas is the one with the highest tar content (considering only experiments with K-feldspar).

Regarding bed materials, the catalytic activity of olivine, as well as its heat transfer capacity, is higher compared to K-feldspar. It is known that K-feldspar is not characterized as an excellent catalytically active bed material; however, the presence of char and ash content due to the chemical composition of the alternative feedstocks can enhance the catalytic reactions to reduce tar content in the product gas.

New biomass feedstocks, and especially the ones that come from waste streams, help operating costs of the gasification process to be lowered. According to that, operating costs from the gasification of woody feedstocks can be cut by 40% when using alternative biomass forms.

RESUMEN

Reducir las emisiones de gases de efecto invernadero, eliminar la dependencia en fuentes de energía no renovables caracterizadas por precios fluctuantes y normalmente localizadas en áreas con una situación política inestable, así como promocionar las fuentes de energía disponibles localmente, son objetivos que pueden contribuir al desarrollo de fuentes de energía renovable. Las energías eólica, solar e hidráulica son ampliamente conocidas e implantadas con el objetivo de reemplazar una parte significante de los combustibles fósiles usados como fuente primaria de energía; sin embargo, estas energías renovables están caracterizadas por estacionalidad e intermitencia, lo que convierte a la biomasa en la única fuente renovable de carbón con capacidad para ser almacenada. La biomasa, tal y como es obtenida, es sólida y difícil de usar si no se convierte previamente a formas líquidas o gaseosas. Así, la gasificación de biomasa, y concretamente, la gasificación con vapor basada en el doble lecho fluidizado (DFB, "dual fluidized bed") es una prometedora tecnología que convierte una amplia gama de materias primas de biomasa en un gas de poder calorífico medio para producir electricidad, calor, combustibles, y productos químicos.

A pesar de que la biomasa es considerada como la alternativa a los combustibles fósiles, es difícil competir contra los bajos precios de dichos combustibles fósiles. Es cierto que los efectos perjudiciales que pueden ocasionar a largo plazo los combustibles fósiles como el carbón, el gas natural, o el petróleo no suelen ser considerados en los estudios económicos. Y es por esta razón por la que los gobiernos deberían promocionar la investigación e inversión en plantas de biomasas recompensando con incentivos a los inversores que han tomado riesgos.

Este trabajo de máster muestra las desventajas económicas al usar biomasa para abastecer la demanda de calor de hornos o calderas, en lugar de usar combustibles fósiles tradicionales. La planta de gasificación industrial elegida para llevar a cabo el estudio económico es Güssing (Austria), puesto que fue allí donde la Universidad de Viena demostró inicialmente la tecnología DFB y donde un sinfín de investigaciones han sido completadas, siendo los datos obtenidos de Güssing de calidad suficiente para llevar a cabo una evaluación económica. Dicho estudio conduce a la conclusión de que incluso incrementando la capacidad de la planta y aprovechando las ventajas de las economías de escala, no sería suficiente para derrocar a los tradicionales combustibles fósiles. Sin embargo, un halo de esperanza vendría motivado por la flexibilidad que ofrece la nueva planta piloto de la Universidad de Viena que permite gasificar combustibles biogénicos alternativos. Esas materias primas alternativas tales como el estiércol de pollo o el orujillo (EOP, "exhausted olive pomace") representan una corriente de residuos y su

gasificación podría ser una solución al problema que supone deshacerse de unos residuos altamente contaminantes.

Tres pruebas de gasificación han sido exitosamente llevadas a cabo en la planta de la Universidad de Viena (TU Wien), lo que demuestra la viabilidad técnica de gasificar combustibles alternativos como cortezas de madera y estiércol de pollo con feldespato como material de lecho, siendo la primera vez que se usa este material en la planta piloto. Concretamente, la gasificación de aglomerados (pellets) de madera, de una mezcla de estiércol de pollo y corteza, así como de estiércol de pollo puro con feldespato de potasio como material de lecho representa el núcleo de la parte experimental del presente trabajo de fin de máster. Además, dichos experimentos son comparados con la gasificación tradicional de madera con olivino.

Los combustibles alternativos analizados en este proyecto son caracterizados por un alto contenido en cenizas con componentes que pueden causar suciedades, obstrucciones y aglomeraciones del material de lecho, causando paradas prematuras de la planta y deterioros en los componentes del proceso posterior a la gasificación. A pesar de la variedad en la composición de las materias primas, la composición del gas producto obtenido no se ve fuertemente afectada. Además, la materia inorgánica del combustible está relacionada no solo con el contenido en polvo, sino también con la actividad catalítica que permite reducir el contenido de alquitrán en el gas producto. Por lo tanto, los gránulos de madera de coníferas (softwood pellets) tienen el menor contenido de ceniza de entre todos los combustibles analizados, pero también presentan el mayor contenido de alquitrán (considerando únicamente experimentos con feldespato).

En cuanto a los materiales de lecho, la actividad catalítica del olivino, así como su capacidad de transferencia de calor, es mayor en comparación con el feldespato. Aunque el feldespato no se caracteriza por ser un material de lecho muy activo catalíticamente, la presencia de compuestos carbonizados y cenizas puede mejorar las reacciones catalíticas que tienen lugar y que reducen el contenido de alquitranes en el gas producto.

Las nuevas materias primas de biomasa, y especialmente aquellas que se originan a partir de corrientes de residuos, ayudan a reducir los costes de operación del proceso de gasificación. Así, los costes de operación incurridos durante la gasificación de biomasa maderera pueden recortarse alrededor de un 40% cuando se usan formas de biomasa alternativas.

ACKNOWLEDGEMENTS

First of all, I thank TU Wien for giving me the opportunity to spend my final year of my Master's studies in a wonderful city surrounded by nice people while studying in a prestigious university. Specially, I would like to express my sincere thanks and appreciation to Hermann Hofbauer for allowing me to carry out this work at the Institute of Chemical Engineering.

I also like to extent my thanks to my supervisors Matthias Kuba and Katharina Wagner for their wisdom and very helpful advices. To the other members of the *Gasification and Gas Cleaning Research Team* as well as *Bioenergy2020+*, thank you for your friendship and shared knowledge and for creating a nice working atmosphere.

I am very thankful for the Spanish support, not only the one received from the people I have met here, but also the unconditional encouragement received from Spain, which has done easier my stay in Vienna, especially during the first months.

To sum up, thanks to everyone who has contributed to fill my suitcase with valuable experiences and unforgettable memories.

Thank you all!

Vienna, July 2017

TABLE OF CONTENTS

ABSTRACT i

RESUMEN iii

ACKNOWLEDGEMENTS v

TABLE OF CONTENTS vi

LIST OF FIGURES viii

LIST OF TABLES x

LIST OF ABBREVIATIONS AND SYMBOLS xii

1. INTRODUCTION 1
  - 1.1. Background 1
  - 1.2. Aim and scope of this work 3

2. FUNDAMENTALS 5
  - 2.1. Biomass 5
  - 2.2. Energy from biomass 9
    - 2.2.1. Current situation of biomass in the energy field 9
    - 2.2.2. Future of biomass in the energy field 12
  - 2.3. Thermochemical conversion 13
  - 2.4. Practical aspects of biomass gasification 16
    - 2.4.1. Fundamentals 16
    - 2.4.2. Gasification technologies 19
    - 2.4.3. Product gas applications 28
    - 2.4.4. Gas treatment 30
  - 2.5. Principles of dual fluidized bed (DFB) gasification 37

3. EXPERIMENTAL SETUP 39
  - 3.1. Motivation and methodology 39
  - 3.2. Description of the 100 kW Pilot Plant TU Wien 40
  - 3.3. Analytics 45
    - 3.3.1. Measurement of main product gas composition and flue gas 45

3.3.2. Tar, char and dust measurements 46
3.4. Biomass feedstocks 47
3.5. Bed materials 50
4. RESULTS 52
4.1. General overview of the gasification of alternative feedstocks 52
4.2. Results of the gasification test run I with softwood 54
4.3. Results of the gasification test run II with chicken manure/bark 57
4.4. Results of the gasification test run III with pure chicken manure 60
4.5. Comparison of the gasification test runs 63
5. ECONOMIC EVALUATION 69
5.1. Introduction 69
5.2. Commercial plants - Güssing, Austria 71
5.3. Gasification of wood chips for co-firing and firing applications 75
5.4. Gasification of different biomass feedstocks 85
6. CONCLUSION 92
REFERENCES 95
APPENDIX 102

LIST OF FIGURES

Figure 1. Global carbon dioxide emissions (Million Mg CO_2), 1850-2030 [3] 1
Figure 2. Percentage of import dependency (%) in the EU-28, 1990-2014 [5] 2
Figure 3. Different generations of biomass and possible uses. Adapted from [18] 6
Figure 4. Different bases for expressing fuel composition [17]... 8
Figure 5. Gross electricity generation (TWh) in the EU-28, 1990-2014 [5] 10
Figure 6. Gross heat generation (PJ-GCV) in the EU-28, 1990-2014 [5] 11
Figure 7. Fuel consumption in the transport sector (ktoe) in the EU-28, 1990-2014 [5].. 11
Figure 8. Promoters for large-scale biomass production. Adapted from [18] 12
Figure 9. Barriers for large-scale biomass production. Adapted from [18]...................... 13
Figure 10. Conversion processes, products and applications of biomass [24] 14
Figure 11. Possibilities for thermal conversion of biomass [25].. 15
Figure 12. Processes during gasification of a single particle [24] 17
Figure 13. Classification criteria for gasification technologies. Adapted from [20]........ 19
Figure 14. Classification of gasification processes based on heat supply and gasification agents. Adapted from [24] 20
Figure 15. Different configurations of biomass gasifiers. Adapted from [31] 21
Figure 16. Types of fixed bed gasifiers. Adapted from [17] 22
Figure 17. Types of fluidized bed gasifiers. Adapted from [24] 24
Figure 18. Typical process routes for electricity generation [24] 25
Figure 19. Types of entrained flow gasifiers [17] 26
Figure 20. Preferred type of gasifier for different scale application [37] 27
Figure 21. Different end-use applications for biomass gasification 29
Figure 22. Main components of the product gas [26] 30
Figure 23. Classification of tars regarding temperature [46]... 34
Figure 24. Available options for tar reduction [17] 35
Figure 25. Operation principle of the DFB gasification process (TU Wien)..................... 37
Figure 26. Methodology for gasification trials at the TU Wien pilot plant 40
Figure 27. Basic flow sheet of the overall DFB gasification facility, adapted from [28] . 41
Figure 28. Schematic illustration of the DFB reactor system (TU Wien [28]) 42
Figure 29. Uninsulated combustion reactor of the DFB system (TU Wien [61]) 44
Figure 30. Overview of the gas measurement equipment [56] 45
Figure 31. Gas cleaning line for gas analysis [10,56] 46
Figure 32. Dust, char, water and tar measurement equipment [10]................................. 46
Figure 33. Product gas composition when carrying out test run I with softwood [57].. 52
Figure 34. Product gas composition when carrying out test run II with chicken manure/bark [57] 53

Figure 35. Product gas composition when carrying out test run III with pure chicken manure [57] 53
Figure 36. Average temperature profiles of the GR and CR for the test run I [57] 54
Figure 37. Average temperature profiles of the GR and CR for the test run II [57] 57
Figure 38. Average temperature profiles of the GR and CR for the test run III [57] 60
Figure 39. Comparison among elemental composition of feedstocks 65
Figure 40. Comparison of main product gas composition 66
Figure 41. Comparison of char and dust content in product gas 67
Figure 42. Comparison of tar content in product gas 68
Figure 43. Renewable energies as a percentage of TPES (%) in IEA member countries, 2014 [75] 69
Figure 44. Front view of the CHP plant in Güssing [76] 71
Figure 45. Flow sheet of the CHP plant in Güssing [77] 72
Figure 46. Flow chart of the gasification process considered in the present economic study. Adapted from [79,82] 76
Figure 47. Selling price of product gas depending on the capacity vs fossil fuel prices (€/MWh) 83
Figure 48. Fuel costs (Mi€) of meeting the boiler energy demand (MW) 84
Figure 49. Breakdown of the OPEX for each of the five considered alternatives (Mi€) . 90

LIST OF TABLES

Table 1. Different sources of biomass [2] ... 6
Table 2. Influence of biomass properties on the gasification system [19] ... 7
Table 3. Gasification reactions [28] ... 18
Table 4. Comparison between gasifier designs [17] ... 26
Table 5. Fuel gas contaminants, problems and cleaning methods [23] ... 31
Table 6. Gas specifications depending on the final gas application [20] ... 31
Table 7. Classification of tars based on the physical properties [49, 50] ... 34
Table 8. Industrial installations with DFB gasifiers [55] ... 38
Table 9. Design values for geometric and operating parameters of the DFB system. Adapted from [61] ... 44
Table 10. Fuel and ash analysis of feedstocks used for the gasification test run: wood pellets, chicken manure/bark and pure chicken manure ... 49
Table 11. Composition of potassium feldspar, calcite and olivine ... 51
Table 12. Main operating conditions of the gasification test run I [57] ... 55
Table 13. Main product gas components of the gasification test run I [57] ... 56
Table 14. Additional product gas components measured offline with toluene as solvent, test run I [57] ... 56
Table 15. Main composition of the flue gas, test run I [57] ... 56
Table 16. Main operating conditions of the gasification test run II [57] ... 58
Table 17. Main product gas components of the gasification test run II [57] ... 59
Table 18. Additional product gas components measured offline with toluene as solvent, test run II [57] ... 59
Table 19. Main composition of the flue gas, test run II [57] ... 59
Table 20. Main operating conditions of the gasification test run III [57] ... 61
Table 21. Main product gas components of the gasification test run III [57] ... 62
Table 22. Additional product gas components measured offline with toluene as solvent, test run III [57] ... 62
Table 23. Main composition of the flue gas, test run III [57] ... 62
Table 24. Process parameters of gasification test runs with different fuels and bed material [57,58] ... 64
Table 25. Characteristic data of the plant in Güssing [55] ... 71
Table 26. Composition of wood chips [9,10] ... 73
Table 27. Operational data of the DFB gasification plant in Güssing ... 74
Table 28. Product gas composition of Güssing [79,53] ... 74
Table 29. Commercial plants for indirect co-firing and for heat production to lime and cement kilns [80,20] ... 75

Table 30. Cost rates for economic calculations 78
Table 31. Parameter for the NPV calculation 79
Table 32. Cost flows of the gasification plant along its expected lifetime (Millions €) .. 80
Table 33. Selling price of the product gas when comparing different capacities based on the base case 82
Table 34. Fossil fuel prices 82
Table 35. Main properties of the different biomass feedstocks and bed materials 87
Table 36. Operational data for a plant when gasifying different feedstock with distinct bed materials 88
Table 37. Unit operating costs of the different alternative 89
Table 38. Operating expenses for each of the five considered alternatives (Mi€) 90

Table A- 1. Operational data of a 16 MW DFB gasification plant 102
Table A- 2. Cost rates for economic calculations of a 16 MW plant 102
Table A- 3. Cost flows of a 16 MW gasification plant along its expected lifetime 103
Table A- 4. Operational data of a 32 MW DFB gasification plant 104
Table A- 5. Cost rates for economic calculations of a 32 MW plant 104
Table A- 6. Cost flows of a 32 MW gasification plant along its expected lifetime 105
Table A- 7. Operational data of a 64 MW DFB gasification plant 106
Table A- 8. Cost rates for economic calculations of a 64 MW plant 106
Table A- 9. Cost flows of a 64 MW gasification plant along its expected lifetime 107
Table A- 10. Operational data of a 96 MW DFB gasification plant 108
Table A- 11. Cost rates for economic calculations of a 96 MW plant 108
Table A- 12. Cost flows of a 96 MW gasification plant along its expected lifetime 109
Table A- 13. Operational data of a 128 MW DFB gasification plant 110
Table A- 14. Cost rates for economic calculations of a 128 MW plant 110
Table A- 15. Cost flows of a 128 MW gasification plant along its expected lifetime 111

LIST OF ABBREVIATIONS AND SYMBOLS

A	Ash
ASU	Air separation unit
BFB	Bubbling fluidized bed
BIGCC	Biomass integrated gasification combined cycle
BioSNG	Synthetic natural gas from biomass
BTX	Benzene, toluene and xylene
CAPEX	Capital expenditure (€/a)
CEN	*Comité Européen de Normalisation* (European Committee for Standardization)
CFB	Circulating fluidized bed
COP21	2015 United Nations Climate Change Conference
CPI	Consumer price index
CPP	Coupled pressure pulse
CR	Combustion reactor
CHP	Combined heat and power
Dep	Depreciation (€/a)
DFB	Dual fluidized bed
DIN	*Deutsches Institut für Normung* (German Institute for Standardization)
E_0	Earnings when the investment is projected (€/a)
ECN	Energy Research Centre of The Netherlands
EF	Entrained flow
E_n	Earnings in year *n* (€/a)
EOP	Exhausted olive pomace
Eq	Equation
ESP	Electrostatic Precipitators
EU	European Union
EU-28	28 member states of the European Union
FC	Fixed carbon
FT	Fischer-Tropsch
GC	Gravimetric Chromatography
GC-MS	Gas chromatography mass spectrometry
GR	Gasification reactor
HHV	Higher heating value
IC	Internal combustion

IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPA	Isopropanol
IRR	Internal rate of return (%)
LHV	Lower heating value
LPG	Liquefied petroleum gas
M	Moisture content
M_i	Inherent moisture
M_s	Surface moisture
MSW	Municipal solid waste
MW_{el}	Electric power
MW_{th}	Thermal power
$MW_{th\ fuel}$	Thermal power of the fuel
N	Expected lifetime (a)
n	Year
NG	Natural gas
Nm^3	Normal cubic meter
NPV	Net present value (€/a)
OCF_n	Operating cash flow in year *n* (€/a)
OECD	Organization for Economic Co-operation and Development
$OPEX_0$	Operating expenses when the investment is projected (€/a)
$OPEX_n$	Operating expenses in year *n* (€/a)
ORC	Organic Rankine cycle
PAH	Polyaromatic hydrocarbons
PG	Product gas
r	Discount rate (%)
R&D	Research and development
r_i	Inflation rate (%)
RME	Methyl ester of rapeseed
SCR	Selective catalytic reduction
SNG	Synthetic natural has
SRC	Selective catalytic reduction
T	Temperature
tax, t	Taxes (€/a)
TPES	Total primary energy supply
TU Wien	*Technische Universität Wien* (Vienna University of Technology)
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollar (currency)
VM	Volatile matter

vol %ppm$_{db}$	Volume in part per million, dry basis
vol%	Volume percent
vol%$_{db}$	Volume percent, dry basis
wt %$_{db}$	Weight percent, dry basis
wt%	Weight percent
XRF	X-ray fluorescence spectroscopy
$\dot{m}_{fuel}$	Fuel mass flow (kg/h)
$\dot{m}_{PG}$	Product gas mass flow (Nm^3/h)
LHV_{fuel}	Low heating value of fuel (biomass) (MJ/kg$_{db}$)
LHV_{PG}	Low heating value of the product gas (MJ/Nm^3)
η_{chem}	Cold gas efficiency

1. INTRODUCTION

1.1. Background

The worldwide energy consumption is growing constantly and the greater part of this demand is covered by fossil fuels. The fossil-fuel industry (in particular gas and oil) will continue to be a bedrock of the future global energy system [1]; however, it influences the amount of greenhouse gases released into the atmosphere. Global CO_2 emissions are expected to further rise at alarming rates due to the energy consumption increase, especially in developing countries where the consumption is still very low and the population is growing, and hence, a step-change in the rate of decarbonisation and efficiency improvement is essential [2]. Figure 1 shows the increase in emitted CO_2 that has occurred since the Technological Revolution began at the end of the 19th century.

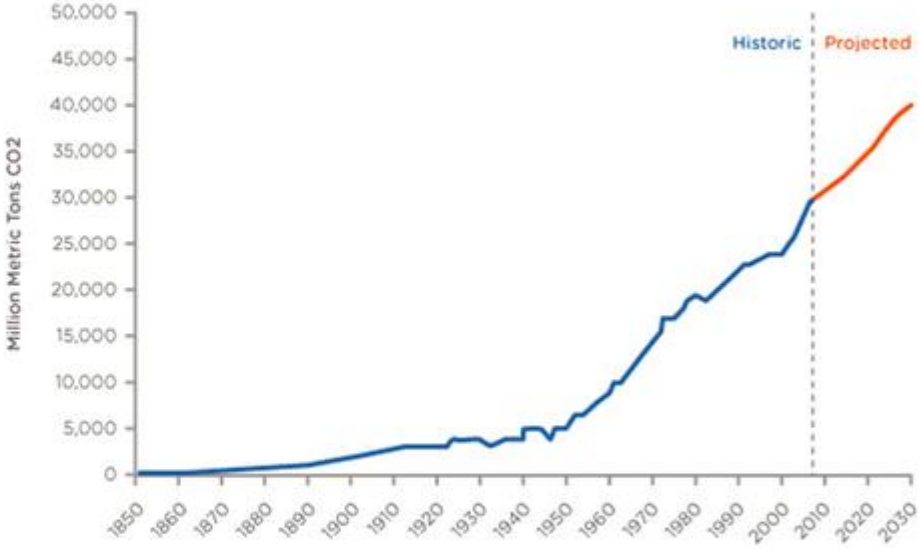


Figure 1. Global carbon dioxide emissions (Million Mg CO_2), 1850-2030 [3]

Greenhouse gas emissions are the main cause of climate change and the concern about this is growing in many countries [2]. The 2015 United Nations Climate Change Conference (COP21) was held in Paris with the goal of mitigating climate change and the agreement of the members includes a commitment: "*to keep a global temperature rise this century well below 2 degrees Celsius and to drive efforts to limit the temperature increase even further to 1.5 degrees Celsius above pre-industrial levels*" [4]. To achieve the objectives of the Agreement, a transformative change in the energy sector is an essential milestone as this sector is considered to be the source of at least two-thirds of greenhouse gas emissions [1].

Not only the reduction of greenhouse gas emissions represents a boost in renewable energies, but there are also other factors. Oil and gas are usually located in countries with a non-stable political situation and these new forms of energy can push for independence and moreover, can avoid fluctuating prices of those fossil fuels. Figure 2 depicts the pattern of the EU import dependency by fuel since 1990.

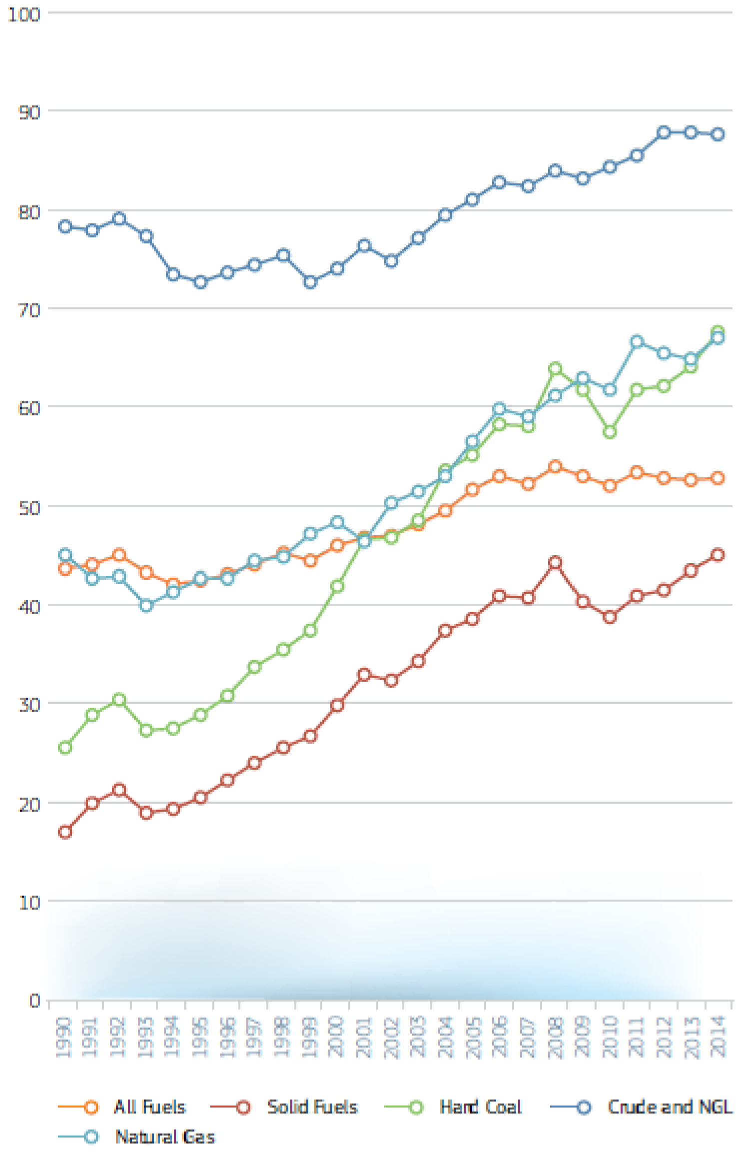


Figure 2. Percentage of import dependency (%) in the EU-28, 1990-2014 [5]

Furthermore, the interest in renewable and locally available energy sources has increased due to the liberalization of energy markets. Thus, the investment in large power plants has become riskier and it has lost ground compared to small and decentralized power plants. Electricity generation from wind, solar power, and hydropower are nowadays well known and widely implemented with the aim of replacing a significant share of fossil fuels as primary energy. However, biomass is the only renewable carbon carrier to produce carbon based fuels via synthesis; thus, the main target markets of biomass will be heat, transport fuels, and electricity produced in cogeneration plants [2]. The former renewable sources are characterized by seasonality, intermittency and their reliance on weather and climate, while gas produced from thermo-chemical or biological conversion of biomass can help to stabilize the electricity grid due to the possibility of being stored and being used for peak loads or periods characterised by unfavourable climate conditions.

As produced, biomass is solid and difficult to be used without conversion to gaseous and liquid energy carriers. Several technologies are available for the conversion of biomass, and this conversion can be carried out by using a thermochemical, biological, or mechanical conversion process. Thermal conversion gives multiple products and takes place in short times, specifically, gasification is considered as an attractive technology that converts a wide range of feedstocks into a medium calorific product gas to produce energy, heat, fuels, and chemicals.

Regarding biomass gasification, dual fluidized bed (DFB) is a promising technology [6] that provides not only a great feedstock flexibility but also a better product gas quality. The Vienna University of Technology (TU Wien) developed this technology in the 1990s and it has been successfully demonstrated in Güssing, Austria, since 2001 and later in Oberwart (also in Austria) and further plants in Senden, Germany and Gothenburg, Sweden, amongst others.

1.2. Aim and scope of this work

Critical voices do not see biomass as an ethical and sustainable way of producing energy because it competes against the food supply of a growing population. These criticisms concern the large-scale generation of biofuels for transportation obtained from agricultural crops such as cane, corn, or oil palms; while millions of people are starving of hunger. Moreover, the food prices increased at the beginning of the 21st century and since the biofuel production grew as well, biofuels were blamed as cause of this rise in food prices although there was no scientist evidence for this affirmation [7]. Therefore, the future challenge concerning biomass gasification is to explore the possibilities of alternative feedstocks that can avoid competition with food and feed, and moreover, can be cheaper than the existing ones.

The novel pilot plant at TU Wien is characterized by its flexibility and it has been demonstrated that various fuels such as coal, sawdust, bark, waste wood chips, straw-wood blends, coal-wood blends, municipal waste fractions, reed, sugar cane bagasse, waste plastics, wheat bran, sewage sludge, and other alternative feedstock can be processed with the DFB technology [8-14]. The aim of this work is to study the gasification of alternative feedstocks such as chicken manure as well as mixtures of chicken manure with bark, and to compare them with the gasification of wood. The variation of feedstocks has some effects on the composition and therefore, on the quality of the product gas.

The use of different bed materials also has impacts on the gasification performance since it can improve the quality of the gas by adding some catalytic activity. Traditionally, olivine has been used as bed material at the TU Wien pilot plant because it is also used in Güssing and several experiments have been carried out in order to study the improved catalytic activity of the used olivine [15,16]. In the present work, K-feldspar (potassium-feldspar) is used as bed material in the novel pilot plant for the first time, and therefore, the definition of bed material properties is essential.

In the first part of this work, a theoretical background with the fundamentals of biomass gasification is described. Besides, the principle of dual fluidized bed steam gasification used at the pilot plant is explained (Chapter 2). Once the fundamentals have been addressed, it is possible to describe the experiments carried out (Chapter 3) and moreover, to present the results (Chapter 4), without neglecting an economic evaluation that enables to make a picture about the feasibility of biomass gasification (Chapter 5). The main goal of this thesis is to address the research question: How do mixtures of different biogenic residues influence the operation of a 100 kW pilot DFB gasifier? (Chapter 6). The final part tries to look into the future when thinking about the challenges of gasification and alternative feedstocks.

2. FUNDAMENTALS

2.1. Biomass

The properties and characteristics of biomass greatly influence the performance of the gasification process, thus, a proper understanding of the resources and types, as well as the physical and chemical properties of biomass feedstocks is essential.

To a large extent, biomass can refer to any organic materials which are derived from plants or animals. A generally accepted definition is difficult to find, and the one used by the United Nations Framework Convention on Climate Change (UNFCCC) is as follows [1]:

[A] non-fossilized and biodegradable organic material originating from plants, animals, and micro-organisms. This shall also include products, by-products, residues and waste from agriculture, forestry, and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes.

Biomass is continuously being formed by the interaction of CO_2, air, water, soil, sunlight plants, and animals; and therefore, it is considered as a sustainable and renewable energy source. When an organism dies, microorganisms break down biomass into elementary constituents such as H_2O, CO_2, and its energy content. Although the conversion of biomass into energy releases CO_2 into the atmosphere, the same amount was absorbed by it and the total CO_2 inventory of the Earth is not increased. Therefore, biomass is considered as "greenhouse gas neutral" or "carbon neutral" fuel [17].

When talking about biomass, it only includes living and recently dead biological species, it does not include organic materials that over millions of years have been transformed by geological processes (coal and petroleum) [2]. One way to distinguish the sources of biomass is: forestry, agriculture, and waste; and these sources include main products, by-products, and different waste streams, as explained in Table 1.

	Forestry	Agriculture	Waste streams
By-products	Felling residues, bark, branches, sawdust, wood chips, residues of the wood industry	Manure, straw, bagasse, kernels, empty fruit branches from oil palms, other residues	Municipal solid waste (MSW), organic waste from industry
Main products	Stem wood, firewood	Energy crops: cereals, corn, oilseeds, energy grass, short rotation coppices	Sewage sludge

Table 1. Different sources of biomass [2]

Based on the source of biomass feedstocks, four categories can be distinguished as Figure 3 shows. The first generation is derived from sources such as sugarcane and corn starch which may be in direct competition with food and feed. The second generation has been developed to overcome the limitations of first generation biofuels and is produced from non-food crops such as wood, organic waste, food crop waste and specific biomass crops. The third generation is new organisms like algae, and the fourth generation uses energy and H_2O, CO, and CO_2 collected from the atmosphere by plants. After a transformation process, biomass applications include electricity, heat, fuels, and chemical products.

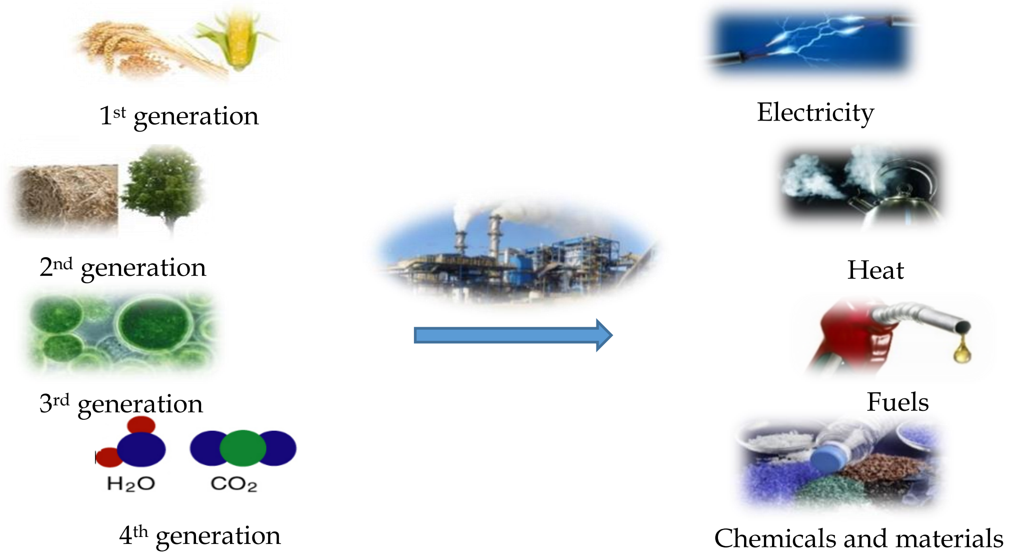


Figure 3. Different generations of biomass and possible uses. Adapted from [18]

Each type of biomass has its own specific properties and these properties determine its performance as a fuel in gasification plants. The properties of biomass feedstocks can be classified into two categories, physical and thermochemical properties, which are summarized in Table 2, coupled with their corresponding influences on the gasification system [19].

BIOMASS PROPERTIES		IMPACT ON GASIFICATION SYSTEM
Physical properties	High moisture content (hygroscopic)	• Decrease in heating value of fuel • Storage durability • Fuel transportation costs • Lower process temperature • Reduction in product gas quality, gasification efficiency and fuel conversion
	Low apparent density	• Energy density → transportation, storage and handling costs • Feeding system
	Shape and distribution of particle size	• Transport and feeding system • Gasification technology • Reactivity of fuel
	Porosity	• Reactivity of fuel
Thermochemical properties	Ultimate analysis	
	- C, H, O content	• Heating value of fuel
	- N content	• Fate of fuel-bound N during gasification: mainly transformed into NH_3 and HCN → design of gas cleaning section • Emissions
	- S content	• Fate of fuel-bound S during gasification: mainly transformed into H_2S and COS → design of gas cleaning section • Interaction with alkali metals: emissions, deposits, corrosion • Deactivation of downstream catalysts
	- Cl content	• Decrease of softening temperature of ash • Enhancement mobility of K → deposition and agglomeration • Emissions, corrosion and ash sintering
	High volatile content, low fixed carbon	• Reactivity of fuel
	Ash content	• Decrease of fuel heating value • Energy density → transportation costs • Emissions • Ash disposal costs • Design of equipment (grates, heat exchangers, gas cleaning)
	Ash composition	• Ash-melting behaviour (softening and melting temperatures) → deposition, agglomeration, fouling
	– Na and K content	• Involved in ash deposition and formation of deposits • Lowering of ash melting temperatures. Formation of eutectics • Reaction with Si and S: deposition, agglomeration, fouling, corrosion • Ash valorisation
	– Mg, P, Ca content	• Increase of ash melting temperature • Ash disposal applications
	– Heavy metals	• Emissions • Ash disposal costs, ash applications

Table 2. Influence of biomass properties on the gasification system [19]

Thermal design of a biomass system necessarily needs the composition of the fuel as well as its energy content, and according to that, the three primary properties which describe the composition and energy content of biomass fuels are: ultimate analysis, proximate analysis, and heating value [17].

The ultimate analysis or the composition of the hydrocarbon fuel is expressed in terms of its basic elements (C, H, O, N, S), moisture content (M), and inorganic constituents (A).

$$C + H + O + N + S + M + A = 100\% \qquad \text{Eq. 2.1}$$

C, H, O, N, and S are the weight percentage of carbon, hydrogen, oxygen, nitrogen, and sulphur in the fuel, respectively.

Ultimate analysis is relatively difficult and expensive compared to proximate analysis. This proximate analysis gives the composition of the biomass in terms of gross components, i.e. moisture (M), volatile matter (VM), ash (A), and fixed carbon (FC).

$$VM + FC + M + A = 100\% \qquad \text{Eq. 2.2}$$

The equations shown above represent the results of ultimate and proximate analysis when using the as-received basis; however, it is possible to use different bases of analysis (as received, air dry, total dry, and dry and ash free) and a comparison of these is shown in Figure 4.

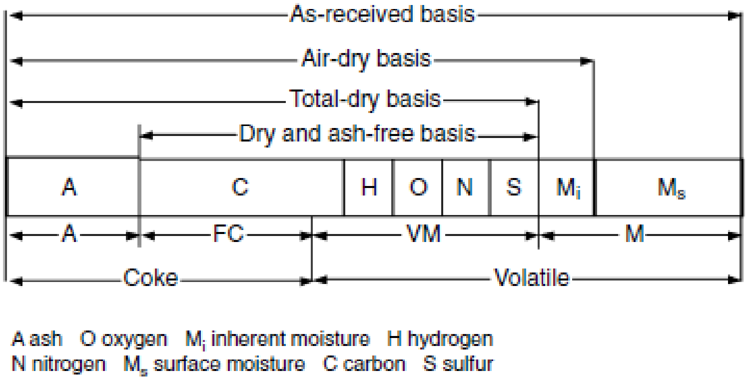


Figure 4. Different bases for expressing fuel composition [17]

The heating value is determined by the elemental composition, the ash content and the moisture content of the biomass. The heating value of the biomass is relatively low when compared with fossil fuels because its density is very low. The higher heating value (HHV) is the maximum amount of energy that can be obtained from combusting the fuel when considering that water is produced as liquid. However, mostly the water is released into the atmosphere as a gas, and the heat of the evaporation is not recovered. The amount of energy obtained when the water escapes as vapour is the lower heating value (LHV) [20].

2.2. Energy from biomass

2.2.1. Current situation of biomass in the energy field

The European Parliament and the council of the European Union plan a share of 20% renewable energy in gross final energy consumption in average of the EU members in the year 2020 [21]. The final energy demand comprises the demand for electricity, heat and transport. However, the existing renewable energies have different properties, as follows:

- Renewables without feedstock costs: wind, solar-thermal power, hydropower, and geothermal power. These energies have in common the high capital costs, the low running costs, the intermittence of supply and the difficulty to store the excess electricity in a cheap way. They are used mainly for the electricity production.
- Biomass, the renewable with feedstock costs. The transformation of biomass for energy is related to different costs such as those regarding the production of biomass as a feedstock (cost of land, production, collecting, transporting, and storing biomass), as well as the costs of the conversion process. Bioelectricity is more expensive than electricity from other renewable energies; however, biofuels are nowadays the only available alternative to fossil fuels for transportation. Moreover, biomass offers the possibility of being stored and supplying electricity when the other intermittent renewable energy sources are not available.

The generation of electricity from renewable energy sources is increasing significantly in the countries of the European Union, as it is shown in Figure 5. And specifically, the use of biomass has increased considerably during the first decade of the 21st century. The increase in renewable energy is a challenge for the operation of the electricity grid. That means a considerable increase in investments in the transmission and distribution facilities.

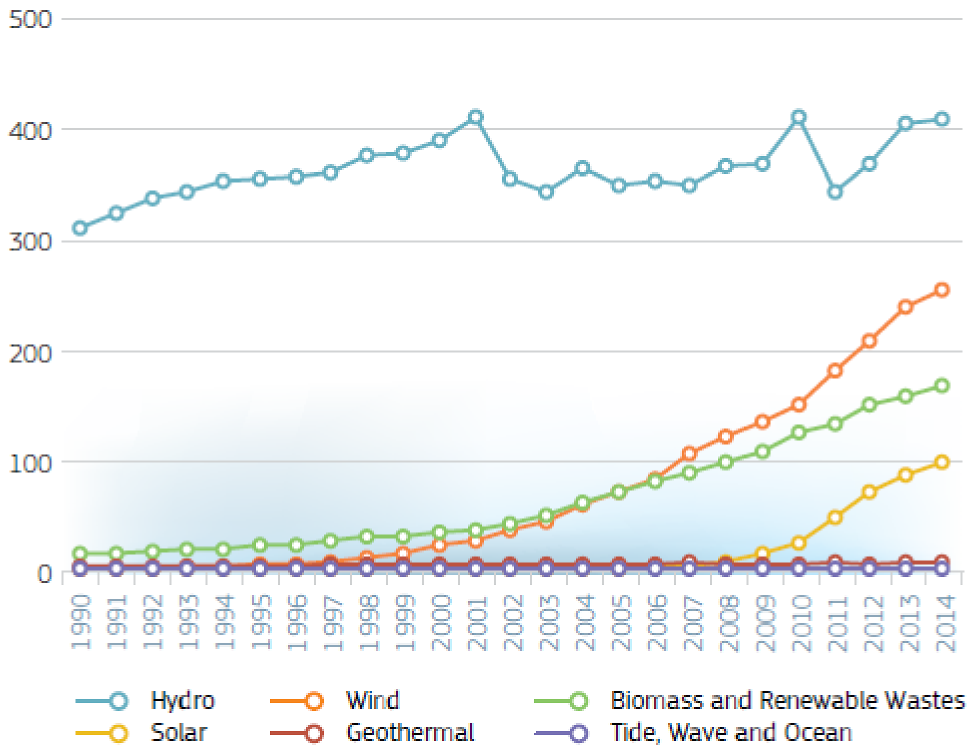


Figure 5. Gross electricity generation (TWh) in the EU-28, 1990-2014 [5]

The heating sector is often overlooked in the discussion about energy strategies, although such a big share of final energy is used as heat (heat for cooking, heat for warm water, space heating, and high-temperature heat for industrial processes). Regarding the use of renewable energy sources in the heating sector, the rate is continuously increasing, as it can be seen in Figure 6.

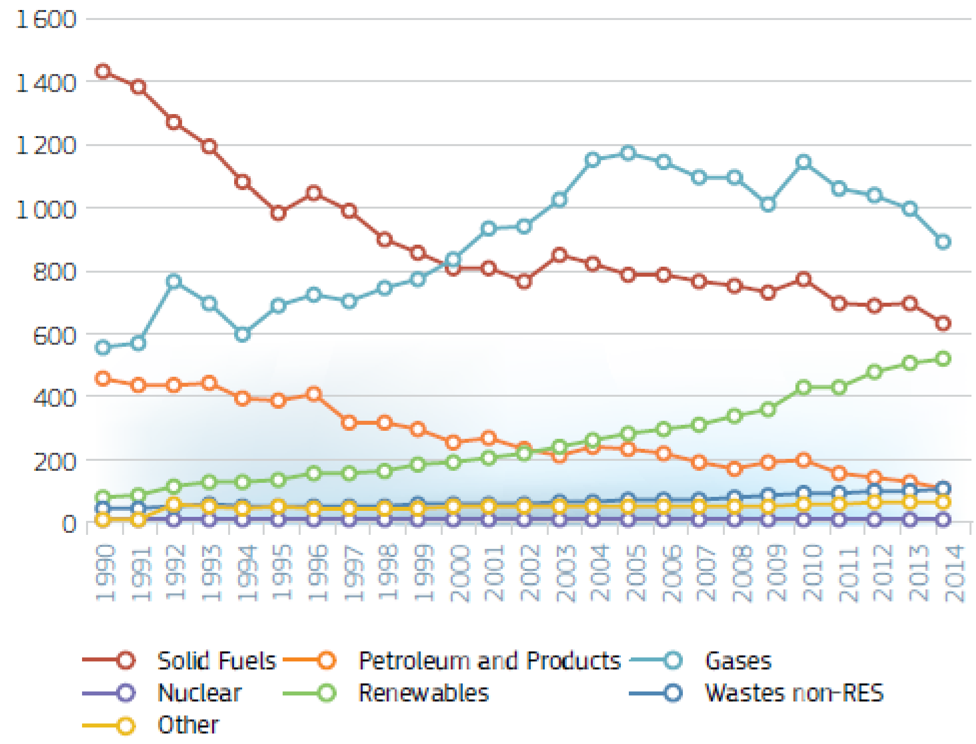


Figure 6. Gross heat generation (PJ-GCV) in the EU-28, 1990-2014 [5]

The share of biofuels for transportation (Figure 7) is increasing very slowly but a considerable growth is expected due to policies promoting them to meet the European requirements.

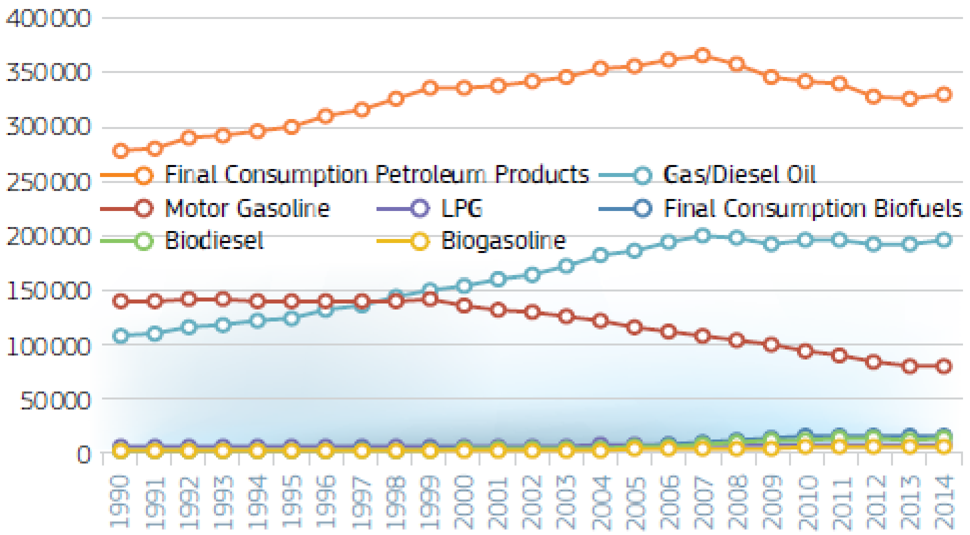


Figure 7. Fuel consumption in the transport sector (ktoe) in the EU-28, 1990-2014 [5]

2.2.2. Future of biomass in the energy field

It is estimated that energy demand may at least double in the next decades and no single renewable energy source alone can provide sufficient energy to fulfil the need. Besides, the consumption rate of fossil fuels exceeds the rate of formation of new fossil fuels, being not sustainable [18]. To overcome this threats, biomass will play an important role in the future.

The worldwide production of biomass will depend on the success of dealing with some obstacles like food competition, biodiversity, questions of landscape and several side effects as well as political issues. To support public acceptance of biomass chain on the long term, governments and international "green certification" systems should work as backup for all these factors. Additionally, some of these critical voices are not scientifically proven, for instance, some biomass detractors argue that biomass for energy competes with the food supply of a growing population; however, the biggest part comes from forests, by-products of agriculture, and from waste streams, which do not compete at all with the food supply [2].

Both booster and obstacles of the biomass expansion in the future are summarized in Figure 8 and Figure 9, respectively.

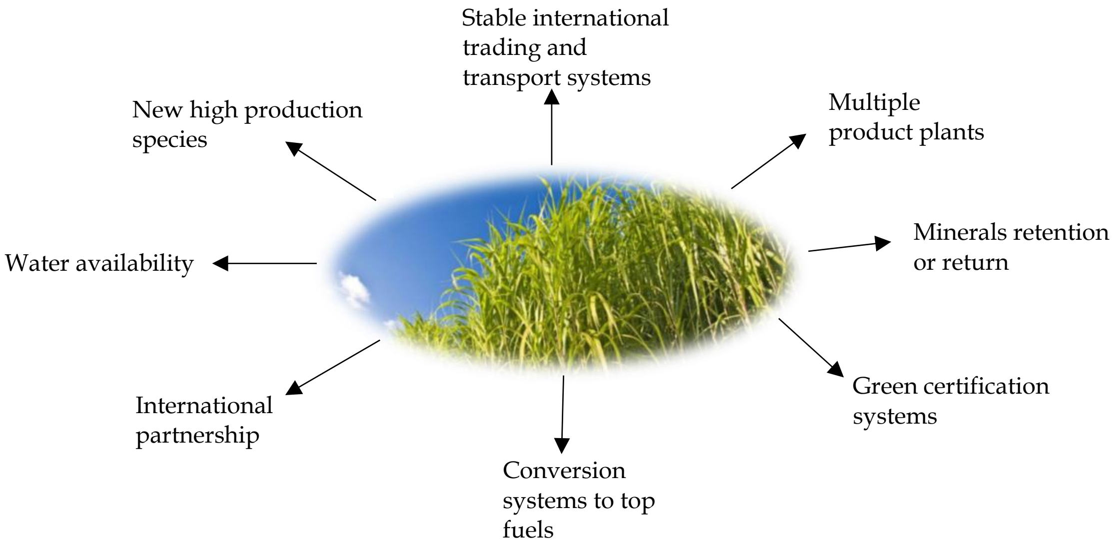


Figure 8. Promoters for large-scale biomass production. Adapted from [18]

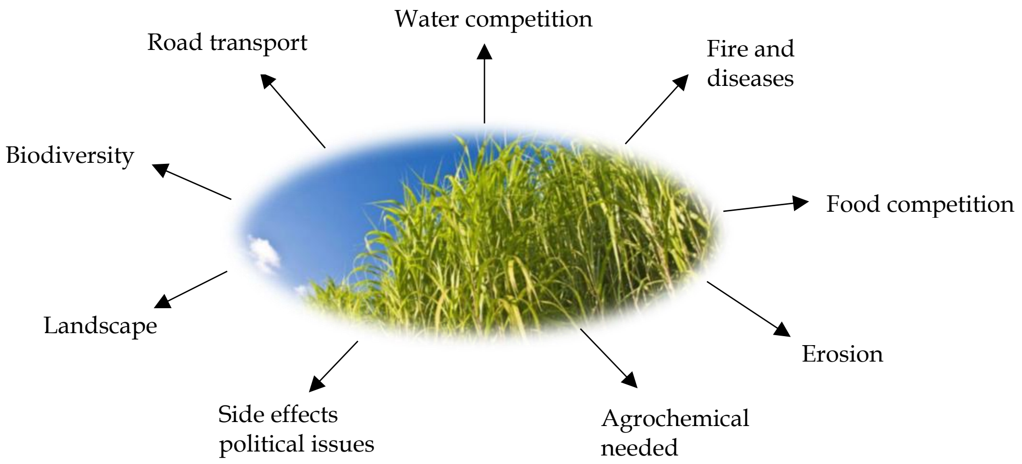


Figure 9. Barriers for large-scale biomass production. Adapted from [18]

The impact of the global warming has increased and the EU is even more conscious about that, thus, the objectives of the European biomass R&D program became more specifically targeted to [22, 23]:

- Guarantee of long-term energy supply in Europe
- Participation in the development of industrial new markets
- Usage of residues and waste to improve the environment
- Decreasing the greenhouse gas emissions
- Diversification of the agricultural production
- Better management of surplus agricultural and marginal land
- Offering opportunities targeted at less developed regions in Europe
- Decentralizing electricity production and promoting local cogeneration

2.3. Thermochemical conversion

Biomass fuels can be converted into energy via thermal (pyrolysis, gasification and combustion), biological (anaerobic or aerobic digestion, and fermentation), and mechanical or physical processes. Some of the main products that can be obtained by processing biomass are summarised in Figure 10.

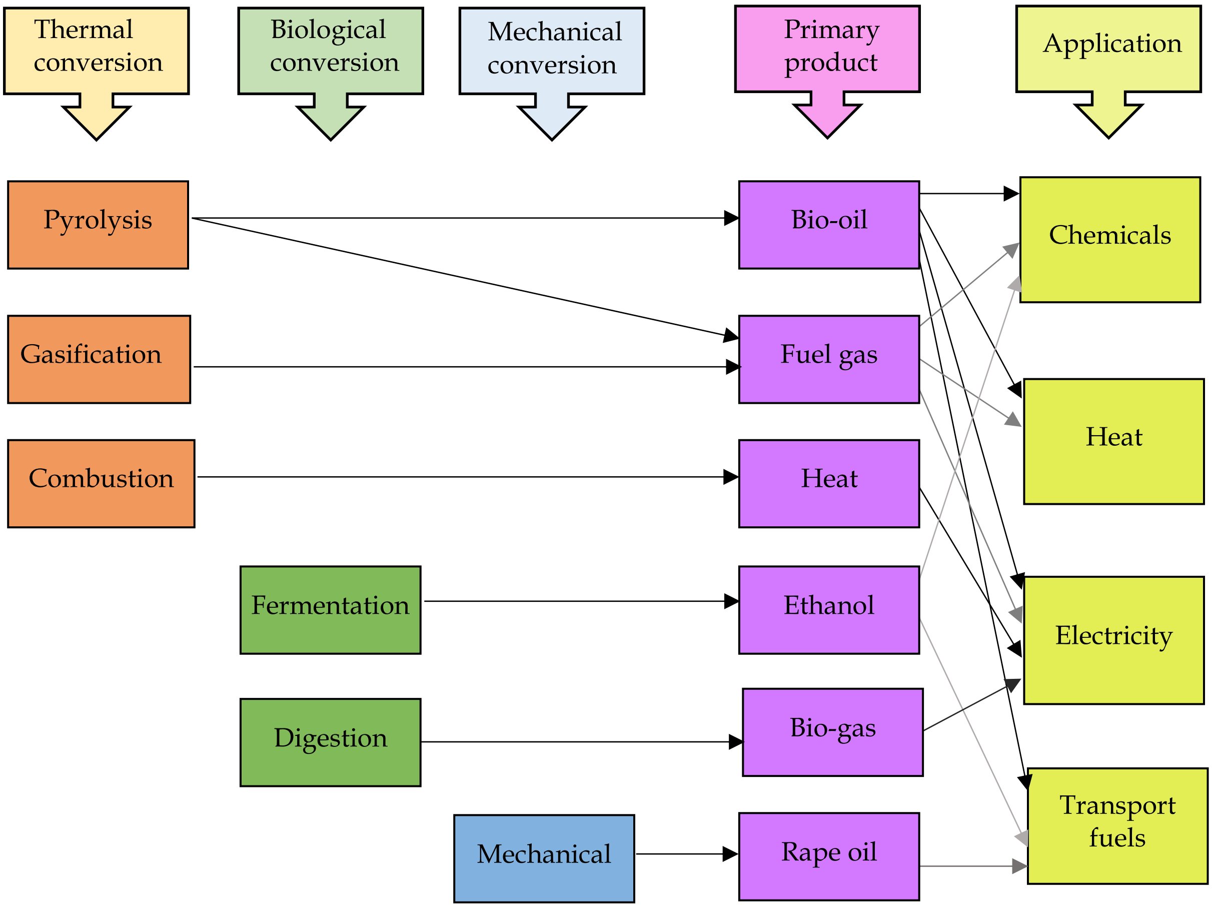


Figure 10. Conversion processes, products and applications of biomass [24]

In biochemical conversion, biomass molecules are broken down into smaller molecules by bacteria or enzymes. Hence, it is a slow process taking typically hours, days, weeks, or years for reactions to be completed and it gives single or specific products such as biogas or ethanol. Mechanical extraction produces energy from biomass mainly in the form of rapeseed methyl ester (RME) bio-diesel. On the other hand, thermal conversion leads to multiple and complex products, and takes place in very short reaction times of seconds or minutes. One advantage of biological conversion is that it does not require much external energy [17, 24]. The subject of the present work is gasification and therefore, only thermal conversion and especially, gasification technologies will be described in more detail [25].

- **Combustion** can ideally be defined as a complete oxidation of the fuel. It involves high temperatures, in the range of 1500 to 2000°C, and the conversion of biomass in excess air into carbon dioxide and steam. Since biomass will not burn (only the gases from biomass burn), biomass combustion is preceded by pyrolysis and possible gasification.

- **Pyrolysis** means the breaking down (lysis) of materials by heat (pyro) in the absence of air. Devolatilization starts at temperatures of about 200ºC and finishes at around 500ºC. Pyrolysis is always also the first step in combustion and gasification, but in these processes, it is followed by total or partial oxidation of the primary products. It has three variations: torrefaction (or mild pyrolysis), slow pyrolysis, and fast pyrolysis. Slow pyrolysis produces some gas and solid charcoal while fast pyrolysis produces mainly liquid fuels. Torrefaction is considered for effective biomass utilization, increasing energy density.
- **Gasification** is the conversion of biomass into gas phase products by partial oxidation in the presence of an oxidizing agent and at temperatures of 700 to 1200ºC. Contrary to the combustion, there is only a limited supply of oxidant (less than stoichiometric required for combustion). The product gas contains mainly H_2, CO, CO_2, and CH_4 but by-products such as condensable tars, nitrogen compounds and solid particles are also found.

The relationship of these three intertwined processes is shown schematically in Figure 11.

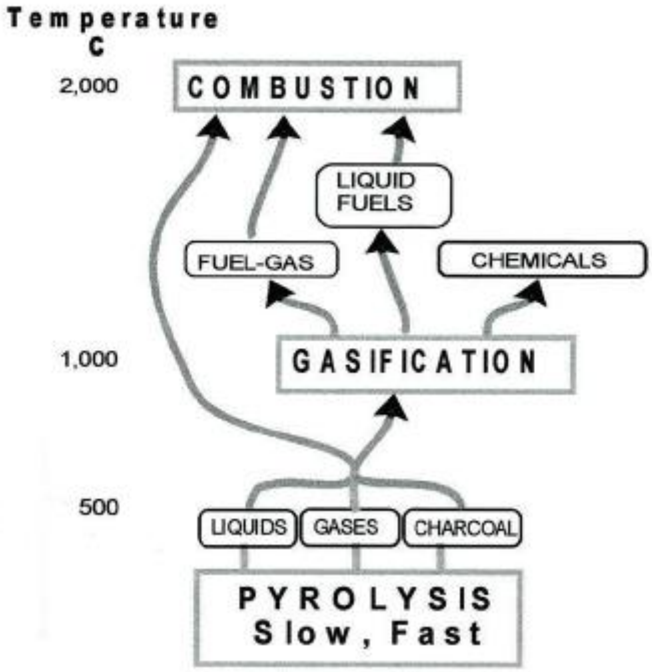


Figure 11. Possibilities for thermal conversion of biomass correlating to temperature [25]

2.4. Practical aspects of biomass gasification

2.4.1. Fundamentals

Gasification is a high-temperature process in which a solid fuel is converted into a combustible gas, called producer gas, product gas, synthesis gas, or syngas (sometimes these last two terms are used once the product gas is cleaned). Gasification of fossil fuels like coal is well-known and commercially available, but gasification of biomass faces several problems related to the characteristics of biomass, such as the high moisture content, the morphology, or the chemical composition (Table 2).

Gasification allows the generation of the product gas which can be used for many applications. Advantages of biomass gasification are [25]:

- Ease of distribution due to the possibility of transporting in pipelines
- Easy control as well as continuous operation
- Possibility of burning the product gas later, being cleaner than direct combustion since impurities are removed from the product gas, and moreover, the volume of product gas is smaller compared to flue gas
- Lower N, S, and Cl content, as well as lower ash content than coal
- Product gas can be used in internal combustion engines or turbines for efficient power generation in compact unit
- Product gas can be used for chemical synthesis and to obtain nitrogen fertilizers and transportation fuels
- Possible integration with CO_2 capture and storage at large scale

Gasification requires a gasifying medium like air, oxygen, or steam, and furthermore, as the overall gasification process of biomass is endothermic, heat must be supplied. A typical biomass gasification process includes the following steps [26, 27], as Figure 12 depicts:

- **Drying.** Biomass is heated up, then the water evaporates and steam is released from the particle structure.
- **Pyrolysis** or devolatilization. As consequence of further temperature increases, irreversible changes in the structure of biomass occur when volatiles and solid residues are released. Hydrocarbon gases, H_2, CO, CO_2, tar, and water vapour are included in the volatile vapours. Char (fixed carbon) and ash are the by-products which are not vaporized.
- **Gasification**. The remaining char is gasified through the reaction with the gasification agent to form the final gasification product.

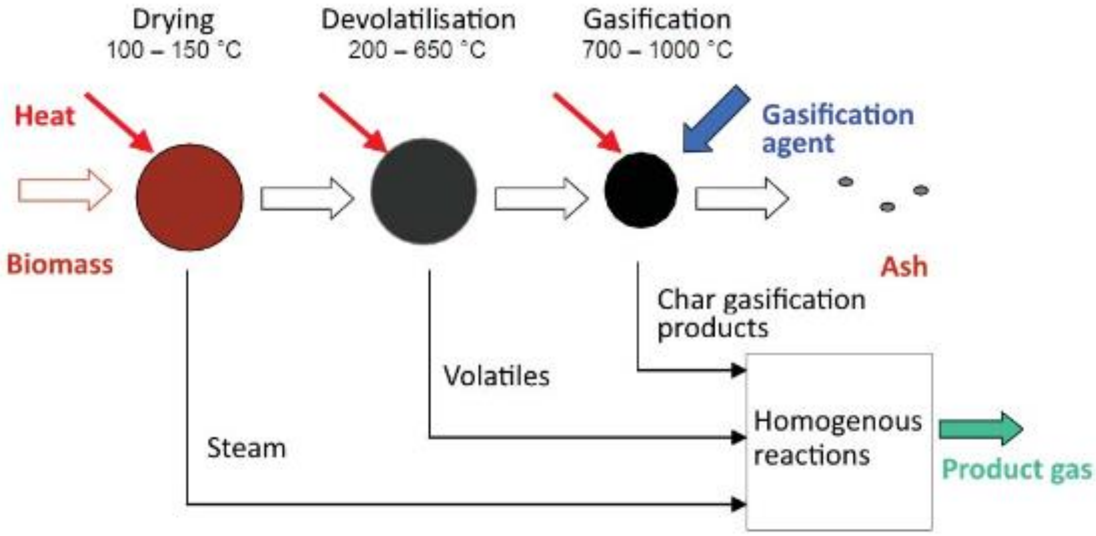


Figure 12. Processes during gasification of a single particle [24]

Table 3 presents the most important gasification reactions. The heterogeneous reactions are slower than homogeneous reactions and may limit the overall rate of the gasification process and the carbon conversion efficiency; while homogeneous reactions determine to a large extent the final gas composition [20].

Type of reaction	Reaction	Reaction enthalpy	Eq.
Heterogeneous gas-solid reactions			
Oxidation of carbon	$C + O_2 \rightarrow CO_2$	Highly exothermic	Eq. 2.3
Partial oxidation of carbon	$C + \frac{1}{2}O_2 \rightarrow CO$	Exothermic	Eq. 2.4
Heterogeneous water-gas reaction	$C + H_2O \rightarrow CO + H_2$	Endothermic	Eq. 2.5
Boudouard reaction	$C + CO_2 \rightarrow 2CO$	Endothermic	Eq. 2.6
Hydrogenation of carbon	$C + 2H_2 \rightarrow CH_4$	Slightly exothermic	Eq. 2.7
Generalised steam gasification of solid fuel (bulk reaction)	$C_xH_yO_z + (x-z)H_2O \rightarrow xCO + \left(x - z + \frac{y}{2}\right)H_2$	Endothermic	Eq. 2.8
Homogeneous gas-gas reactions			
Oxidation of hydrogen	$2H_2 + O_2 \rightarrow 2H_2O$	Highly exothermic	Eq. 2.9
Water-gas shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	Slightly exothermic	Eq. 2.10
Methanation	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	Exothermic	Eq. 2.11
Generalised steam reforming of hydrocarbons	$C_xH_y + xH_2O \rightarrow xCO + \left(x + \frac{y}{2}\right)H_2$	Endothermic	Eq. 2.12
Generalised dry reforming of hydrocarbons	$C_xH_y + xCO_2 \rightarrow 2xCO + \frac{y}{2}H_2$	Endothermic	Eq. 2.13

Table 3. Gasification reactions [28]

The *water-gas shift reaction* (Eq. 2.10) is very important when producing a H_2-rich syngas. Even though CH_4-rich and hydrocarbons-rich product gases can be characterised by higher heating values, they are associated with high tar contents and poor carbon conversion, which can affect downstream steps and involve expensive processes. H_2 is appropriate for engines as it only forms water when it becomes combusted. Different rate of the water-gas shift reaction can be obtained by modifying parameters such as reactor temperature, pressure, bed material structure, and composition [29].

The *steam reforming reaction* (Eq. 2.12) is another important reaction because it can influence the tar content of the product gas due to the possibility of interactions between hydrocarbons (tars) and steam to produce H_2 and CO. The purpose of this reaction is to supply steam and transform tars into CO_2 and H_2 through water-gas shift reaction. Moreover, the presence of catalytically active bed materials can enhance the reaction and reduce the energy needed for steam production [29].

2.4.2. *Gasification technologies*

Gasification technologies can be classified in different ways, classification is usually done by the following four main criteria [20]: type of gasification agent, type of heat supply, pressure level in the gasifier, and fluid mechanics in the gasifier (or reactor design). Figure 13 summarizes these four categories and the corresponding types.

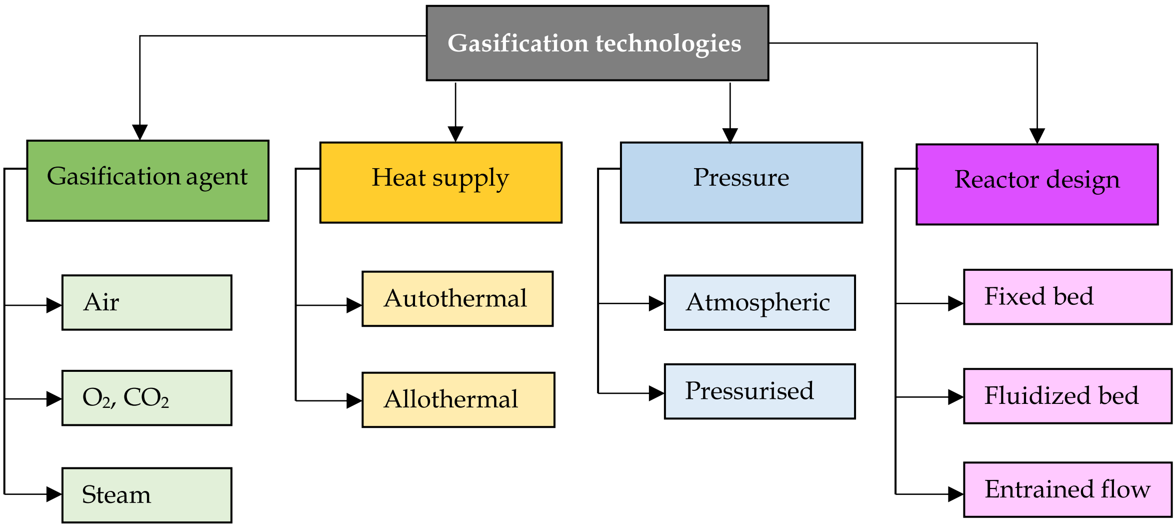


Figure 13. Classification criteria for gasification technologies. Adapted from [20]

Regarding the gasifying agent, if air is used as gasification agent, the product gas will contain a high amount of nitrogen. However, a mixture of steam and oxygen, as well as pure steam, can lead to a nitrogen free product gas. Finally, and regarding carbon dioxide, it is a promising gasification agent that can also lead to a nitrogen free product gas [24].

In relation to heat supply, gasifiers can be either autothermal (internal or direct) or allothermal (external or indirect). Autothermal gasifiers provide the necessary heat for gasification by means of partial combustion of the biomass in the same reaction chamber. Allothermal gasification means that the heat is supplied indirectly via a heat exchanger or a circulating heat carrier of bed material. It is characterized by the separation of the heat production and heat consumption. Allothermal gasification facilities usually consist of two reactors, in the first reactor biomass is gasified and the remaining char or product gas is combusted in the second reactor to produce the heat for the first process (this is further explained in Section 2.5) [24]. The great advantage of the autothermal gasification is the direct internal heating of the reactants and consequently, more efficient energy utilisation and lower process costs. Related to the advantages of allothermal gasification, it is possible to produce a N_2-free product gas, and moreover, the complete carbon conversion avoids problematic waste produced [26].

Concerning the gasification agent and the heat supply, air is used in many applications because it is cheap and drives the process autothermally. The main problem of using air is that the amount of N_2 dilutes the products and consequently, lowers the heating value of the product gas down to about 3-6 MJ/Nm^3 [30]. Using steam or CO_2 as gasification agent, N_2-free gas can be obtained and the calorific value is higher, being possible to reach values between 10 and 18 MJ/Nm^3 for steam [31]. The benefit of operating with steam instead of CO_2 is that the reactivity of steam is on average about four times higher than that of CO_2 [32], hence residence times of the char in the gasifier would have to be longer and gasification efficiency would suffer. The process becomes allothermal when H_2O or CO_2 is used as gasification agent and in this way, heat needed for the endothermic gasification reactions must be provided externally [33]. Figure 14 shows the characteristics of the obtained product gas according to the classification based on heat supply and gasification agents.

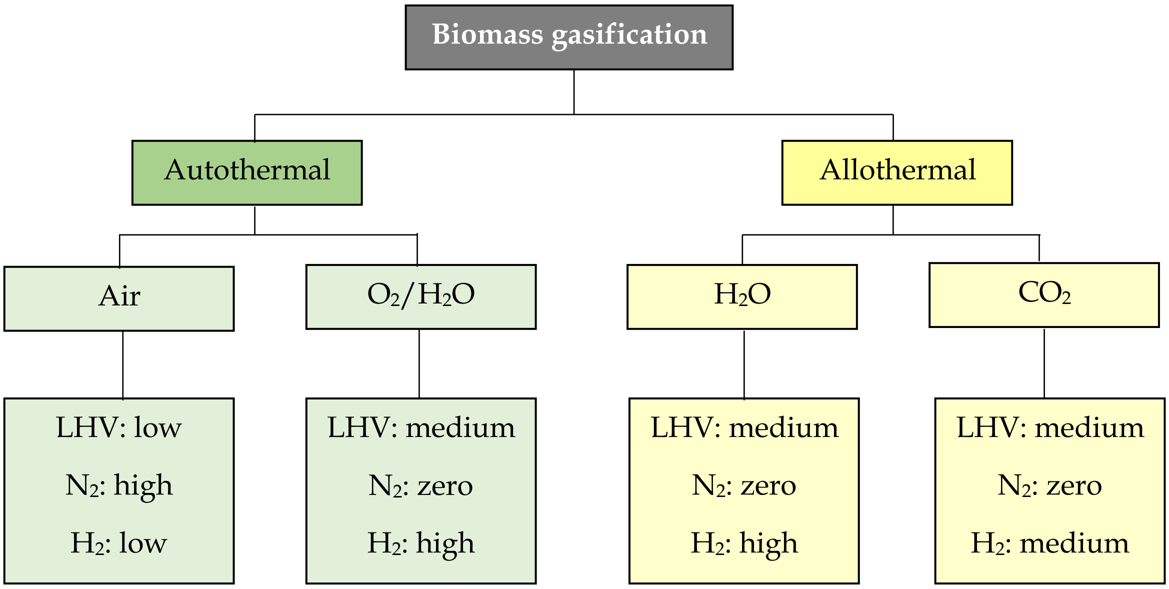


Figure 14. Classification of gasification processes based on heat supply and gasification agents. Adapted from [24]

Depending upon the design of the fuel bed and how the fuel and the gas contact each other, the gasifiers can be further divided into the following three types [31]: fixed or moving bed, fluidized bed, and entrained flow. Each is further subdivided into specific types as shown in Figure 15.

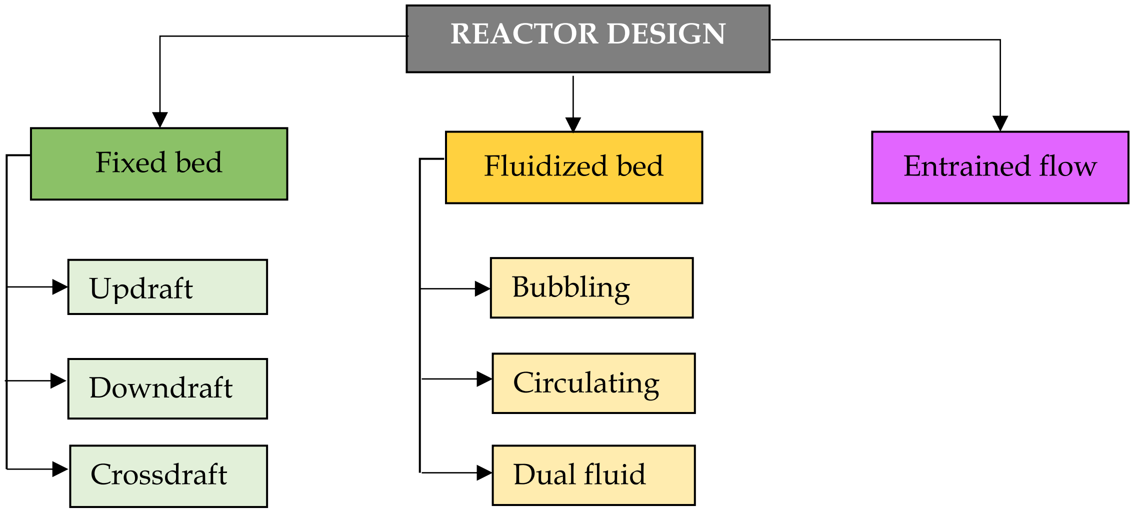


Figure 15. Different configurations of biomass gasifiers. Adapted from [31]

- **Fixed bed gasifiers**

In a fixed bed gasifier, solid fuel particles are usually added at the top of the gasifier and are not moved by the gasifying agent stream, so the fuel moves down through the gasifier due to gravity and continuous decomposition [34]. The major attraction of fixed bed gasifiers is that they can be built inexpensively in small sizes. However, mixing and heat transfer within the fixed bed are quite poor, and therefore, it is difficult to achieve uniform distribution of fuel, temperature, and gas composition across the section of the gasifier. For this reason, this type of gasifiers is not very flexible when handling different biomass fuels [17].

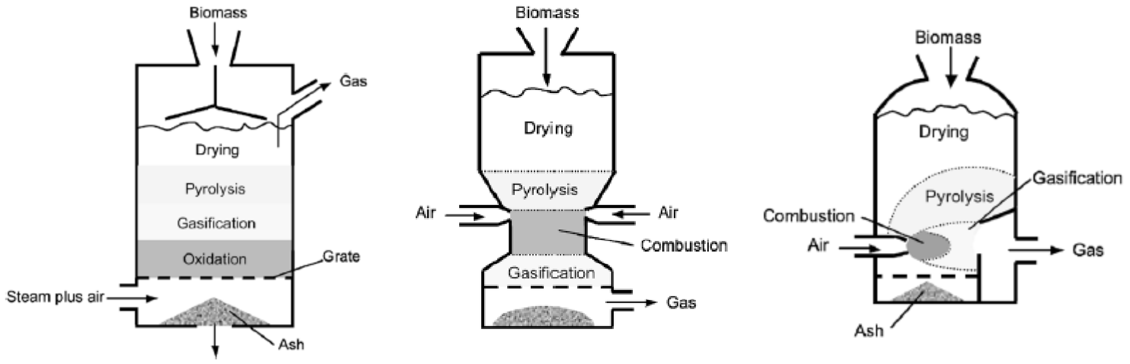
Depending on the flow direction of the gasification agent through the bed of fuel, this type of gasifier can be: downdraft gasifier, updraft gasifier, and crossdraft gasifier.

In an ***updraft gasifier***, air is introduced at the bottom and the product gas leaves at the top, biomass fuel moves counter currently to the gas flow, and passes through the drying, pyrolysis, reduction and oxidation zone, which are clearly defined [26]. See in Figure 16.

In a ***downdraft gasifier***, the fuel is fed at the top and the gasification agent enters also from the top or from the side. As product gas moves the same direction as gasification agent, that leads to a co-current overall flow behaviour and the gas leaves at the bottom of the reactor [24].

The ***crossdraft gasifier*** is a special type of fixed bed gasifier operating in a co-current way, the fuel is fed from the top and air is injected through a nozzle from the side. The product gas is released from its side wall opposite to the entry point of the air for gasification [17].

The designs of these three subtypes of fixed bed gasifiers are shown in Figure 16.



Updraft gasifier

Downdraft gasifier

Crossdraft gasifier

Figure 16. Types of fixed bed gasifiers. Adapted from [17]

- **Fluidized bed gasifiers**

Fluidized bed gasifiers contain bed material, which is made of granular solids and is kept in a semi-suspended condition (fluidized state) when the gasifying medium passes through it at the appropriate velocities [17]. The fuel particles are very quickly mixed with the bed material and heated up to the bed temperature. Due to this intense mixing, the different zones (drying, pyrolysis, oxidation, and reduction) cannot be distinguished and the temperature is uniform throughout the bed [26].

Advantages of fluidized bed reactors over fixed reactors are [20]:

- High heat exchange and reaction rates due to intensive mixing in the bed that leads to compact units
- Uniform temperatures without hot spots
- Ability to deal with different fuels, even those with high moisture and ash content and low bulk density
- Low ash melting points are allowed due to the low reaction temperatures
- Suitable for small particles
- Scale-up capabilities of this technology

On the other hand, drawbacks of fluidized beds are [20]:

- Product gas with high tar and dust content
- High gas temperatures containing alkali metals in the vapor state
- Carbon burn out not complete
- Supply of both air and solid fuel must be carefully controlled and hence, the operation is complex

There are three principal fluidized bed types: bubbling, circulating, and dual fluidized bed gasifiers.

In a ***bubbling (stationary) fluidized bed gasifier (BFB)***, the gasification agent enters the reactor at the bottom with velocities higher than the minimum fluidization velocity, but low enough not to carry away the bed material [26]. These conditions allow the fuel to optimally mix with the hot bed material, leading to uniform conditions in the reactor and flexibility for processing a wide variety of fuels.

Circulating fluidized bed gasifiers (CFB) have no distinct interface between the fluidized sand bed and the freeboard. They are similar to BFB gasifiers with the main difference that the velocity of the gasification agent is high enough to carryover of the bed material. These entrained particles are usually removed by using a cyclone and then, returned to the fluidized bed. The contact between product gas and bed material takes longer and thus, the conversion efficiency of this process is improved [27]. One disadvantage is that dust content of the product gas is high because of the high fluidization velocities.

Dual fluidized bed (DFB) gasification, also called as twin or two-bed, is a type of indirect gasification that uses circulating bed material as a heat carrier. DFB gasification is understood as the combination of BFB and CFB gasification, allowing for coupling the advantages of each gasification system in one compact system. Using air as a gasification medium produces a gas diluted with nitrogen and gasifying with oxygen would solve this problem but it is expensive [17]. Another solution is to use a DFB gasifier and to separate combustion and gasification in two different reactors. This type of fluidized bed gasifier works with allothermal heat supply, unlike the processes mentioned above. That is the operating principle for the pilot plant developed at TU Wien.

Figure 17 shows these three types of fluidized bed gasifiers.

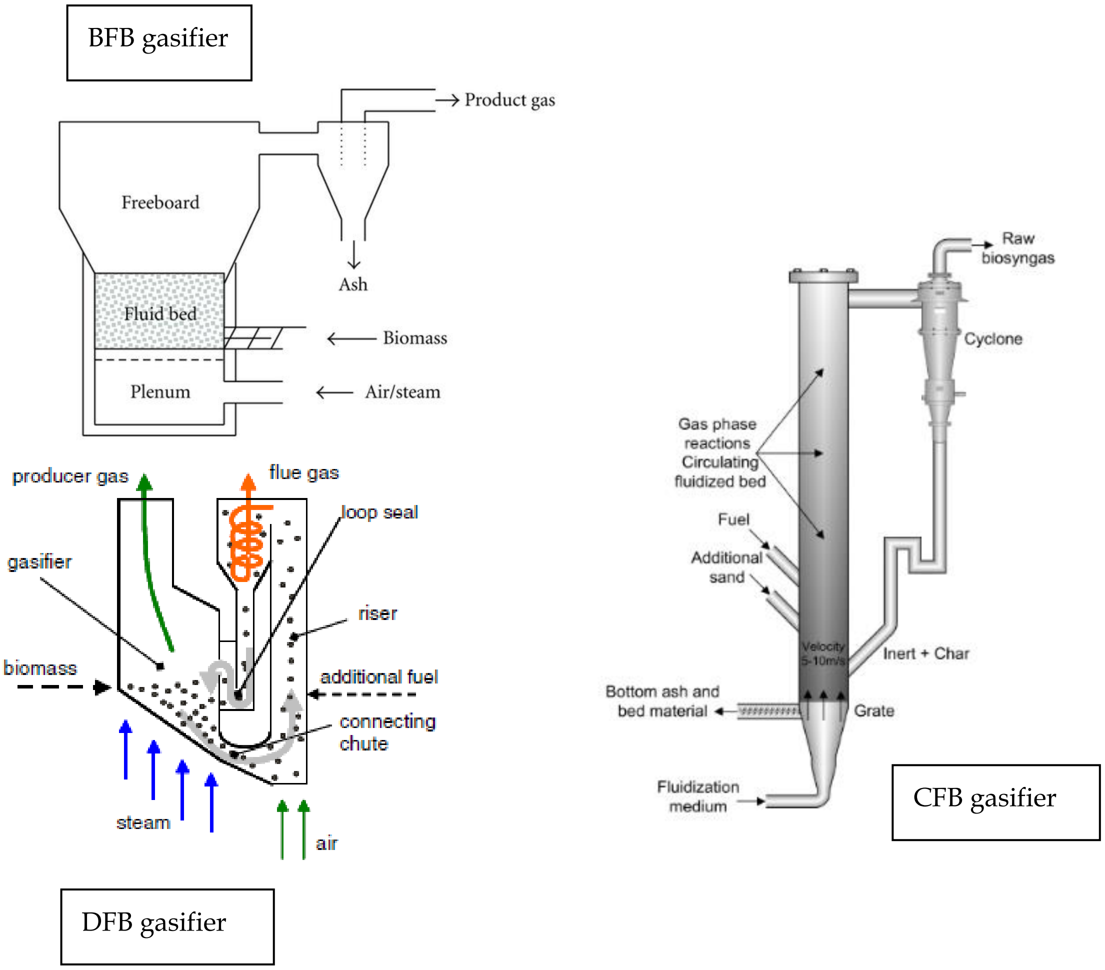


Figure 17. Types of fluidized bed gasifiers. Adapted from [24]

Fluidized bed gasifiers can be operated at either atmospheric pressure or at elevated pressures, being the latter better suited for IGCC (integrated gasification combined cycle) operation because the pressure of the product gas leaving the pressurized gasifier will be sufficient to go directly to the gas turbine control system. The hot product gas from an atmospheric gasifier has to be cooled and compressed in a fuel gas compressor after the clean-up process, resulting in a high level of internal power consumption in such concepts [35]. IGCC plant configurations are economic feasible only at large scales (50-200 MW), whilst atmospheric gasification and gas engines are more common in smaller scale (quite frequent in case of biomass gasification). Combined cycles can also be realized in this case by using gas turbines or organic Rankine cycles (ORC). The process scheme influences the electrical efficiency; in this way, plants using gas engines only are able to reach efficiencies about 25%, while combined cycles can reach higher electrical efficiencies (30-34%) [23, 24]. These different patterns for electricity production are shown in Figure 18.

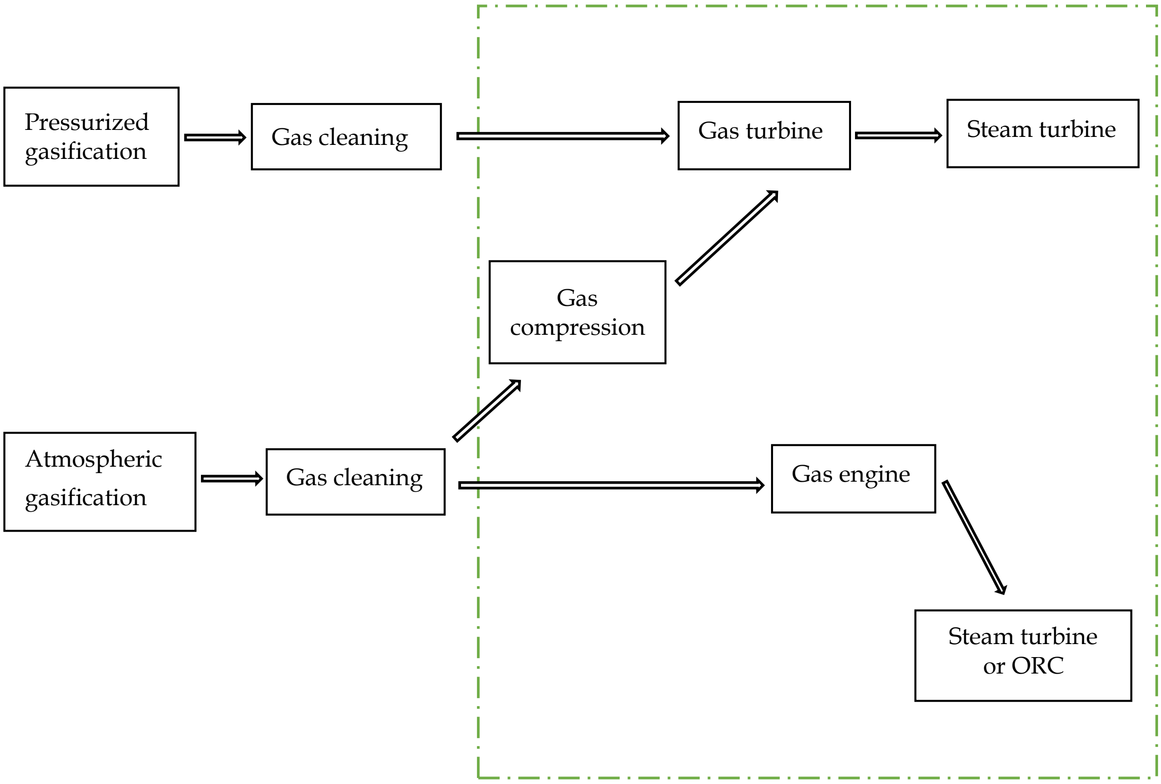
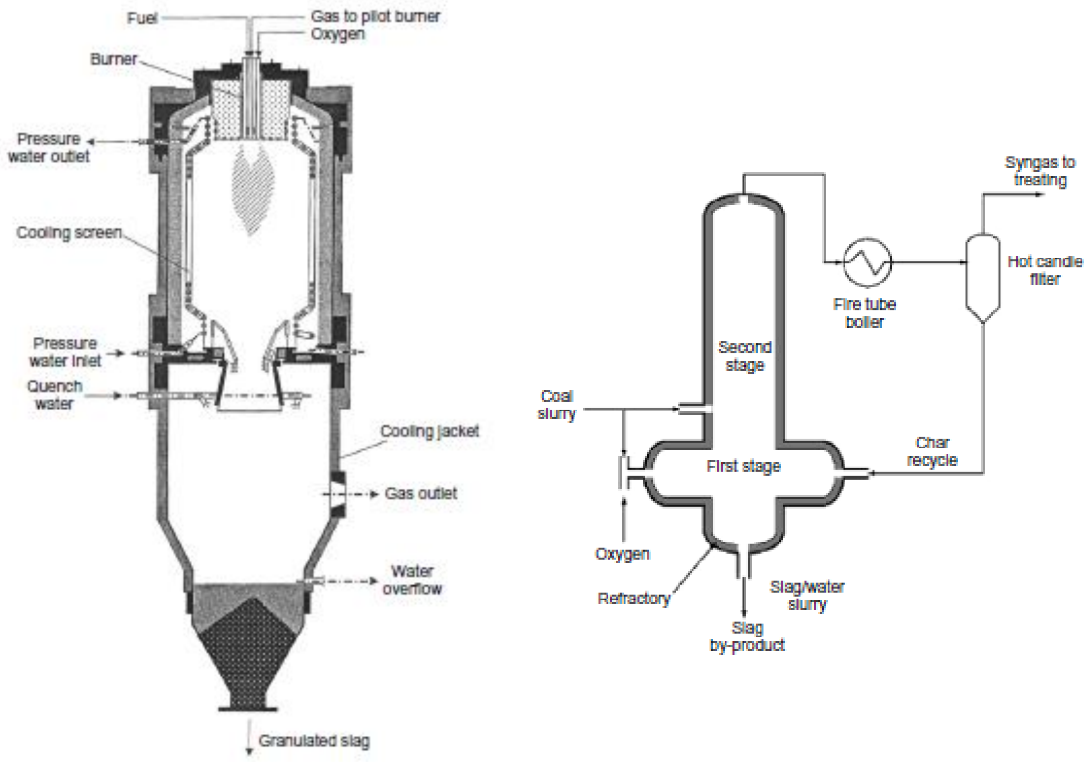


Figure 18. Typical process routes for electricity generation [24]

- **Entrained flow gasification**

Entrained flow (EF) gasification is widely used for large scale gasification of coal, petroleum coke, and refinery residues. However, its suitability for biomass gasification is questionable, as the residence time is quite short and the gasification reactions have to be finished within a few seconds, the feedstock must be pre-processed before and must be converted into a slurry or fine dust [17]. Although the high temperatures (usually >1200ºC) allow the generation of a tar free product gas, handling these temperatures needs a considerable technical effort. Further advantages of entrained flow gasifiers are that the product gas is characterised by a low methane content and by a high conversion rate of carbon, moreover, pressurized operation is easily possible [36]. Entrained flow gasifiers are mostly used in IGCC plants and receive increasing attention for large scale applications (> 100 MW_{th} fuel feed) [23].

Regarding the principle of entrained flow gasifiers, they are co-current reactors where the processed feedstock material enters the gasifier together with the gasification agent. It can be distinguished mainly between two types of entrained flow gasifiers: top-fed downflow and side-fed upflow gasifiers, both shown in Figure 19.



Top-fed EF gasifier

Side-fed EF gasifier

Figure 19. Types of entrained flow gasifiers [17]

A comparison of the three main types of gasifier design is shown in Table 4.

Parameters	Fixed Bed	Fluidized Bed	Entrained Bed
Feed size	<51 mm	<6 mm	<0.15 mm
Tolerance for fines	Limited	Good	Excellent
Tolerance for coarse	Very good	Good	Poor
Exit gas temperatures	450-650 ºC	800-1000 ºC	>1200 ºC
Feedstock tolerance	Low-rank coal	Low-rank coal and excellent for biomass	Any coal but questionable for biomass
Oxidant requirements	Low	Moderate	High
Reaction zone temperature	1000 ºC	800-1000 ºC	2000 ºC
Steam requirement	High	Moderate	Low
Nature of ash produced	Dry	Dry	Slagging
Cold-gas efficiency	80%	89%	80%
Problems areas	Tar production and utilization of fines	Carbon conversion	Raw-gas cooling

Table 4. Comparison between gasifier designs [17]

Furthermore, when choosing the type of gasifier, it is important to take into account the final application of the product gas as well as the scale of the gasification plant, as shown Figure 20.

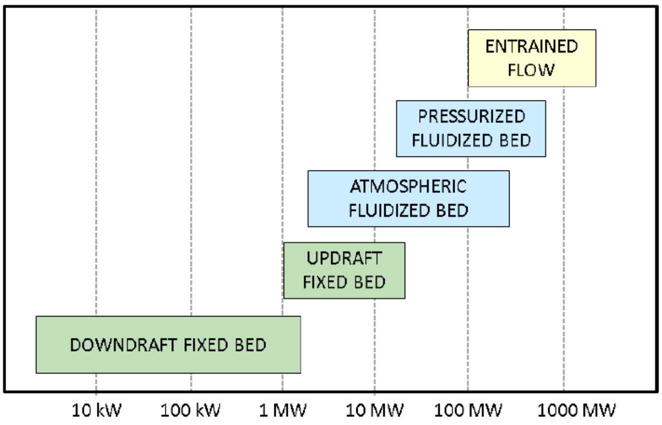


Figure 20. Preferred type of gasifier for different scale application [37]

The composition of the gasification product gas is very dependent not only on the type of gasification agent, the type of heat supply, the pressure or the reactor design, but also it depends on the gasification temperature. According to that, gasification systems can be divided in low temperature gasifiers (<1000 ºC) and high temperature gasifiers (>1200 ºC). The main difference is that the gas produced in low temperature gasifiers contains hydrocarbons or tars, while high temperature gasification allows all the biomass to be completely converted into H_2 and CO (besides CO_2 and H_2O) [20]. This leads to different requirements regarding gas cleaning and conditioning depending on the application (more details in following sections).

Low temperature gasifiers are usually operated below 1000 ºC and include the following processes:

- Fixed bed gasifiers (updraft, downdraft and crossdraft)
- Fluidized bed gasifiers (BFB, CFB and DFB)

High temperature gasification includes processes operated above 1200 ºC and with short residence time (only a few seconds) where the biomass feedstock is completely converted and tars are avoided. The main reactor type is the entrained flow gasifier and the preferred process is the slagging entrained flow gasification because it allows to deal with feedstock containing ash. In these gasifiers, ash melt forming a slag layer that protect the wall and the liquid slag is removed from the bottom of the gasifier [38].

2.4.3. *Product gas applications*

The product gas which is obtained directly from gasification contains carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), moisture (H_2O), methane (CH_4), aliphatic hydrocarbons (C_xH_y), benzene (C_6H_6), and toluene (C_6H_5-CH_3), as well as small amounts of ammonia (NH_3), hydrochloric acid (HCl), hydrogen sulphide (H_2S), tars, and other impurities. The desired compounds such as H_2 and CO must be separated from this mixture and hence, a process of gas cleaning is required [17]. Depending on the final gas application, different cleaning technologies have to be used in order to remove the impurities and to reach the required gas quality (further explanation of gas cleaning is given in Section 2.4.4).

Syngas is a mixture of H_2 and CO gases that nowadays is mainly produced from natural gas, but it can also be produced from biomass, solid fossil fuels, and liquid fuels. Syngas that is produced from biomass is sometimes called biosyngas to distinguish it from that generated from fossil fuels. Since the field of this work is biomass gasification, here both syngas and biosyngas are referred to that derived from biomass unless specified otherwise.

Biomass gasification is a key technology for future biomass utilization because it can overcome the problems when handling solid biomass by converting it into a gaseous product that can be used for a lot of applications [39], Figure 21 gives an overview about the product obtained from biomass using gasification technology.

Nowadays, biomass gasification is mainly used for efficient heat and power production and for firing and co-firing at small- and medium-scale plants. However, development is expected to lead to large-scale synthesis of biofuels and chemicals.

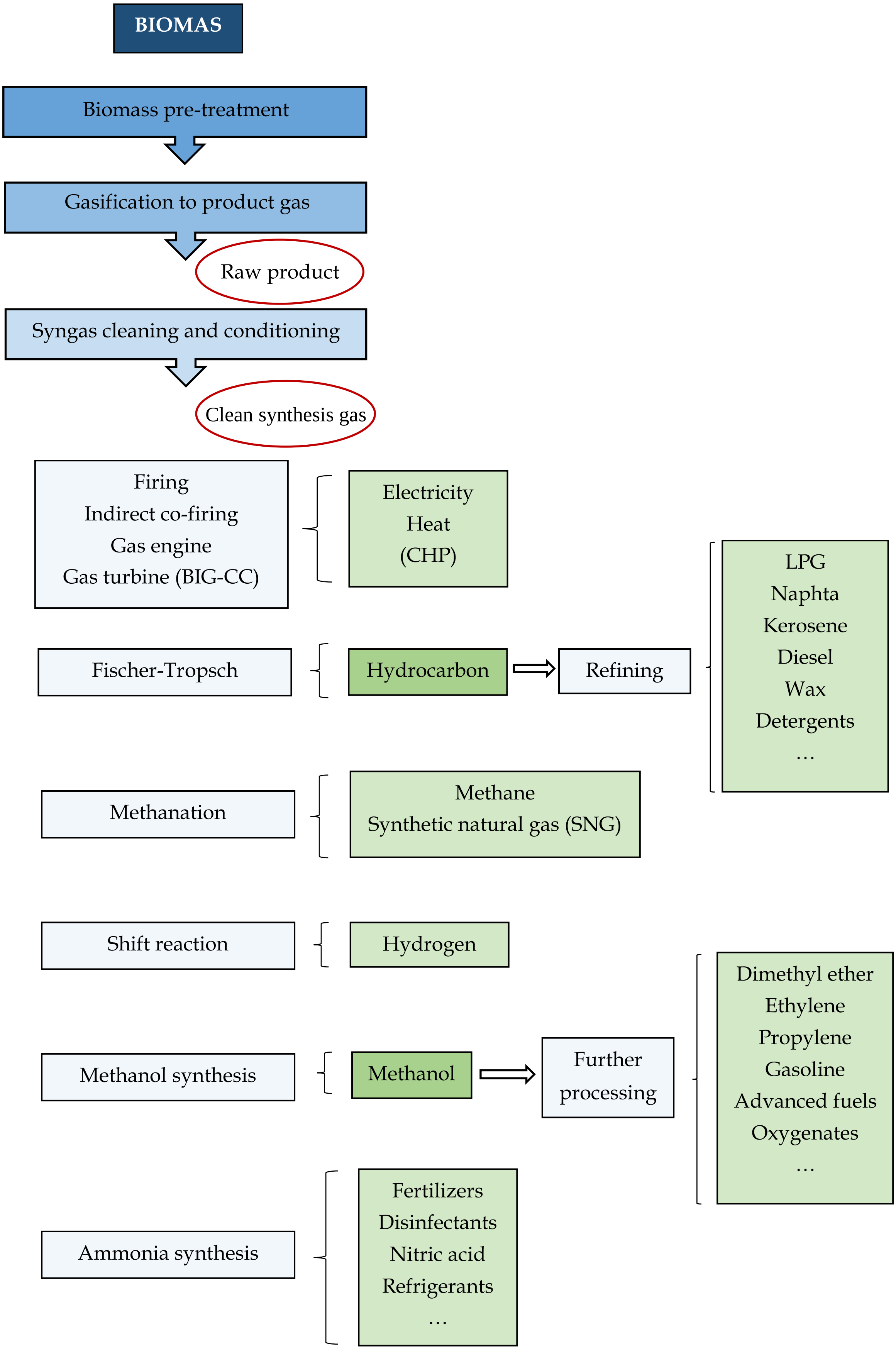


Figure 21. Different end-use applications for biomass gasification

2.4.4. Gas treatment

The raw product gas obtained from a gasifier contains undesirable compounds such as particles (dust or char), tars (condensable higher hydrocarbons), alkali metals, sulphur components, nitrogen compounds, and chlorine compounds [26]. Figure 22 shows the main components of the product gas, both desired components and impurities which must be removed.

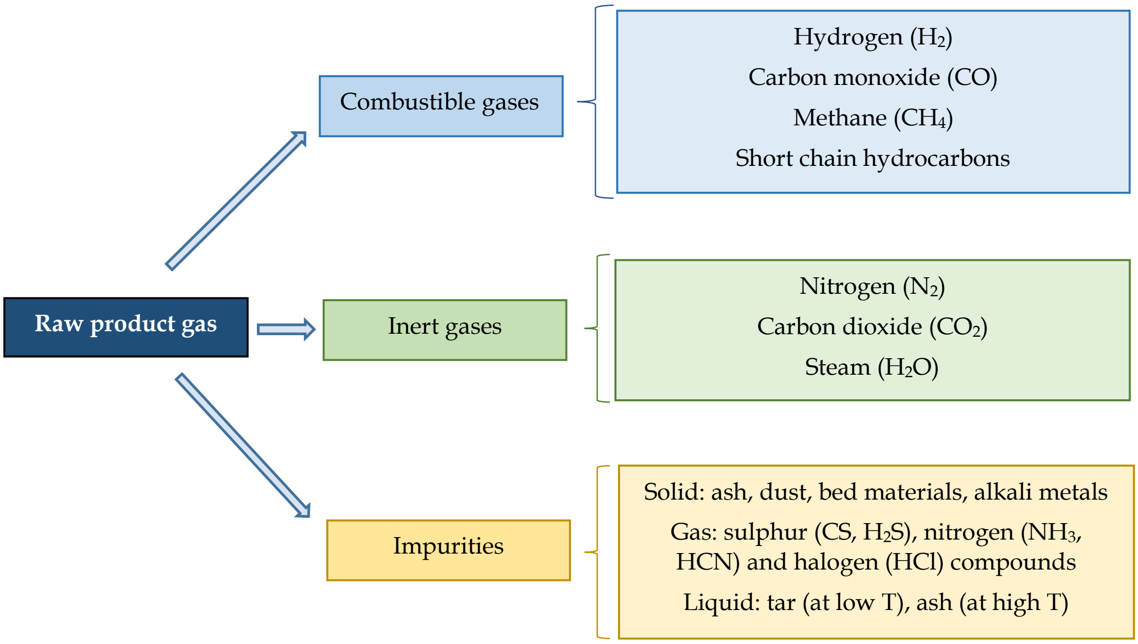


Figure 22. Main components of the product gas [26]

Those contaminants not only can cause operational problems in downstream process, but they are also incompatible with the end-use systems, either if the gas is used for heat and power generation or for synthesis processes. The amount of these components depends on the design of the gasifier and its operation (temperature, pressure, oxygen-fuel ratio, fluidizing agent), as well as the type of biomass used as fuel. Table 5 summarizes the main problems resulting from each contaminant and the common cleaning method.

Contaminant	Example	Problems	Clean-up method
Particulates	Ash, char, fluid bed material	Erosion	Filtration Scrubbing
Alkali metals	Sodium and potassium compounds	Hot corrosion	Cooling Condensation Filtration Adsorption
Tars	Refractory aromatics	Clog filters, difficulties to burn, deposit internally	Tar cracking Tar removal
Nitrogen	NH_3 and HCN	NO_x formation	Scrubbing Selective catalytic reduction (SCR)
Sulphur, chlorine	H_2S and HCl	Corrosion, emissions	Lime or dolomite scrubbing Absorption

Table 5. Fuel gas contaminants, problems and cleaning methods [23]

The final gas application sets the acceptable levels for the concentration of impurities and the required main gas composition, which in turn determines the cleaning processes that are needed. Applications such as kilns or co-firing systems allow the raw product gas to be used directly or with little clean-up. Extensive gas clean-up is needed to meet gas quality requirements when operating gas turbines or internal combustion (IC) engines. Furthermore, if the gas is used for syntheses applications, the product gas not only must be cleaned but also must be conditioned and upgraded to reach specified molecular ratios of components such as H_2 or CO [40]. Table 6 summarizes the requirements for gas quality in some applications.

Application	Gas quality requirements
Firing and co-firing in boiler	No restrictions or particulates-free
Heat	Clean-up, low HCl content
Power – Combined cycle	Clean-up, dust- and alkali metals-free
Power – CHP gas engine	Strict clean-up, low tar content
Power – CHP fuel cell	Strict clean-up, low hydrocarbon & organic content
SNG	Strict clean-up, nitrogen-free, high methane content
Liquid fuel synthesis	Very strict clean-up & upgrading, nitrogen-free
Chemical synthesis	Very strict clean-up & upgrading, nitrogen-free
Hydrogen production	Very strict clean-up & upgrading, nitrogen-free
Ammonia production	Very strict clean-up & upgrading, containing nitrogen

Table 6. Gas specifications depending on the final gas application [20]

Gas cleaning systems are determined by the end-use application and must be made in accordance to the overall conversion system. In the following paragraphs, technologies for removal of impurities are described and typically, more than one cleaning step is required.

- **Particulate removal**

Particulates are defined as solid-phase materials and originated from the ash of the feedstock, dust, unconverted carbon (at low temperature gasification), soot (at high temperature gasification), and carry-over bed material (in fluidized bed gasifiers). Thus, it can be said that particulates entrained in the raw product gas are highly dependent on the gasifier type, being the fluidized configurations those which produce high particulate loadings in the product gas [20]. Although particulates are unavoidable in gas streams, they are undesirable because can damage the downstream equipment and moreover, the amount of fly ash emitted is regulated.

Some of the basic technologies for particle removal are:

- Cyclone filters
- Barrier filters
- Electrostatic filters
- Wet scrubbers

Cyclone filters are the first step of the cleaning process because they are effective at removing larger particles, being possible to remove more than 90% of particulates above about 5 µm in diameter. In circulating fluidized bed or entrained bed gasifiers, cyclones are part of the reactor, allowing the separation of the bed material and other particulates from the gas stream. In some systems, cyclones are placed in series where the subsequent ones capture some of the finer particles. Additionally, the temperature of operation can be high and thus, the heat of the product gas can be retained [40].

Barrier filters include a range of porous materials that prevent particles to penetrate. These filters work effectively when dealing with particles in the range of 0.5 to 100 µm in diameter. They are usually placed downstream from cyclone filters in order to reduce the particle load. Although barrier filters are effective when removing dry particulates, they are less suitable for wet or sticky contaminants [40]. Different barrier filters suitable for biomass are [20]:

- Rigid porous “candle” or cross-flow filters constructed or metal or ceramic
- Coupled Pressure Pulse Recleaning (CPP)
- Bag house filters
- Packed-bed filters

In electrostatic filters (ESPs – Electrostatic Precipitators) the product gas flow passes high voltage electrodes that impart an electric charge to particulates, but do not affect the permanent gases.

Regarding wet scrubbers, they are effective systems than can remove 99,9% of particles over 2 µm and 95-99% of those over 1 µm [41] and moreover, are installed for combined removal of particles and tars. Wet scrubbing need the water to remain in liquid phase, thus the product gas must be cooled to below 100ºC, causing an undesirable loss of sensible heat [40].

- **Alkali removal**

Biomass feedstocks contain high levels of alkali salts, especially those containing potassium. Alkali metals can vaporize at temperatures of about 800ºC and given that in the vapour phase they can pass through particulate removal devices, problems regarding deposition on cooler surfaces downstream can be created [40]. It should be considered that gasification operates at high temperatures (700-1200ºC) and thus, alkali vapours are likely to be present in many systems.

In existing technology, alkali vapours are removed by cooling the product gas below about 600ºC to allow these vapours to condensate into solid particulates [23]. The solids are then removed at the particulate removal stage by using filtration systems as those described above.

- **Tar removal**

The need of gas cleaning technology, and in particular of tar removal technology, when the gas is used either for CHP or synthesis purposes is still the Achilles heel of biomass gasification [42]. Tar is a thick, black, highly viscous liquid that condenses in the low-temperature zones of the gasifier, blocking the gas passage, and leading to unexpected system disruptions [17].

The definition of term tar has been discussed without reaching a uniform definition. Tar can be understood as a complex mixture of condensable hydrocarbons, such as oxygen-containing, 1- to 5- aromatic, and complex polyaromatic hydrocarbons [43]. Tars are also defined as all organic contaminants present in the gasification gas larger than benzene [44]. The members of the Gasification Task of the IEA Bioenergy Agreement, the US Department of Energy and the DGXVII of the European Commission were aware of these multitude of definitions (more than 30) when developing a standard sampling and analysis for tar; hence, they agreed to identify as tar all component having a molecular weight higher than benzene [20].

The main property of tars is the dew point, defined as the temperature below which tars can condense [45]. The dew point depends on tar composition and content; and establishing a classification of tar becomes crucial when designing tar removal systems. However, several classification criteria have been defined.

Evans and Milne [46-48] suggested that the tar composition is based on the severity of conditions it encounters including temperature and residence time. Figure 23 shows how the different types of tars are formed depending on the temperature. According to that, tars are classified as primary, secondary and tertiary.

- Primary tars: mainly consist of oxygenated compounds
- Secondary tars: phenolics and olefins
- Tertiary tars:
    - Alkyl tertiary tars: methyl derivatives of aromatics
    - Condensed tertiary tars: polyaromatic hydrocarbons (PAH), including benzene, naphthalene, acenaphtylen, anthracene/phenanthrene, pyrene

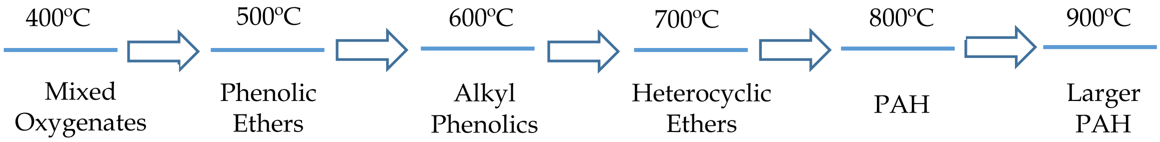


Figure 23. Classification of tars regarding temperature [46]

Table 7 includes another approach for classification of tars based on the physical properties of the compounds, which was proposed by the Energy Research Centre of the Netherlands (ECN) [49, 50].

Tar class	Class name	Property	Representative compounds
1	GC-undetectable (>6 rings)	Heaviest tars that condense at high temperature even at very low concentrations	Gravimetric tars
2	Heterocyclic aromatics	Highly water soluble compounds	Pyridine, phenol, cresol, quinoline
3	Aromatics (1 ring)	Light hydrocarbons that are not important in condensation and water solubility issues	Xylene, styrene, toluene
4	Light PAHs (2-3 rings)	Condense at relatively high concentrations and intermediate temperatures	Naphthalene, biphenyl, acenaphthylene, fluorene, phenanthrene, anthracene
4	Heavy PAHs (4-6 rings)	Condense at high temperature and low concentration	Fluoranthene, pyrene, chrysene, benzo-fluoranthene, benzo-pyrene, perylene

Table 7. Classification of tars based on the physical properties [49, 50]

Tar removal is especially needed in systems where the gas is cooled prior to use because condensation in pipes and other equipment can lead to operational problems. Tars are also a big problem in systems where the gas must be compressed prior to use as well as in some mechanical systems such as engines [44]. There are several technologies for tar removal but they are usually divided into two groups: in-situ (or primary) tar reduction, and post-gasification (or secondary) tar reduction. The former approach avoids tar formation, the process is carried out inside the gasifier and thus, the quality of the product gas is improved without the need for any downstream removal process. On the other hand, secondary tar reduction does not interfere with the process inside the gasifier but they are more expensive than primary methods [17]. When applications demand a high quality of product gas, combination of in-situ and post-gasification reduction is very effective. Figure 24 summarizes different technologies for tar removal.

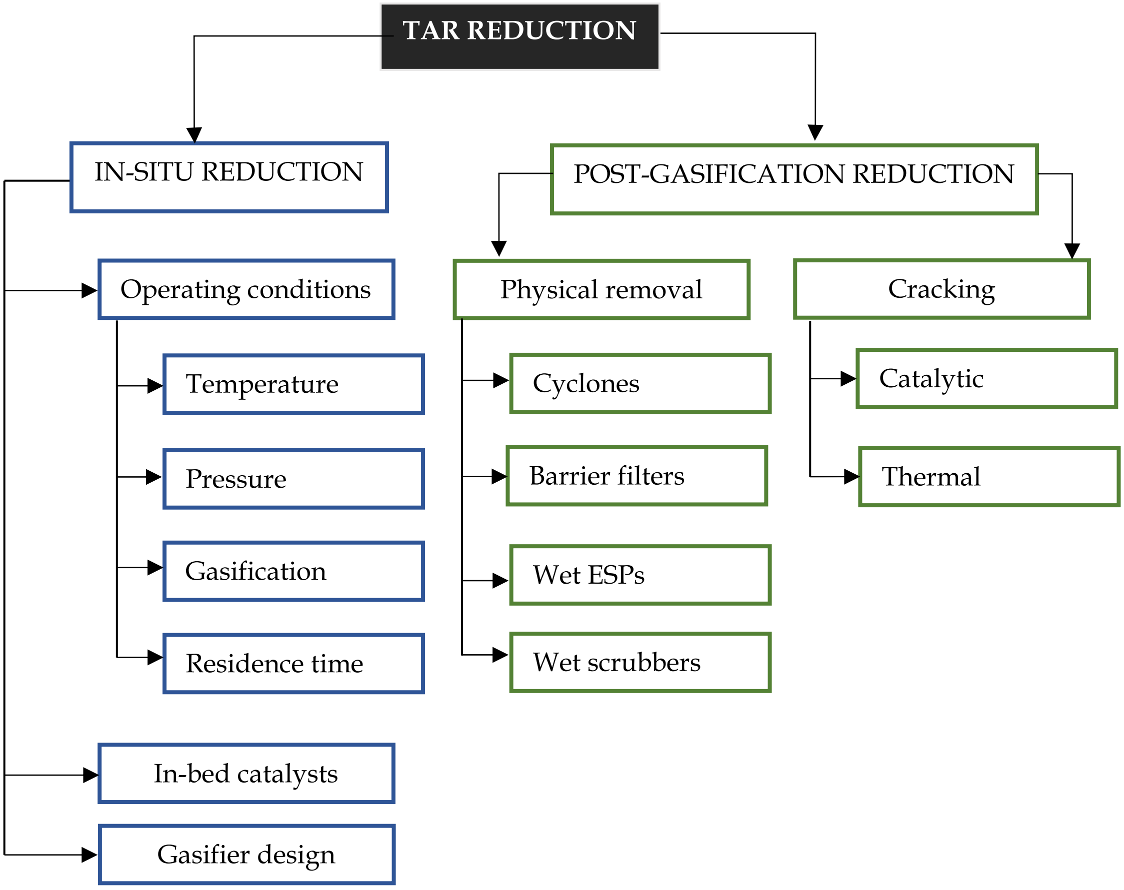


Figure 24. Available options for tar reduction [17]

- **Removal of nitrogen containing compounds**

Most of the biomass nitrogen (50-80%) is converted to ammonia (NH_3) and smaller quantities of other gaseous nitrogen compounds such as hydrogen cyanide (HCN). These components are converted to NO_x when the gas is burned, causing potential emissions problems [23]. There are four ways that are feasible to clean the product gas of nitrogen:

- Limiting fuel-bound nitrogen in the feedstock
- Wet scrubbing
- Usage of low-NOx combustion techniques
- Usage of selective catalytic reduction (SCR) at the exhaust of the engine or turbine

- **Sulphur compounds removal**

Sulphur in the biomass feedstock is mainly converted into hydrogen sulphide (H_2S) and carbonyl sulphide (COS). Although sulphur concentrations produced in biomass gasification are lower than those produced in the combustion of fossil fuels, the presence of sulphur must not be neglected as it results in issues in downstream processes such as pollution due to emission of SO_x after burning, corrosion in turbines, and catalyst deactivation [40]. Technologies for sulphur removal have been developed successfully in coal gasification/synthesis processes and some of the possibilities to reduce sulphur compounds are [51]:

- Dry sorption/reaction
- Physical absorption
- Absorption in alkali solution
- Liquid oxidation
- Adsorption
- Biological removal

- **Chlorine compounds removal**

The chlorine in biomass is mainly converted into hydrogen chloride (HCl). Chlorine is another potential contaminant that becomes highly corrosive when is dissolved in condensed water. Problems regarding corrosion also occur when chloride combines with metals present in the feedstock such as potassium and sodium. Furthermore, it is important to mention that chlorine has effects regarding bed agglomeration and the higher the gasification temperature, the greater the concentration of chlorine in the product gas. [51]. Methods for removing chlorine and its compounds are:

- Absorption in active material: inside the gasifier or in a secondary reactor
- Dissolution in a wet scrubbing system

2.5. Principles of dual fluidized bed (DFB) gasification

The dual fluidized bed gasification is a type of indirect (allothermal) fluidized-bed gasification where the combustor reactor is physically separated from the gasification reactor [52]. Between these two areas, a circulation loop of bed material is created while the gases remain separated. The circulation of bed material transports heat from the combustion to the gasification zone, working in this way with allothermal heat supply. Exothermic oxidation heats up the bed material in the combustor reactor, whereas endothermic reactions demand heat in the gasification reaction [53]. The principle of the dual fluidized bed gasification process is shown in Figure 25.

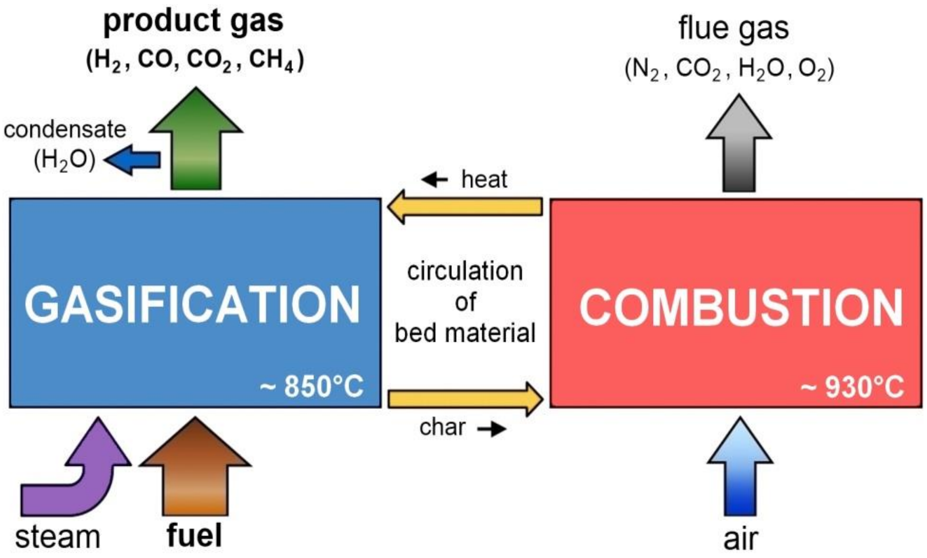


Figure 25. Operation principle of the DFB gasification process (TU Wien)

Steam is used as gasification agent, which coupled with the fuel, is fed into the gasification zone. The biomass is converted into gaseous products, char, and tar in the gasification reactor. Afterwards, the product gas is separated from the bed material, which together with the unconverted biomass, char, and tar, circulates to the combustion reactor. This zone is fluidized with air and the non-gaseous biomass residues, char and tar are burned. This exothermic reaction in the combustion zone heats the bed material and after removing the ash, the bed material is recirculated back to the gasification reactor, providing in this way the energy for the endothermic gasification. The flue gas will not come into contact with the product gas, allowing a high-grade product gas [53]. Advantages of using dual fluidized bed steam gasification are [52, 54]:

- Obtaining a product gas which is almost free of N_2
- No need for an expensive air separation unit (ASU)
- High fuel flexibility
- More efficient conversion of the biomass fuel
- Good gas-solid contact and excellent heat transfer
- Use of catalytic active bed material
- Potential for scale up
- Reactors can be optimized separately

This gasification technology was developed at TU Wien where the Institute of Chemical Engineering operates a 100 kW DFB pilot plant for research purpose. Furthermore, it has been successfully demonstrated and some examples are shown in Table 8.

Location	Usage/Product	Fuel/Product (MW, MW)
Güssing (Austria)	Gas engine	$8.0_{fuel}/2.0_{el}$
Oberwart (Austria)	Gas engine/ORC	$8.5_{fuel}/2.8_{el}$
Villach (Austria)	Gas engine	$15.0_{fuel}/4.0_{el}$
Senden/Ulm (Germany)	Gas engine/ORC	$15.0_{fuel}/5.0_{el}$
Gothenburg (Sweden)	BioSNG	$32.0_{fuel}/20.0_{BioSNG}$

Table 8. Industrial installations with DFB gasifiers [55]

3. EXPERIMENTAL SETUP

3.1. Motivation and methodology

The novel test plant is expected to face new challenges and one of them is the fuel flexibility. The gasification of conventional woody feedstocks has been extensively studied and several gasification plants have been built not only in Austria but also in other countries (Table 8). Test runs based on alternative feedstocks and carried out at TU Wien can represent a basis for future industrial scale-ups, but dealing with the high tar contents in the product gas obtained from new biomass feedstock is the major issue. For that reason, a new design of a dual fluidized bed reactor is available at TU Wien and its goal is to focus on the in-situ tar reduction in the gasification reactor.

The gasification of pellets of softwood, a mixture of chicken manure/bark and pure chicken manure when using a mixture of potassium feldspar and calcite as bed material represent the core of the present work and the basis for the coming discussion. Moreover, some data regarding the gasification of exhausted olive pomace (EOP) is included in the Section 5.4 because EOP is an abundant source of biomass in Spain and it is interesting to analyse the economic feasibility and potentials of its gasification. It is also important to define the used bed material and the differences when comparing to olivine, which is the bed material that has been traditionally used at the novel pilot plant. All data have been obtained from the three technical reports of scientific research [56-58] containing the experiments based on the gasification of the previously mentioned feedstocks.

To sum up, the present chapter includes:

- Detailed description of the plant parts as well as the measurement equipment of the novel DFB system at TU Wien.
- Characterization and fuel preparation of the three biomass feedstocks used for the test run: softwood, 30% chicken manure/70% bark and finally, pure chicken manure.
- Characterization of the bed material used (potassium feldspar with calcite) and the one which has been traditionally used (olivine with calcite).

The execution of test runs should be carried out following the procedure presented in Figure 26.

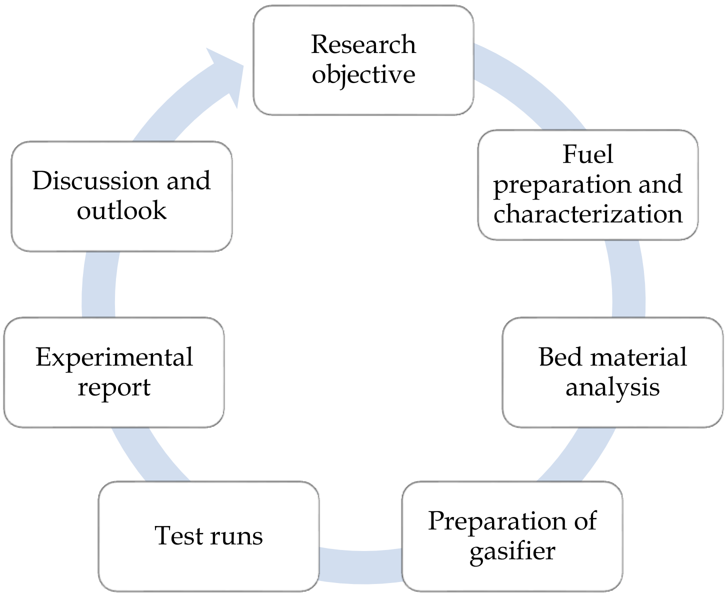


Figure 26. Methodology for gasification trials at the TU Wien pilot plant

3.2. Description of the 100 kW Pilot Plant TU Wien

TU Wien operates a 100-kW dual fluidized bed (DFB) gasification reactor for pilot scale experiments. Figure 27 illustrates a schematic drawing of the overall test plant which is divided in four main parts:

- solid fuel supply;
- gas production;
- gas cooling, cleaning and utilization; and
- control station for measurement and control technology.

Furthermore, the red labels indicate where different measuring points of the product gas were allocated when experiments were carried out. In this way, two extra measuring points were adapted to the current used measuring point at sample point A: (i) sample point B, a measuring point after the bubbling bed; and on the other hand, (ii) a measuring point before the radiant cooler.

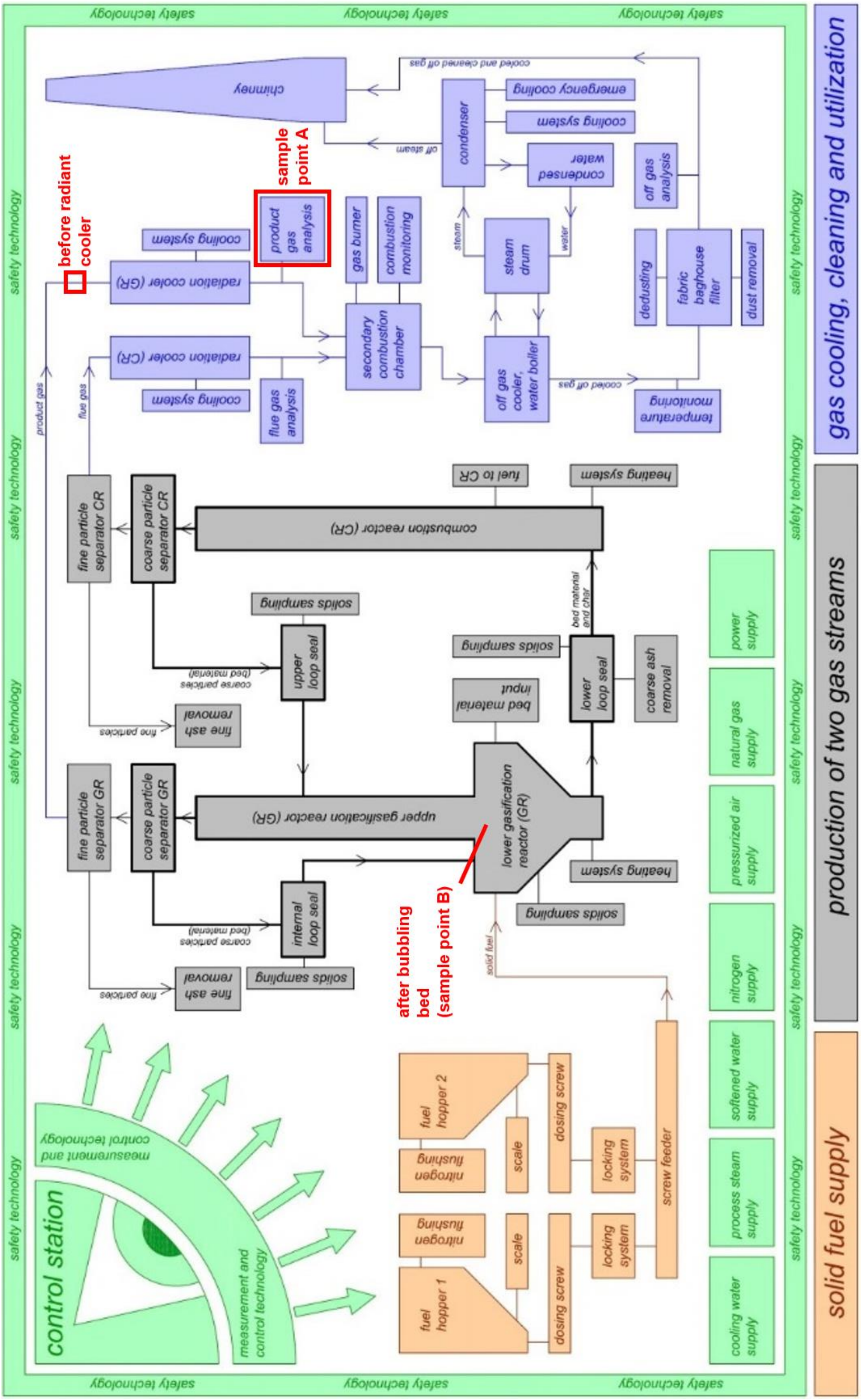


Figure 27. Basic flow sheet of the overall DFB gasification facility (sample points in red). Adapted from [28]

The test plant contains the DFB gasification system consisting of a gasification reactor and a combustion reactor as it is shown in Figure 28.

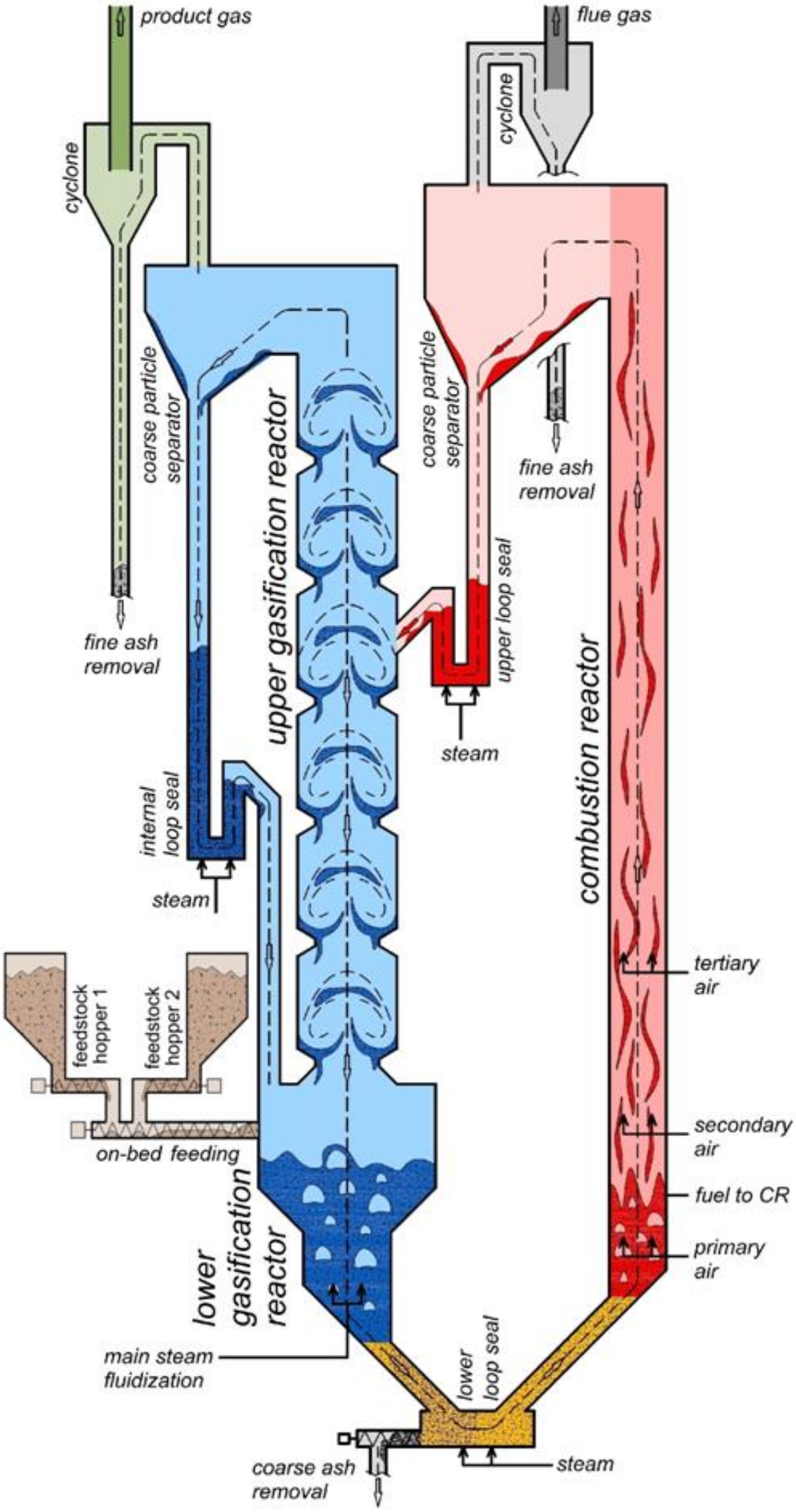


Figure 28. Schematic illustration of the DFB reactor system (TU Wien [28])

The main characteristic of this system is that the gasification zone and the combustion zone are separated as two fluidized bed reactors and connected by loop seals. The gasification reactor is fluidized with superheated steam and both bubbling and turbulent zones can be distinguished inside it. The biomass fuel is fed into the bubbling bed, allowing a better contact between fuel and bed material. [54,59]. The remaining residual char and the bed material leave the gasification reactor at the bottom and circulate to the combustion reactor through the lower loop seal. In the same gasification reactor, there is an internal loop seal through which the bed material particles are redirected back into the same reactor once they have been separated from the product gas. The upper turbulent part of the gasifier allows an improvement of hydrocarbon conversion as well as higher gas-particle interaction [28].

The combustion reactor is operated as a fast fluidized bed using air as a fluidisation medium [33]. The bed material is heated up by burning char and additional fuel in the combustor. In industrial gasifiers, there is no need for added fuel because tar and char from the product gas as well as other combustible streams are recycled to the combustion reactor. However, in the pilot plant, light fuel oil is needed instead of recycle streams in order to control the temperature in the gasification reactor [14]. Bed material is separated (gravity separator) from the flue gas and is recirculated to the gasification reactor via the upper loop. The bed material leaves the combustion reactor at higher temperatures than it leaves the gasification reactor and hence, it supplies heat for the endothermic gasification reactions. The process produces two separate streams at high temperature, a high-quality product gas and on the other hand, a conventional flue gas.

All loop seals are fluidized with superheated steam, avoiding any leakage of the two gas streams between reactors. Additionally, it is possible to eliminate any flow of air or flue gas through the upper loop seal as that would cause a dilution of the product gas with nitrogen [28,60].

The basic geometry data of the reactor design of the DFB pilot plant at TU Wien are summarized in Table 9. Additionally, Figure 29 provides an image of the uninsulated combustion reactor.

Parameter	Unit	Lower gasification reactor	Upper gasification reactor	Combustion reactor
Geometry	-	Conical bottom section	Square-shaped upper constriction section	Cylindrical
Inner dimensions of reactor part	mm	560 x 490 68 x 490	128 x 128	Ø125
Height of reactor part	m	1.03	3.33	4.73
Operable temperature range	°C	700 - 850	800 - 950	830 - 980
Pressure	-	Close to atmospheric conditions		
Fluidization agent	-	Steam	Steam	Air
Fluidization regime	-	Bubbling fluidized bed	Turbulent zones	Fast (circulating) fluidized bed

Table 9. Design values for geometric and operating parameters of the DFB system. Adapted from [61]

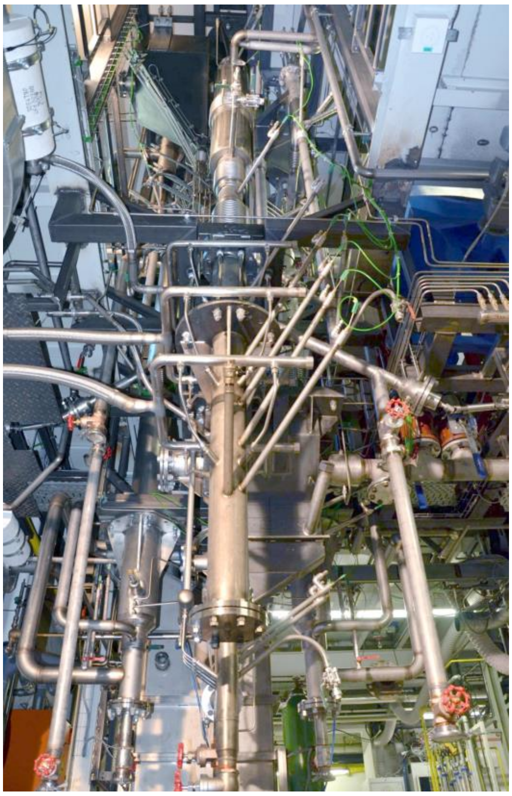


Figure 29. Uninsulated combustion reactor of the DFB system (TU Wien [61])

Finally, it is important to mention that heat losses to the environment in the 100 kW pilot plant are higher when comparing it to industrial plants due to the quality of the insulation as well as the disadvantageous volume-to-surface ratio [14].

3.3. Analytics

3.3.1. Measurement of main product gas composition and flue gas

A deep analysis of the product gas stream, as well as of the flue gas and exhausted gas stream, is crucial to study the gasification process. Hence, the main product gas components, H_2, CO, CO_2, CH_4, and O_2; and flue gas components CO, CO_2, O_2, NO, NO_2, SO_2 and N_2O are analyzed online (continuously) by a Rosemount NGA 2000 device. Additionally, the exhausted gas components CO, CO_2 and O_2 are measured by the same device Rosemount NGA 2000. Moreover, a gas chromatograph (Perkin Elmer ARNEL – Clarus 500) determines the product gas components CO, CO_2, CH_4, N_2 and the hydrocarbons C_2H_3, C_2H_6, and C_3H_8 every 15 minutes [61]. An overview of the measuring chain to determine the composition of the product gas and flue gas streams is shown in Figure 30.

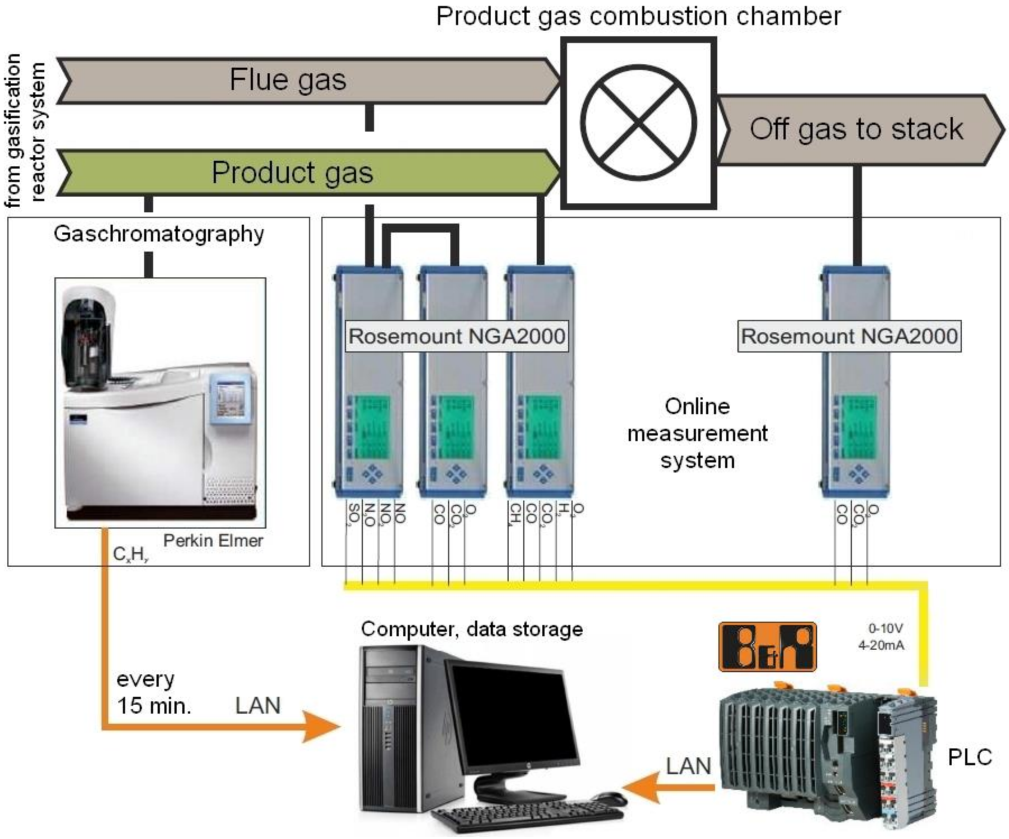


Figure 30. Overview of the gas measurement equipment [56]

The Rosemount NGA2000 and the gas chromatograph devices are sensitive in terms of particulate matter, condensable components, and moisture, therefore, the gas stream has to undergo a special cleaning line before the measurement, as it shown in Figure 31. The cleaning line consists of six impinger bottles cooled by a freezing bath. The first two bottles are empty and here is where the separation of condensed water takes place. The following three bottles are filled with rapeseed oil methyl ester (RME) with the purpose of removing tar. Finally, there is an empty bottle which ensures that liquids do not pass through the measurement equipment [59].

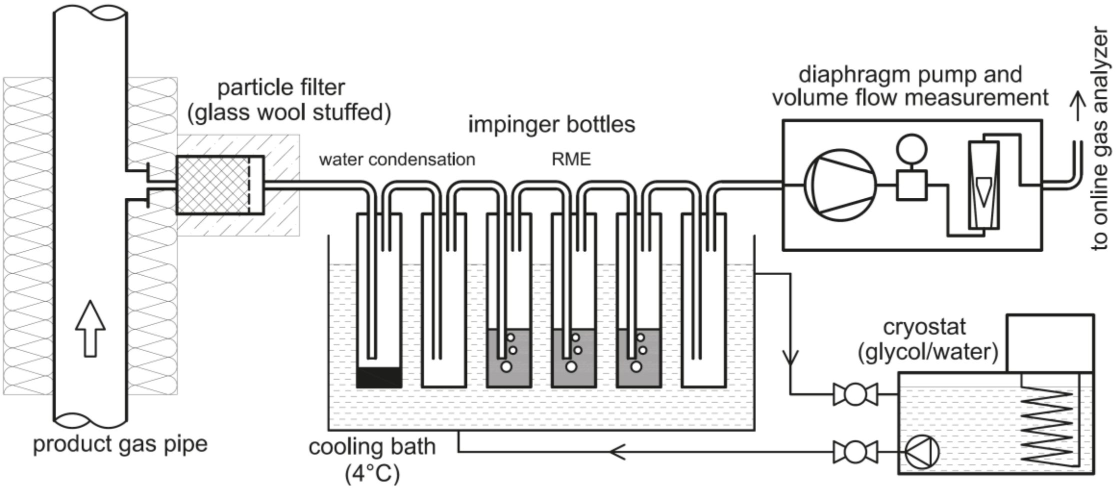


Figure 31. Gas cleaning line for gas analysis [10,56]

3.3.2. *Tar, char and dust measurements*

The analysis of tar, char and dust in the product gas stream is measured discontinuously as it is presented in the scheme shown in Figure 32.

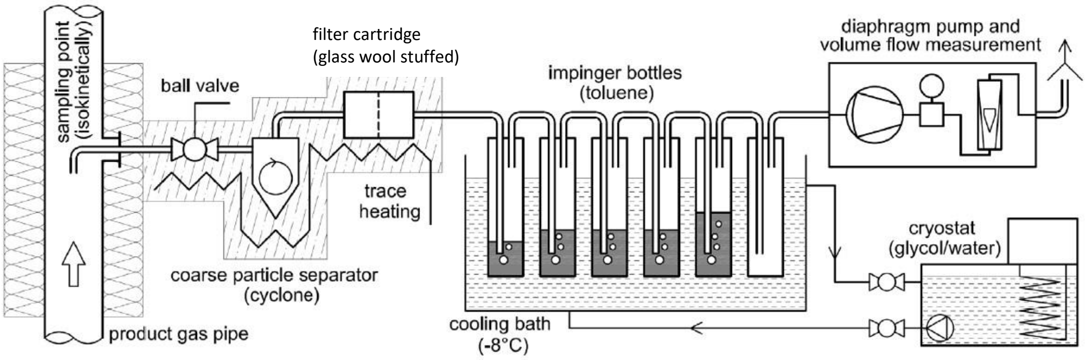


Figure 32. Dust, char, water and tar measurement equipment [10]

Tar is sampled isokinetically and afterwards, solid particles (dust and char as well as the condensed tars) are removed by using a cyclone and a glass wool stuffed filter cartridge. Tar condensation of tars is avoided by heating the sampling line. Subsequently, the gas is circulated through six impinger bottles, the first five bottles contain toluene and the last one is empty (to protect the measurement equipment of passing liquids as happened in the product gas sampling line). The impinger bottles are located in a cooling bath and are cooled down to -8ºC due to the action of a cryostat, where the tars and steam condense. The condensed tars are dissolved in the solvent of the impinger bottles and separated from the water phase. Toluene is used as a solvent (instead of isopropanol, IPA), because it allows an easier measurement of the water content in the product gas.

However, benzene, toluene and xylene (BTX) components cannot be detected when using toluene instead of IPA. Heavy tars are referred as gravimetric or GC-undetectable tars and are quantified as the mass of tars left after vacuum evaporation of the solvent. On the other hand, medium molecular weight tar compounds are detected by gas chromatography coupled with mass spectrometry (GC-MS). Further information can be found in several publications [44,46,62,63]. Tar content is analysed gravimetrically and by GCMS according to an internal guide used at the TU Wien [64] which is based on the standards [65 (*CEN/TS 15439:2006*)].

3.4. Biomass feedstocks

The flexibility of the novel DFB steam gasifier at TU Wien allows the use of different feedstocks beyond the conventional woody feedstocks. Hence, the gasification of three different biomass fuels represents the basis of the present work, these are:

- 100% softwood
- Mixture of 70% bark and 30% chicken manure
- 100% chicken manure

Biomass received from its source cannot be fed directly into the gasifier, thus, it is necessary to transform the raw biomass feedstock into pellets. It is important to take into account that for the gasification of biomass in a power plant, wood chips are mostly the selected fuel, but for the pilot plant at TU Wien, the pieces must be smaller and the quality of the fuel has to be constant for the entire test. Hence, wood pellets are used instead of wood chips, given that it was found out during previous tests that both pellets and chips behave in a similar way in the gasifier, being possible to compare results [66]. Hence, the first step of the transformation process is milling, allowing a reduction of the size. Once the biomass fuel is reduced in size, is ready to be fed into the pelletizing equipment in order to prepare the biomass pellets for the gasification experiment. Finally, a drying process of the achieved pellets is required to reduce the initial water content.

Since a detailed analysis of the feedstock is essential for the interpretation of the gasification process, Table 10 lists the main elemental composition, volatiles, water, and ash content of the three different types of fuels used in the experiment. The characterization of the feedstocks is done according standard methods by governmentally certified and established by DIN-Standards (*Deutsches Institut für Normung,* German Institute for Standardization). The X-ray fluorescence spectroscopy (XRF) offers an overview of the main elemental ash composition. Moreover, four temperatures can be measured: the deformation or softening temperature (A), where the first rounding of the edges of a cubic sample takes place, the spherical temperature (B), the hemispherical temperature (C), and the flow temperature (D), where the sample melts to a flat disk with specific height. To avoid solid agglomerations and plugging in the fluidized bed systems due to ash melting, the ash softening and melting temperature is a critical issue and therefore, problems in the gasifier related to attrition, agglomeration and fouling would occur if the melting point is lower than the gasification temperature.

Fuel parameter	Unit	Softwood pellets [58]	Chicken manure/bark [57]	Chicken manure [57]
General parameter				
Water content	wt%	7.2	9.5	9.1
Volatiles	wt%$_{db}$	85.4	68.8	67.7
LHV (dry)	kJ/kg$_{db}$	18 940	17 100	13 900
LHV (moist)	kJ/kg	17 397	15 240	12 420
Elemental composition				
Ash content	wt%$_{db}$	0.2	13.0	25.4
Carbon (C)	wt%$_{db}$	50.7	46.3	38.0
Hydrogen (H)	wt%$_{db}$	5.9	5.2	4.9
Oxygen (O)	wt%$_{db}$	43.0	33.4	26.8
Nitrogen (N)	wt%$_{db}$	0.2	1.72	4.11
Sulphur (S)	wt%$_{db}$	0.0	0.19	0.33
Chloride (Cl)	wt%$_{db}$	0.0	0.21	0.49
Ash analysis				
Silicon dioxide (SiO_2)	wt%$_{db}$	6.62	7.95	5.66
Aluminium oxide (Al_2O_3)	wt%$_{db}$	1.63	3.03	1.57
Calcium oxide (CaO)	wt%$_{db}$	55.16	39.95	25.97
Iron oxide (Fe_2O_3)	wt%$_{db}$	0.91	2.88	0.79
Potassium oxide (K_2O)	wt%$_{db}$	13.4	22.97	6.64
Sodium oxide (Na_2O)	wt%$_{db}$	1.07	1.57	4.37
Magnesium oxide (MgO)	wt%$_{db}$	8.35	4.45	10.32
Phosphorous pentoxide (P_2O_5)	wt%$_{db}$	3.07	12.79	31.86
Ash melting behavior				
Deformation or softening temperature (A)	ºC	1 335	1 300	-
Spherical temperature (B)	ºC	-	1 340	-
Hemi-spherical temperature (C)	ºC	-	1 390	-
Flow temperature	ºC	1 438	1 460	>1 490

Table 10. Fuel and ash analysis of feedstocks used for the gasification test run: wood pellets, chicken manure/bark and pure chicken manure

The ash content of the alternative feedstocks, both mixture of chicken manure-bark and pure chicken manure, is significantly high, being especially relevant the share of alkali metal in the ash. As exhibited in Table 10, the share of potassium oxide (K_2O) and sodium oxide (Na_2O) are relatively higher than in ash of common wood pellets. This characteristic was an important issue to consider at the first steps of the investigations because a high alkali content means problems regarding low ash softening/melting temperatures. Low ash softening temperature can lead to agglomeration of the bed materials, and in turn, to stop the gasification test at an early stage. However, the presence of phosphor pentoxide (P_2O_5) and magnesium oxide (MgO) raise the ash melting point, compensating the high amount of potassium and sodium and hence, the softening temperature of the alternative feedstocks does not mean a problem to carry out the test run.

3.5. Bed materials

Traditionally, olivine has been used as bed material for experiments at the novel DFB gasification system because it has been proven to be a suitable bed material regarding attrition resistance, high heat capacity and catalytic tar reduction activity [67]. Moreover, pre-calcination of the olivine before its use can improve catalytic activity substantially [68,69]. For the long-term utilization of olivine, it has been found out that the bed material interacts with the fuel ash and forms calcium-rich layers around the bed particles, improving also in this way the catalytic activity [15].

The reason of trying a new bed material is that olivine contains small amounts of heavy metals (like chromium or nickel) that end up in the ash, leading to higher deposition costs for the plant operator. The aim is to research in new bed material forms as alternatives to olivine that are widely available, heavy metal free, and cheap.

The gasification experiment which represents the core of the present work was carried out with a mixture of 89wt% potassium feldspar and 11wt% calcite, this mixture with calcite is done with the purpose of simulating Ca-rich particle layers. An important characterization is crucial for further discussion, therefore Table 11 collects the results of XRF analysis and the mechanical properties of potassium feldspar and calcite as well as the ones of the olivine in order to establish a comparison between different options regarding bed material. Additionally, it is important to say that a first test run had to be cancelled due to a large particle size of the bed material, and after sieving the particles, the test run was successfully repeated.

Parameter	Unit	Potassium feldspar [57]	Limestone/calcite [57]	Olivine [58]
$CaCO_3$	wt%	-	95 - 97	< 0.1
$MgCO_3$	wt%	-	1.5 – 4.0	-
SiO_2	wt%	65.7	0.4 – 0.6	39 - 42
Al_2O_3	wt%	17.9	0.2 – 0.4	-
$Al_2O_3+Cr_2O_3+Mg_3O_4$	wt%	-	-	0.7 – 0.9
Fe_2O_3	wt%	0.041	0.1 – 0.3	8.0 – 10.5
TiO_2	wt%	0.028	-	-
CaO	wt%	0.03	-	< 0.4
MgO	wt%	0.01	-	48 - 50
Na_2O	wt%	0.84	-	-
K_2O	wt%	14.74	-	-
P_2O_5	wt%	0.09	-	-
BaO	wt%	0.33	-	-
NiO	wt%	-	-	< 0.1
Hardness	Mohs	6	3	6-7
Particles density	kg/m^3	2600	≈2650	≈2850
Particles density (after full calcination)	kg/m^3	-	≈1500	-

Table 11. Composition of potassium feldspar, calcite and olivine

4. RESULTS

4.1. *General overview of the gasification of alternative feedstocks*

The results of the gasification experiment conducted at the novel DFB pilot plant, including the gasification of

- softwood,
- chicken manure/bark, and
- pure chicken manure,

are shown by using several tables and graphs [57]. In the following three sections, the operating parameters and an overview of the main results are presented for each type of feedstock. The bed material used in the experiment is a mixture of 89wt%potassium feldspar and 11wt% calcite. A comparison of the gasification performance and product gas obtained from the gasification of these three feedstocks is conducted in Section 4.5, where it is also included some key data when gasifying softwood with olivine as bed material.

During the first part of the experiment, the gasification of 100% softwood pellets was carried out (test run I) and Figure 33 depicts the pattern of the product gas composition. From 12:00 to 13:40 took place the heat-up phase and afterwards, the fluidization was switched to steam and air was additionally used to fluidize the gasification system with the purpose of reaching the required temperature. Steam became the only gasification medium from 14:18. Once the system was ready to start with the real gasification, the fuel bunker (with light oil) used to heat up the system was switched off and the bunker with softwood started to play its role. A tuning phase and a stationary operation occurred since 14:31, and thenceforward all the measurements were carried out until 15:40, when the test run with softwood was successfully finished.

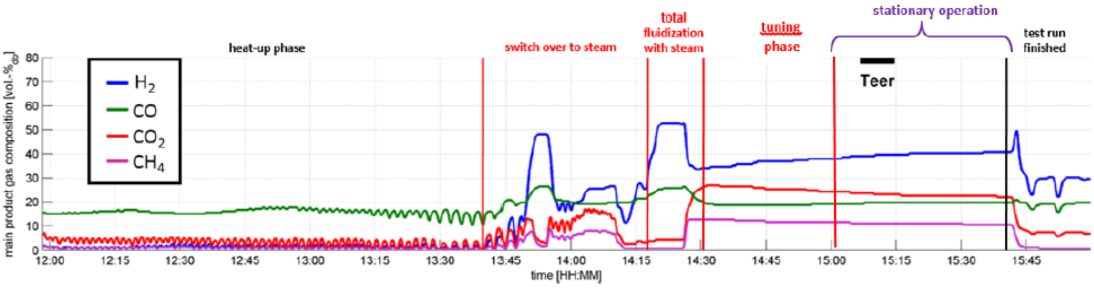


Figure 33. Product gas composition when carrying out test run I with softwood [57]

The composition of the product gas obtained from a mixture of chicken manure and bark as a fuel is displayed in Figure 34. No product gases are shown between 16:13 and 16:24 because during these minutes the washing bottles were changed. The system reached a stationary mode from 16:50 to 18:45 and the NH_3 measurement took place at 16:52. Once the measurement was carried out, the measuring point was relocated to the point before the radiant cooler (ii), shown in Figure 27, and the product gases were measured from 17:31 to 17:47. Afterwards, the product gas was measured in the point located after the bubbling bed (i) since 17:49. At 18:17 the measuring point was changed to the traditional point A, and the tar content was measured from 18:22 to 18:30, being completed the test run at 18:45.

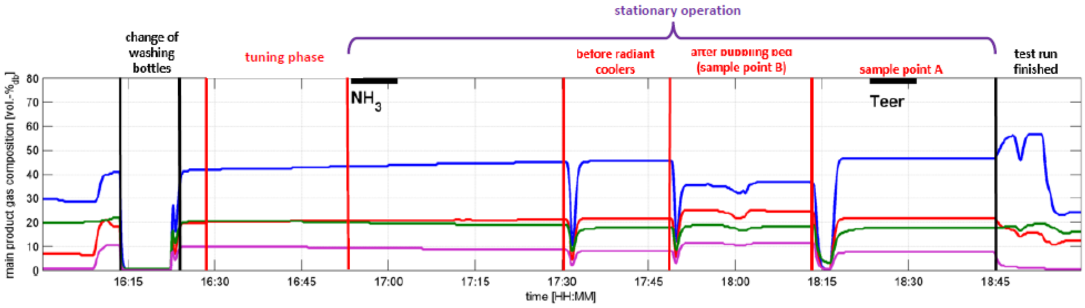


Figure 34. Product gas composition when carrying out test run II with chicken manure/bark [57]

During the third part of the experiment, the gasification of pure chicken manure as biomass fuel was carried out and the product gas composition is shown in Figure 35. From 18:45 to 19:00 the change of the fuel was performed and the stationary mode was reached at 20:00. Point A was the point where samples were taken and tar content was measured from 20:18 to 20:27. As it was done in the test run II, first at 20:38 the gas was measured before the radiant cooler (ii), ten minutes later product gas measurements was performed after the bubbling bed (i). The measuring point was changed to the original point (at sample point A) at 21:06 and product gas were recorded until the end of the test run at 21:28.

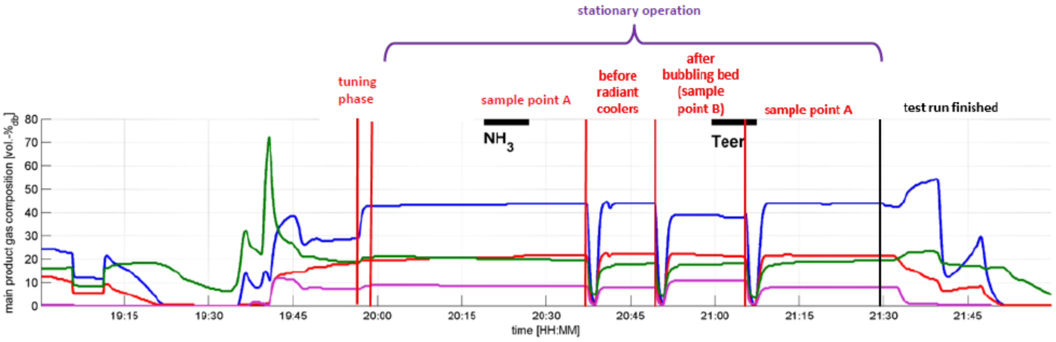


Figure 35. Product gas composition when carrying out test run III with pure chicken manure [57]

Samples of the three test runs were taken and analysed, and once the data were evaluated and validated by using mass and energy balances with the software package IPSEpro, were available to be presented below.

4.2. Results of the gasification test run I with softwood

In the present section, the results of the first test run with traditional softwood pellets are presented. Figure 36 displays the temperature profile of both gasification reactor (GR) and combustion reactor (CR) and the main operating conditions are collected in Table 12. Product gas composition, tar content and additional measurements such as dust and water content were sampled at sampling point A and are shown in Table 13 – Table 14. Finally, Table 15 lists the components of the flue gas from the combustion reactor.

The temperature profile of the reactors is drawn in Figure 36 and the diagram illustrates that the temperature over the height of both reactors changes due to the circulation of bed material. The hot bed material transports the heat from the combustion reactor to the gasification reactor and then, is recirculated to the combustion reactor through the lower loop seal. The bed material is heated up by burning char with additional air, which causes a local hot spot where the highest temperature (1000ºC) in the CR is measured. The lowest temperature (700ºC) is produced in the GR occurring when the steam for fluidization is introduced into the lower part of the GR. This temperature differences are correlated with the type of bed material and its heat transfer capacity.

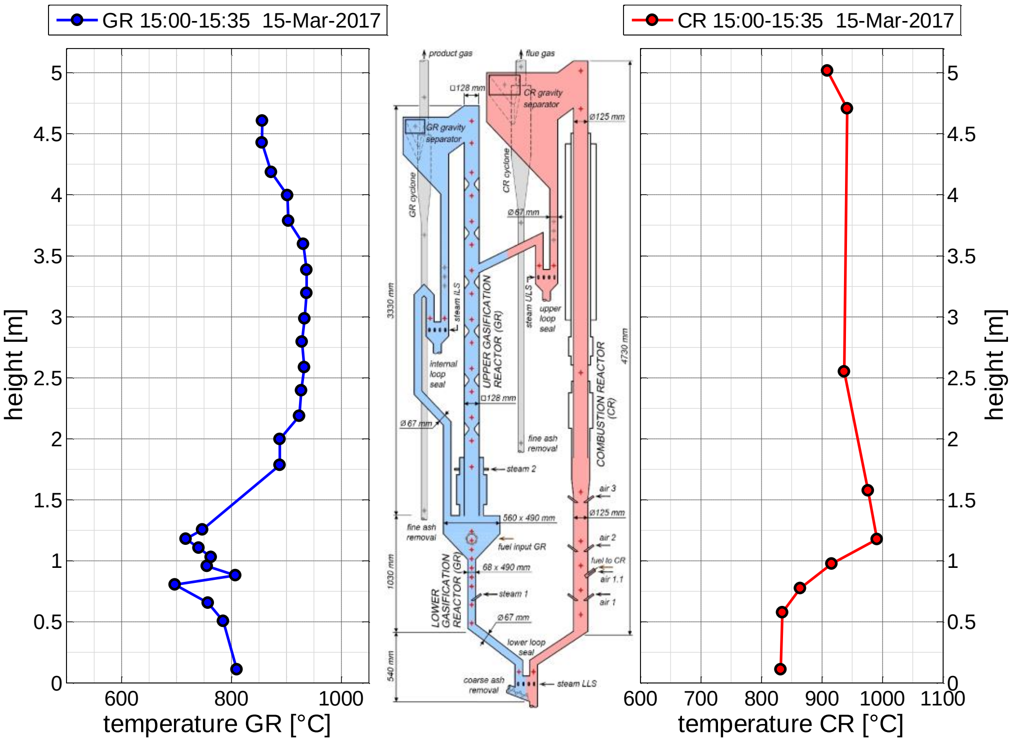


Figure 36. Average temperature profiles of the GR and CR for the test run I [57]

Parameter	Unit	Gasification reactor	Combustion reactor
Bed material types	µm	Potassium feldspar (d_{sv}=287), calcite (d_{sv}=480)	
Bed material mixture	wt%	89 (potassium feldspar) + 11 (calcite)	
Overall initial bed material inventory	kg	80	
Feedstock type	-	Softwood	
Feedstock mass flow	kg/h	20.4	-
Feedstock/fuel power into GR	kW	95	-
Fuel to CR	kW	-	61*
Heat losses of reactor system (GR & CR)	kW	29*	
Temperatures lower reactor part	°C	771	991
Temperatures upper reactor part	°C	933	942
Water content in the gas stream	vol%	35.1* - 39.0	14.5*
Product gas volume flow	Nm^3_{db}/h	25.7*	-
Product gas lower heating value (free of char & tar)	MJ/Nm^3_{db}	13*	-
Product gas power (free of char & tar)	kW	92*	-
Overall cold gas efficiency, novel 100 kW test plant	%	72*	-
Overall cold gas efficiency, estimated for a 50 MW plant	%	70 - 77	-

** calculated with IPSEpro mass and energy balance*

Table 12. Main operating conditions of the gasification test run I [57]

The DFB gasification process yields two separate gas streams, a product gas stream from the gasification reactor and on the other hand, a flue gas stream from the combustion reactor. The product gas mainly consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and other hydrocarbons, as well as unconverted water (H_2O) and impurities such as dust, char and tars. The shares of the main product gases are collected in Table 13, and Table 14 gathers additional product gas components.

Product gas composition, sample point A		**NGA 2000 online values**	**PE Arnel GC TU Wien**	**PE GC values Bioenergy**	**IPSEpro simulation values**
Component	**Unit**				
Hydrogen (H_2)	vol %$_{db}$	39.6	-	-	38.9
Carbon monoxide (CO)	vol %$_{db}$	23.1	24.4	23.6	25.1
Carbon dioxide (CO_2)	vol %$_{db}$	19.7	21.4	20.9	20.8
Methane (CH_4)	vol %$_{db}$	11.1	11.6	11.2	11.8
Ethylene (C_2H_4)	vol %$_{db}$	-	2.06	1.96	2.01
Ethane (C_2H_6)	vol %$_{db}$	-	0.17	0.17	0.17
Propane (C_3H_8)	vol %$_{db}$	-	0.00	-	0.00
Acetylene (C_2H_2)	vol %$_{db}$	-	-	0.008	0.00
Ammonia (NH_3)	vol %$_{db}$	-	-	-	0.06

Table 13. Main product gas components of the gasification test run I [57]

Product gas analytics, measured discontinuous, sample point A		
Parameter	**Unit**	**Offline measured: toluene as solvent**
Dust content	g/Nm$^3_{db}$	3.25
Char content	g/Nm$^3_{db}$	1.88
Tar content GC-MS (without BTX)	g/Nm$^3_{db}$	13.39
Tar content gravimetric	g/Nm$^3_{db}$	5.38
Water content H_2O	g/Nm$^3_{db}$	39
Tar dew point	°C	201

Table 14. Additional product gas components measured offline with toluene as solvent, test run I [57]

The main components of the flue gas from the combustion reactor are listed in Table 15.

Flue gas composition		**NGA 2000 online values**	**IPSEpro simulation values**
Component	**Unit**		
Carbon dioxide (CO_2)	vol %$_{db}$	13.8	15.1
Oxygen (O_2)	vol %$_{db}$	0.02	0.0
Carbon monoxide (CO)	vol %$_{db}$	0.49	0.53
Nitrogen (N_2)	vol %$_{db}$	-	83
Nitrogen monoxide (NO)	vol %ppm$_{db}$	43.0	0.0
Sulphur dioxide (SO_2)	vol %ppm$_{db}$	6.0	0.0
Nitrogen dioxide (NO_2)	vol %ppm$_{db}$	0.0	0.0
Nitrous oxide (N_2O)	vol %ppm$_{db}$	5.0	0.0

Table 15. Main composition of the flue gas from the combustion reactor, test run I [57]

4.3. Results of the gasification test run II with chicken manure/bark

The structure when presenting the results of the second test run with a mixture of chicken manure and bark is similar as the structure used to expound the results of the test run I with softwood. Hence, temperature profiles of the gasification and combustion reactors are displayed in Figure 37.

Table 16 lists the key operating conditions of the test run. The main product gas composition is shown in Table 17, and Table 18 collects additional product gas components such as dust, char, tar, and water contents, both tables correspond to the measuring point located in the sampling point A. To complete the presentation of the results concerning the test run II, Table 19 includes the composition of the flue gas that exits the combustion reactor.

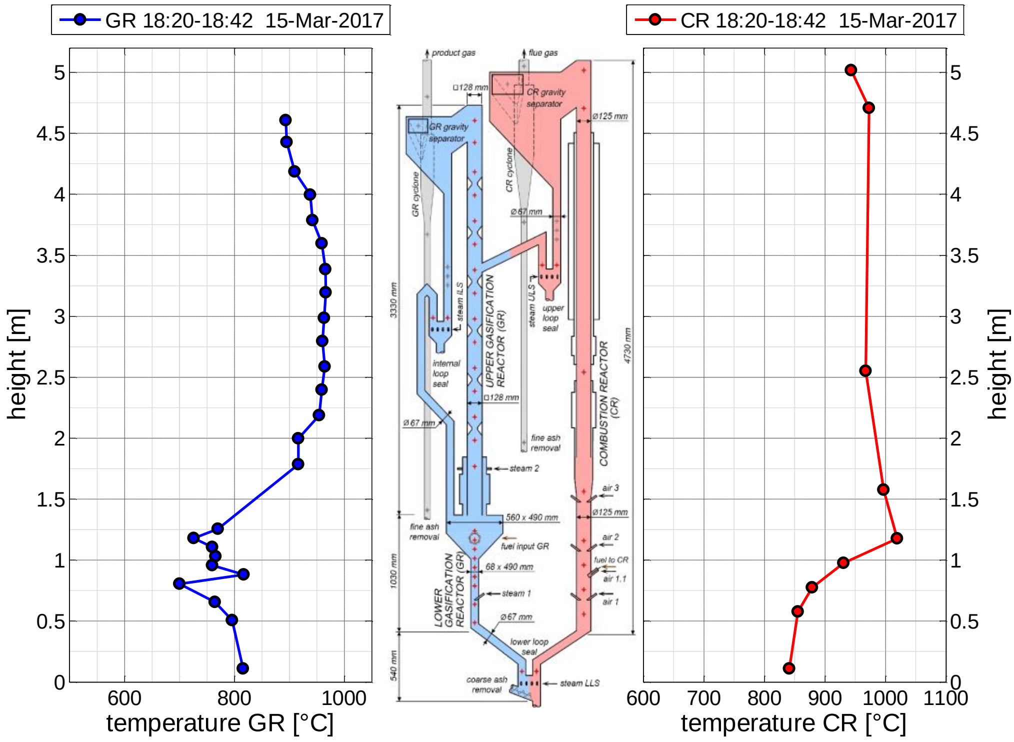


Figure 37. Average temperature profiles of the GR and CR for the test run II [57]

As it can be seen when comparing Figure 36 and Figure 37, no remarkable difference is found between both temperature profiles due to the equality of operation conditions between both test runs.

Parameter	Unit	Gasification reactor	Combustion reactor
Bed material types	µm	Potassium feldspar (d_{sv}=287), calcite (d_{sv}=480)	
Bed material mixture	wt%	89 (potassium feldspar) + 11 (calcite)	
Overall initial bed material inventory	kg	80	
Feedstock type	-	Chicken manure (30%) + Bark (70%)	
Feedstock mass flow	kg/h	24.3	-
Feedstock/fuel power into GR	kW	100	-
Fuel to CR	kW	-	55*
Heat losses of reactor system (GR & CR)	kW	28*	
Temperatures lower reactor part	°C	777	1 019
Temperatures upper reactor part	°C	964	973
Water content in the gas stream	vol%	30.6* - 31.0	13.5*
Product gas volume flow	Nm^3_{db}/h	28.2*	-
Product gas lower heating value (free of char & tar)	MJ/Nm^3_{db}	12*	-
Product gas power (free of char & tar)	kW	91*	-
Overall cold gas efficiency, novel 100 kW test plant	%	72*	-
Overall cold gas efficiency, estimated for a 50 MW plant	%	70 - 77	-

** calculated with IPSEpro mass and energy balance*

Table 16. Main operating conditions of the gasification test run II [57]

Product gas composition, sample point A		NGA 2000 online values	PE Arnel GC TU Wien	PE GC values Bioenergy	IPSEpro simulation values
Component	Unit				
Hydrogen (H_2)	vol %$_{db}$	46.7	-	-	43.8
Carbon monoxide (CO)	vol %$_{db}$	21.8	23.2	19.1	23.5
Carbon dioxide (CO_2)	vol %$_{db}$	17.7	19.4	20.9	19.9
Methane (CH_4)	vol %$_{db}$	7.7	8.1	7.9	8.0
Ethylene (C_2H_4)	vol %$_{db}$	-	1.15	1.08	1.07
Ethane (C_2H_6)	vol %$_{db}$	-	0.12	0.11	0.11
Propane (C_3H_8)	vol %$_{db}$	-	0.00	-	0.00
Acetylene (C_2H_2)	vol %$_{db}$	-	-	0.034	0.00
Ammonia (NH_3)	vol %$_{db}$	-	-	-	2.22

Table 17. Main product gas components of the gasification test run II [57]

Product gas analytics, measured discontinuous, sample point A		
Parameter	Unit	Offline measured: toluene as solvent
Dust content	g/Nm$^3_{db}$	4.05
Char content	g/Nm$^3_{db}$	2.43
Tar content GC-MS (without BTX)	g/Nm$^3_{db}$	5.71
Tar content gravimetric	g/Nm$^3_{db}$	1.59
Water content H_2O	g/Nm$^3_{db}$	31
Tar dew point	ºC	170

Table 18. Additional product gas components measured offline with toluene as solvent, test run II [57]

Finally, and following the same structure than in the previous section, the composition of the flue gas stream is presented in Table 19.

Flue gas composition		NGA 2000 online values	IPSEpro simulation values
Component	Unit		
Carbon dioxide (CO_2)	vol %$_{db}$	13.9	15.4
Oxygen (O_2)	vol %$_{db}$	0.25	0.25
Carbon monoxide (CO)	vol %$_{db}$	0.46	0.46
Nitrogen (N_2)	vol %$_{db}$	-	83
Nitrogen monoxide (NO)	vol %ppm$_{db}$	43.0	0.0
Sulphur dioxide (SO_2)	vol %ppm$_{db}$	6.0	0.0
Nitrogen dioxide (NO_2)	vol %ppm$_{db}$	0.0	0.0
Nitrous oxide (N_2O)	vol %ppm$_{db}$	5.0	0.0

Table 19. Main composition of the flue gas from the combustion reactor, test run II [57]

4.4. Results of the gasification test run III with pure chicken manure

For the third and last test run, structure is also the same as the used to present the previous test runs. In this way, Figure 38 depicts temperature profiles of both reactors and Table 20 lists operating parameters of the test run. Table 21 and Table 22 are responsible for showing the main and additional product gas components, respectively. Finally, the flue gas composition is included in Table 23.

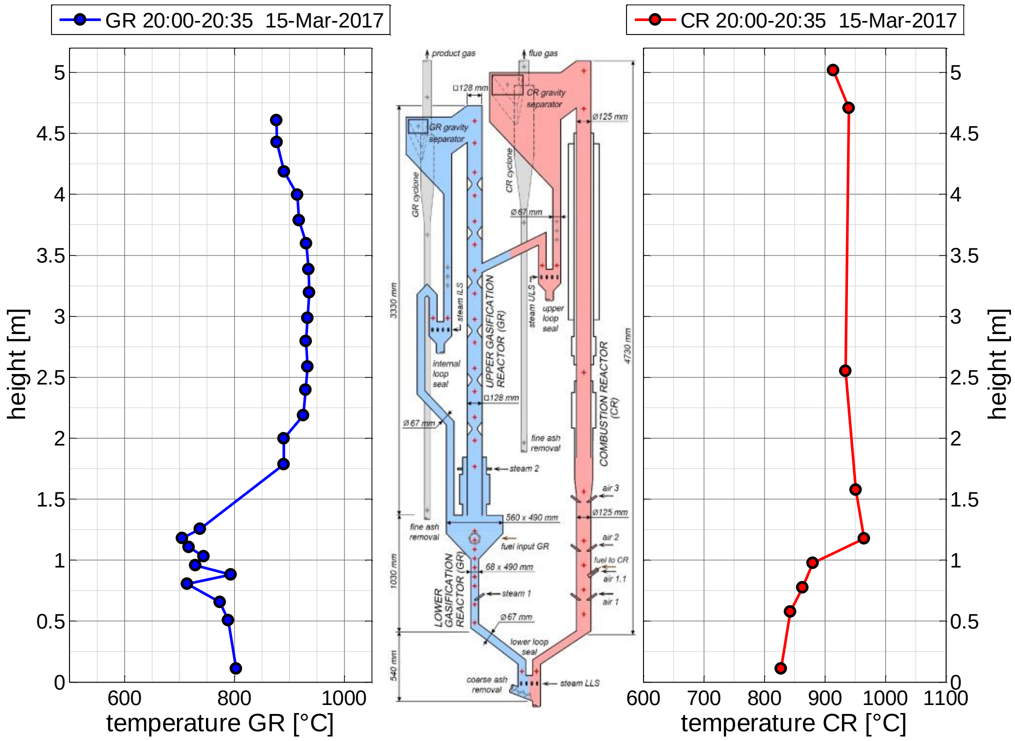


Figure 38. Average temperature profiles of the GR and CR for the test run III [57]

One more time, when comparing Figure 36, Figure 37 and Figure 38, no noteworthy differences are noticed since the gasification operating conditions remain unchanged.

Parameter	Unit	Gasification reactor	Combustion reactor
Bed material types	µm	Potassium feldspar (d_{sv}=287), calcite (d_{sv}=480)	
Bed material mixture	wt%	89 (potassium feldspar) + 11 (calcite)	
Overall initial bed material inventory	kg	80	
Feedstock type	-	Chicken manure	
Feedstock mass flow	kg/h	30.6	-
Feedstock/fuel power into GR	kW	114	-
Fuel to CR	kW	-	62*
Heat losses of reactor system (GR & CR)	kW	26*	
Temperatures lower reactor part	°C	766	965
Temperatures upper reactor part	°C	933	939
Water content in the gas stream	vol%	31.2* - 35.0	14.2*
Product gas volume flow	Nm^3_{db}/h	31.4*	-
Product gas lower heating value (free of char & tar)	MJ/Nm^3_{db}	12*	-
Product gas power (free of char & tar)	kW	107*	-
Overall cold gas efficiency, novel 100 kW test plant	%	71*	-
Overall cold gas efficiency, estimated for a 50 MW plant	%	70 - 77	-

** calculated with IPSEpro mass and energy balance*

Table 20. Main operating conditions of the gasification test run III [57]

Product gas composition, sample point A		NGA 2000 online values	PE Arnel GC TU Wien	PE GC values Bioenergy	IPSEpro simulation values
Component	**Unit**				
Hydrogen (H_2)	vol %$_{db}$	43.3	-	-	40.1
Carbon monoxide (CO)	vol %$_{db}$	20.7	22.5	21.8	21.0
Carbon dioxide (CO_2)	vol %$_{db}$	20.4	21.7	21.1	19.8
Methane (CH_4)	vol %$_{db}$	8.7	8.8	8.9	8.4
Ethylene (C_2H_4)	vol %$_{db}$	-	2.22	2.13	2.05
Ethane (C_2H_6)	vol %$_{db}$	-	0.20	0.19	0.18
Propane (C_3H_8)	vol %$_{db}$	-	0.00	-	0.00
Acetylene (C_2H_2)	vol %$_{db}$	-	-	0.057	0.00
Ammonia (NH_3)	vol %$_{db}$	-	-	-	6.7

Table 21. Main product gas components of the gasification test run III [57]

Product gas analytics, measured discontinuous, sample point A		
Parameter	**Unit**	**Offline measured: toluene as solvent**
Dust content	g/Nm$^3_{db}$	6.15
Char content	g/Nm$^3_{db}$	0.94
Tar content GC-MS (without BTX)	g/Nm$^3_{db}$	8.12
Tar content gravimetric	g/Nm$^3_{db}$	2.69
Water content H_2O	g/Nm$^3_{db}$	35
Tar dew point	°C	177

Table 22. Additional product gas components measured offline with toluene as solvent, test run III [57]

Finally, the components of the flue gas stream from the combustion reactor are shown in Table 23.

Flue gas composition		NGA 2000 online values	IPSEpro simulation values
Component	**Unit**		
Carbon dioxide (CO_2)	vol %$_{db}$	13.4	13.7
Oxygen (O_2)	vol %$_{db}$	0.17	0.00
Carbon monoxide (CO)	vol %$_{db}$	2.09	2.93
Nitrogen (N_2)	vol %$_{db}$	-	82
Nitrogen monoxide (NO)	vol %ppm$_{db}$	43.0	0.0
Sulphur dioxide (SO_2)	vol %ppm$_{db}$	6.0	0.0
Nitrogen dioxide (NO_2)	vol %ppm$_{db}$	0.0	0.0
Nitrous oxide (N_2O)	vol %ppm$_{db}$	5.0	0.0

Table 23. Main composition of the flue gas from the combustion reactor, test run III [57]

4.5. Comparison of the gasification test runs

Three test runs with three different types of feedstocks while using a mixture of potassium feldspar and calcite as bed material represent the core of the present work. Olivine is considered to be a suitable bed material due to its properties not only for pilot plants but also for industrial plants such as Güssing. For that reason, it is interesting to include and establish as a benchmark the gasification of traditional softwood pellets with olivine [58] when comparing the three test runs previously presented.

The main process parameters when gasifying alternative feedstocks with K-feldspar are summarized in Table 24 and compared to ones from the gasification of traditional wood with olivine. Since it is important to considerer the thermochemical properties of the fuels when setting the operating conditions, a graph compiling the elemental composition of the three different types of feedstocks is shown in Figure 39.

Parameter	**Unit**	**Type of biomass feedstock + Bed material**			
		Softwood + olivine	**Softwood +K- feldspar**	**Chicken manure/bark + K-feldspar**	**Chicken manure + K-feldspar**
Feedstock type, GR	-	Softwood pellets	Softwood pellets	Chicken manure/bark pellets	Chicken manure pellets
Bed material	%	73 (olivine 200-300µm), 16 (olivine 100-200µm), 11 (calcite 300-600µm)	89 (K-feldspar 287µm), 11 (calcite 480µm)	89 (K-feldspar 287µm), 11 (calcite 480µm)	89 (K-feldspar 370µm), 11 (calcite 480µm)
Gasification temperature, GR	ºC	892	852	870	850
Combustion temperature, CR	ºC	953	966	996	952
Feedstock mass flow, GR	kg_{db}/h	20.1	20.4	24.3	30.6
Feedstock mass flow, GR	$kg_{db,af}/h$	18.64	18.9	19.7	20.7
Feedstock power, GR	kW	97.2	95	100	114
LHV_{fuel}, GR	kJ/kg_{db}	18 940	18 940	17 100	13 900
Fuel to combustion reactor, CR	kW	50	61	55	62
Product gas volume flow, GR	Nm^3_{db}/h	26.8	25.7	28.2	31.4
LHV_{PG}, GR	MJ/Nm^3_{db}	11.6	13	12	12
Product gas power, GR (cold, tar & char free)	kW	86.4	92	91	107
Gas yield, GR (per dry, ash free fuel input)	$Nm^3_{db}/kg_{fuel,db,af}$	1.4	1.4	1.4	1.5
Steam to fuel ratio, GR	$kg_{H2O}/ kg_{fuel,db,af}$	0.9	0.8	0.8	0.9
Steam to carbon ratio, GR	$kg_{H2O}/ kg_{fuel,C}$	1.8	1.7	1.6	1.8
Cold gas efficiency, GR	%	89	97	91	94

Table 24. Process parameters of gasification test runs with different fuels and bed material [57,5]

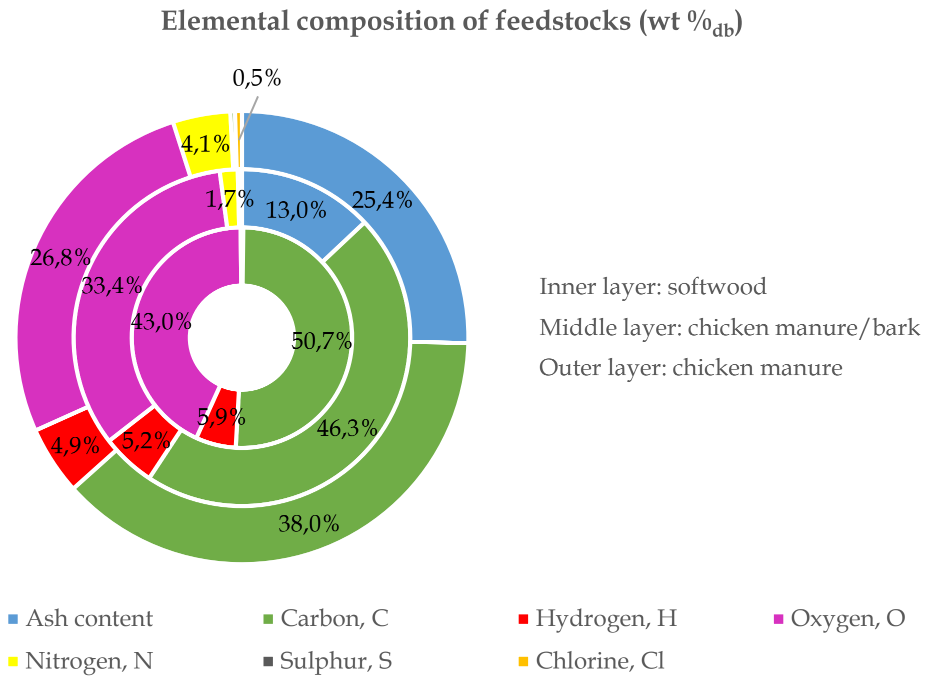


Figure 39. Comparison among elemental composition of feedstocks

As it can be seen in Figure 39, feedstock composition varies over a wide range, especially regarding ash content. The main problem concerning ash content has to do with the high alkali content and thus, the ash melting temperature; however, it does not mean a problem because the presence of compounds that are able to rise the ash softening temperature (magnesium, phosphorus, and calcium) compensates the high sodium and potassium presence. Even though high ash contents are potential sources of deposition and agglomeration in the gasification system, the experiment was successfully carried out and no premature interruptions due to agglomeration were done. Regarding carbon and hydrogen contents, they have a strong impact on the heating value of the fuel, being the LHV_{fuel} higher as the C, H content increase. In this way, the LHV of wood pellets with 99.6 wt$\%_{db}$ C, H content is 18.94 MJ/kg$_{db}$, 17.10 MJ/kg$_{db}$ corresponds to chicken manure/bark (84.9% wt$\%_{db}$ C, H content) and 13.90 MJ/kg$_{db}$ corresponds to pure chicken manure (69.7% wt$\%_{db}$ C, H content). Additionally, LHV_{fuel} is also affected by the water and ash content (Table 10), being wood the fuel with lower ash and water content and therefore, the fuel with higher LHV_{fuel}. Furthermore, the lower the LHV_{fuel}, the higher should be the feedstock mass flow to keep the same feedstock power. Finally, and regarding the nitrogen content, it can be seen in Figure 39 that alternative feedstocks have higher N content than the traditional wood, especially chicken manure. The N content is linked to the ammonia content in the product gas as well as to the emissions that are generated from the gasification process.

Despite the diversity in chemical composition of fuels, process parameters can be set to similar values, as Table 24 shows. Hence, temperature profiles are similar in all test runs, being the gasification temperature in a range of 850-900ºC and the combustion temperature 950-1000ºC. Likewise steam to fuel ratio and steam to carbon ratio remain unchanged for all test runs. The difference between gasification and combustion temperature is connected to the heat transfer of the bed material, and thus, the lower the difference in temperature, the higher the circulation rate with the same bed material. Only for the case of gasification with wood and olivine the difference between temperatures remains below 100ºC, which leads to the fact that olivine has higher heat transfer capacity than K-feldspar. That is also proven by the fact that more additional fuel into the combustion reactor is required when gasifying wood with K-feldspar than when doing with olivine. It should be reminded that light fuel oil is injected into the combustion reactor with the purpose of controlling the temperature in the gasification reactor.

Parameters that are related to the product gas are linked to the product gas compositions, which are shown in Figure 40.

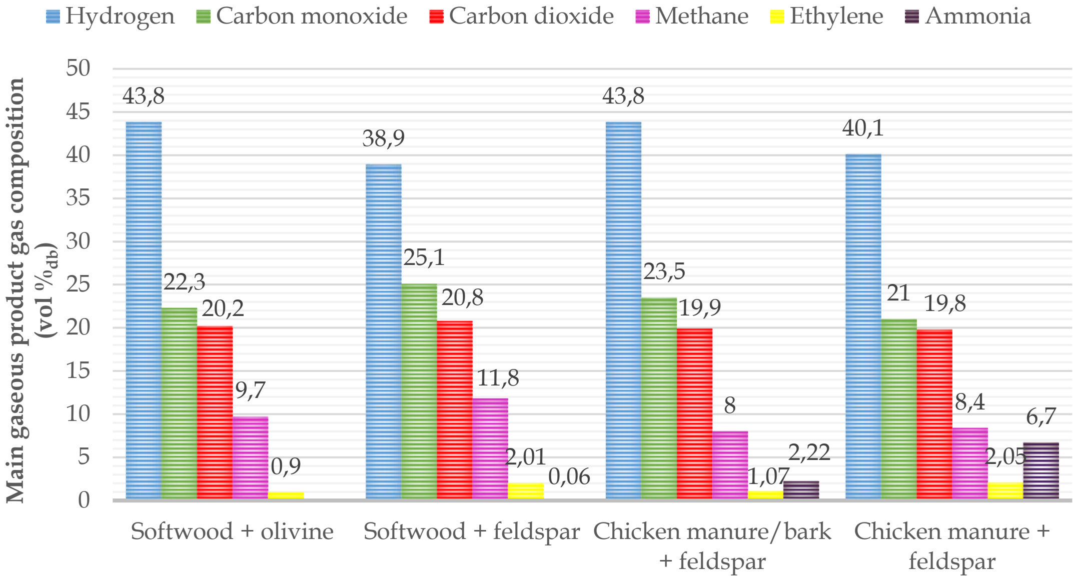


Figure 40. Comparison of main product gas composition

Figure 40 leads to the fact that even alternative feedstock with high ash content do not have a strong impact on the main product gas composition. It is the gas composition what explains the parameters of Table 24 in relation to the product gas. In this way, LHV_{PG} from the gasification of wood and K-feldspar is the highest because its hydrocarbon content (especially methane) is also the highest when comparing with the gas composition from the other types of feedstocks. Regarding the product gas volume flow, the one corresponding to the gasification of chicken manure is higher due to the higher feedstock mass flow. All of that leads to a high product gas power obtained from chicken manure feedstock. Applications such as the production of heat in boilers or kilns do not have strong restrictions regarding the quality of gas product, however, it is more important the product gas power and the amount of product gas. Therefore, it can be said that when considering the thermal properties of the product gas, alternative feedstocks such as chicken manure and bark are good options when using the product gas for heating applications. Finally, it is important to look at the ammonia content in the product gas, which is higher in the product gas from the chicken manure as its N content is also higher when comparing to the other feedstocks.

Figure 41 displays the dust and tar content in product gases obtained from the four test runs. Chars are carbonic particulates, while dust is understood as mineral particulates without carbonic content [10].

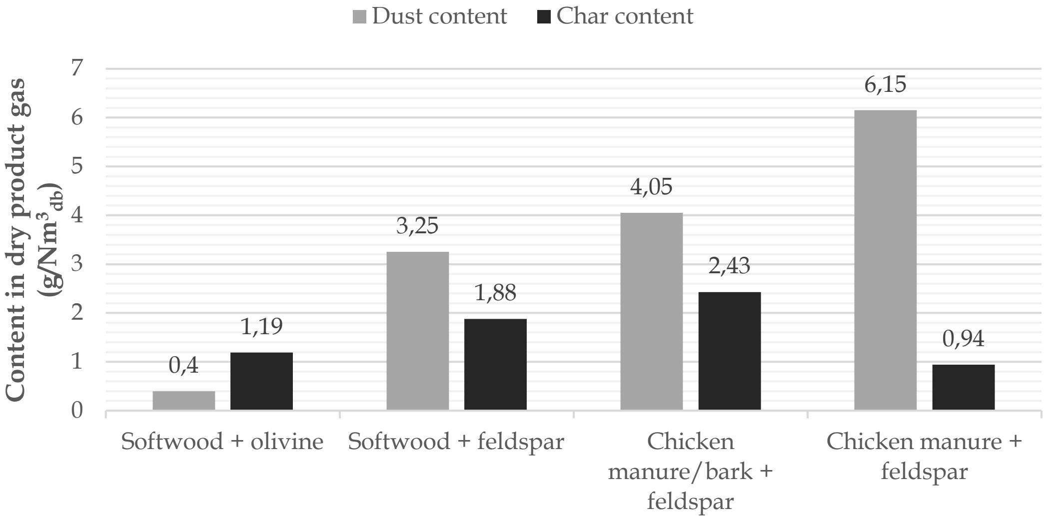


Figure 41. Comparison of char and dust content in product gas

The dust content is highly influenced by the ash content in the biomass feedstocks. Therefore, looking at the three test runs when using K-feldspar in Figure 41, it can be observed that the high fraction of dust in the product gas from chicken manure is in good agreement with the high ash content in the feedstock. On the other hand, the bed material used is also a strong influencer in the dust content, being higher the dust content when gasifying with K-feldspar than when doing with olivine. The first two experiments were done with the same operating conditions and only the bed material was changed, this change means a dust content eight times higher than with olivine. Additionally, the bed material shift leads to an increase of 58% in char content. Char content plays an important role in tar reduction because biomass char can behave as a catalyst, which means an advantage because char is produced continuously inside the gasifier, and in turn it means that char can avoid catalytic deactivation and additionally, it is cheaper than other catalysts [70]. Figure 42 displays tar contents, both gravimetric tars (non-detectable by GC-MS) and GCMS tars, for the four different product gases obtained from the test runs that have been carried out at the novel DFB pilot plant.

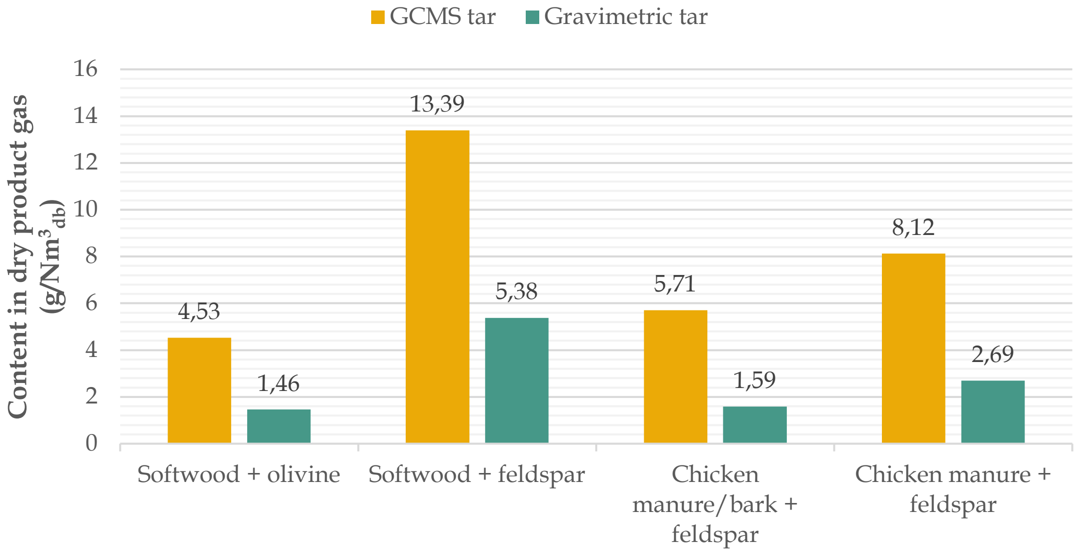


Figure 42. Comparison of tar content in product gas

If only the three test runs with K-feldspar are considered, it can be seen in Figure 42 that the gasification of a mixture of chicken manure and bark yields less tar content than the gasification of softwood or pure chicken manure does. The main reason is the higher hydrogen content of the product gas, which has to do with the water-gas shift reaction. The water-gas shift reaction occurs in the reactor especially in contact with catalytic active particles and promotes the water conversion, increasing the hydrogen yield and boosting the decomposition of tar compounds [71]. K-feldspar is not characterized by its intensive catalytic activity, but the gasification of chicken manure/bark produces a high char yield and here is where its potential to act as a catalyst for tar reduction has to be taken into account. Moreover, the high alkali content in the chicken manure/bark feedstock (22.97 wt%$_{db}$ K_2O, Table 10) also plays a role as tar cracking catalyst. Other aspects that influences tar content is the ash content of the feedstock, thus, softwood is nearly ash-free content (0.2 wt%$_{db}$) and its tar content is higher compared to alternative feedstocks. The effect has been also observed in previous researches [10,72] and it has been explained by the catalytic reactions that take place when tars and ash particles enter in contact. Regarding the influence of bed materials in tar content, the comparison between the tar content of the product gas obtained from the gasification of wood with olivine and the one with K-feldspar proves that olivine has higher catalytic activity than K-feldspar.

Finally, it is important to mention that fresh bed materials (not layered ones) are used, only calcite imitates the layer. Layered bed materials influence the tar content, as it has been proven in earlier studies [15].

5. ECONOMIC EVALUATION

5.1. Introduction

The share of energy from renewable sources in Austria amounts 32.6% of the total primary energy supply (TPES), biofuels and waste are the main form of renewable energy, accounting for 19.9% of TPES. Electricity and heat production are the main applications of renewable energy. Specifically, biomass and wastes contribute with 7.9% of total electricity supply and account for 50.5% of total heat production in Austria. Biomass and waste are also important for the transport sector, representing 6.1% of energy consumed in transportation in Austria in 2012. Austria is the country among IEA members with the highest penetration of biofuels in transport, followed by Sweden and France [73]. The situation of Spain regarding renewable sources and bioenergy should improve because the share of renewable energies only accounts 14.9% of the total primary energy supply, being 5.5% of this TPES provided by biomass and waste [74]. The pattern of the share of renewable energies in both countries Austria and Spain is shown in Figure 43, the situation in other IEA member countries is also shown.

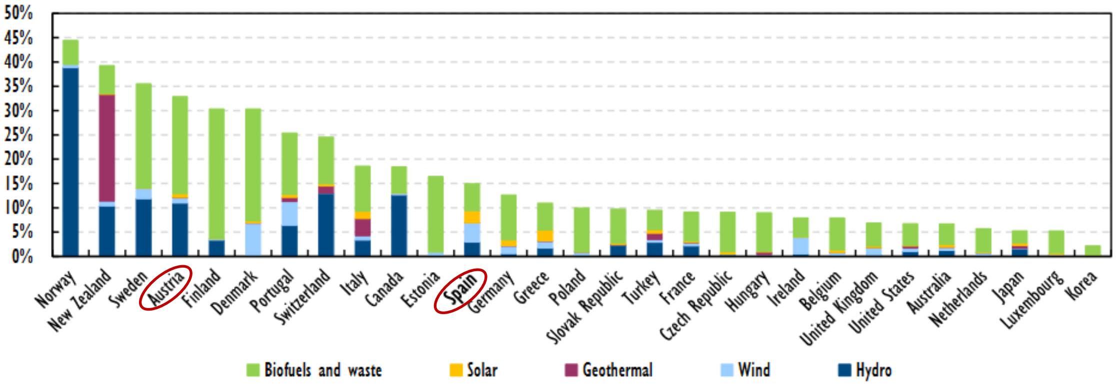


Figure 43. Renewable energies as a percentage of TPES (%) in IEA member countries, 2014 [75]

Biomass gasification is an attractive technology for the conversion of sources such as biomass and wastes into a combustible gas. Specifically, the DFB steam gasification allows a high-grade product gas as well as several advantages, as it has already been discussed in Section 2.5. This technology was developed at the TU Wien and it was demonstrated at industrial scale in Güssing (Austria) for the first time. TU Wien has played an important role since its start-up in late 2001 and a large amount of researches and investigations have been carried out. Therefore, Güssing is the reference plant from which data are obtained since these are enough and of satisfactory quality to carry out the present economic study. Regarding that, a brief description of the plant located in Güssing should be done prior to performing any economic estimation, as it is done in the Section 5.2.

This fifth chapter deals with economic aspects regarding biomass gasification and includes two parts. The aim of the first part is to determine the costs of gasifying wood chips with the purpose of selling the product gas for firing or indirect co-firing as end-use application. That allows the substitution of non-renewable energy sources and in turn, the reduction of CO_2 emissions as well as the diminution of the dependency on fossil fuels which are characterized by an unequal and monopolized distribution throughout the world and thus, their prices are volatile and their supply is often attached to political conditions. Additionally, increases in the gasification plant capacity are considered in order to study the potential benefits of economies of scale. As the final objective of the Section 5.3 is to determine the economic feasibility of substituting a certain amount of fossil fuels, results are shown considering fossil fuel prices as benchmarks.

The second part of the present chapter consists in establishing a comparison among the costs incurred during the gasification of different feedstocks when using different bed materials. It is expected that the use of first generation biomass will be reduced more and more due to its direct competition with important other applications as food or feed. Production forests and wood thinning are an intensively exploited source of energy next to high-value materials; however, the expansion of these resources in the future is yet unclear and will depend on many factors, such as degradation biodiversity [2,18]. For that reason, alternative feedstocks such as agricultural by-products or waste streams can support the further development of the biomass as source of energy. Furthermore, the advantages of alternative feedstocks are not only related to environmental and ethical reasons, but also to economic reasons. Section 5.4 includes the costs of gasifying different biomass fuels while setting woody feedstocks as the benchmark.

When studying the economic feasibility of one project, capital budgeting methods are crucial in the decision-making process for accepting or reject the process. In this way, investment decisions can be evaluated by following different rules such as the net present value (NPV), the payback period, the internal rate of return (IRR), and the profitability index [75]. For the present work, the chosen method is the NPV since the aim of the Section 5.3 is to determine the selling price of the product gas when NPV=0, meaning that earnings equal expenses. The NPV is the difference between the sum of the present values of the project's future cash flows and the initial cost of the project, as Eq. 5.2 represents. Cash flows can be classified depending on the activity that they come from, these activities are: operating, investing, and financing. Operating cash flow is a measure of the amount of cash generated by a company's normal business operations. To simplify the present evaluation, only operating cash flows (OCF) are considered, which are defined by Eq. 5.1.

$$OCF_n = [E_n - OPEX_n](1 - tax) + Dep \cdot tax \qquad \text{Eq. 5.1}$$

where OCF_n, E_n, $OPEX_n$ are the operating cash flows, earnings and operating expenses in each year (n) along the expected lifetime, Dep is depreciation attached to the capital investments and tax are taxes according to the Austrian law.

$$NPV = \sum_{n=1}^{N} \frac{OCF_n}{(1+r)^n} - CAPEX \qquad \text{Eq. 5.2}$$

where $CAPEX$ is the capital expenditure, r is the discount rate, and n is each year of the expected lifetime (N).

5.2. Commercial plants - Güssing, Austria

Güssing, a small town with about 4000 inhabitants, is located near to the Hungarian border, which was called the iron curtain for a long time and thus, no industry settled there. The installation of the CHP plant was a relief for the economy of the region. Nearly half of the region is covered with wood and therefore, raw material is available for supplying the city with energy and heat from biomass [55]. An overall view of the CHP plant in Güssing can be seen in Figure 44.

Figure 44. Front view of the CHP plant in Güssing [76]

The most important data of the plant are summarized in Table 25 and a process flow sheet is shown in Figure 45.

Operation parameter	Value
Fuel power	8 $MW_{th, fuel}$
Electrical output	2 MW_{el}
Thermal output	4.5 MW_{th}
Electrical efficiency	25 %
Thermal efficiency	56.3%
Total efficiency	81.3 %

Table 25. Characteristic data of the plant in Güssing [55]

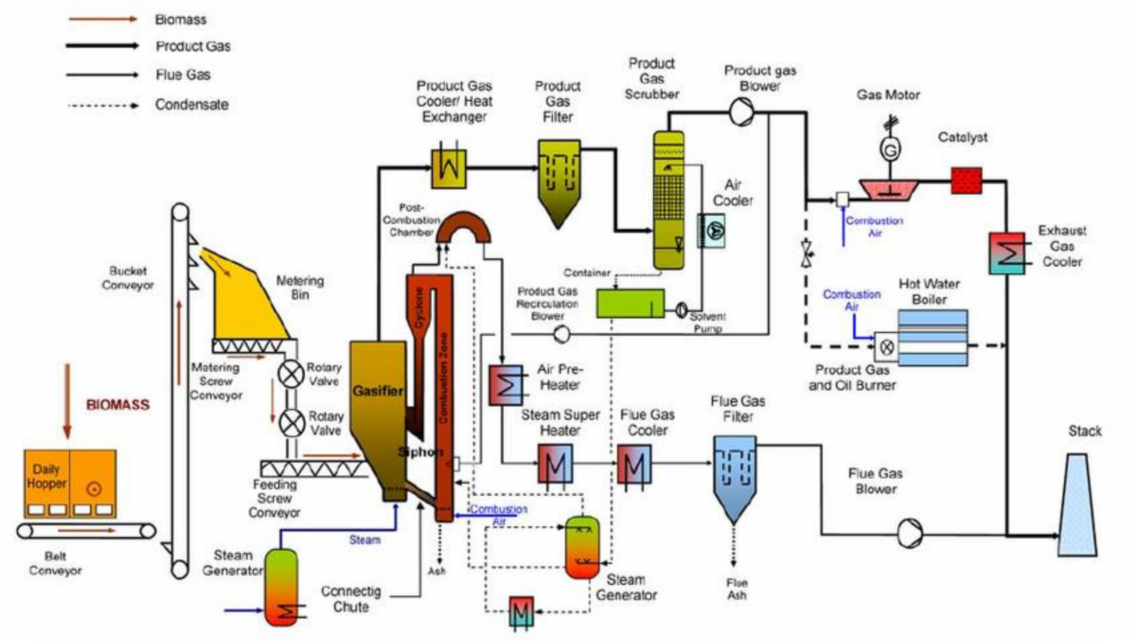


Figure 45. Flow sheet of the CHP plant in Güssing [77]

The plant operates with forestry residues which are harvested in the local area. Biomass is gasified in a circulating dual fluidized bed reactor and once the product gas is cooled and cleaned in two stages, it is used in a gas engine to produce electricity and heat [26]. The product gas can be burnt in a boiler if the gas engine is not in operation [55].

Woody chips are gasified with steam and the required heat is provided by the bed material from the combustion reactor. The product gas has to be cooled and a water cooler heat exchanger reduces its temperature from 850ºC-900ºC to about 150ºC-180ºC. The first step of the cleaning process is a fabric filter whose purpose is to separate the particles and some of the tar from the product gas. These particles are recirculated to the combustion zone of the gasifier. The second stage is a scrubber, where the gas is liberated from tar. Tars are washed out by methyl ester of rapeseed (RME) and once the organic solvent is saturated with tar, it is vaporized and circulated to the combustion zone of the gasifier. The temperature at which the gas exits the scrubber is about 40 ºC [20,36]. Regarding the flue gas of the combustion zone, a gas filter separates the particles before it is released via a chimney to the environment for the purpose of meeting all emission requirements. The heat of the flue gas from the combustion is partly used internally for air preheating and steam production [26].

A detailed analysis of the feedstock including fuel and ash properties is essential for setting the gasification parameters. Thus, Table 26 lists main properties of the wood chips used as biomass fuel in Güssing.

Properties	Unit	Value
Water content (H_2O)	wt %	5.70
Volatile matter	wt %$_{db}$	84.02
Ash content	wt %$_{db}$	1.0
Lower heating value (LHV)	kJ/kg$_{db}$	18 178
Carbon (C)	wt %$_{db}$	48.82
Hydrogen (H)	wt %$_{db}$	5.87
Oxygen (O)	wt %$_{db}$	44.15
Nitrogen (N)	wt %$_{db}$	0.15
Sulphur (S)	wt %$_{db}$	0.015
Chlorine (Cl)	wt %$_{db}$	0.003

Table 26. Composition of wood chips [9,10]

A special parameter when characterising the gasification process and which links the fuel power in the feedstock with the fuel power of the product gas is the cold gas efficiency, often known as the chemical efficiency. The cold gas efficiency is defined as the chemical energy contained in the product gas (tar- and char-free) with respect to the energy contained in the initial solid fuel [78]:

$$\eta_{chem} = \frac{\dot{m}_{PG} \cdot LHV_{PG}}{\sum \dot{m}_{fuel} \cdot LHV_{fuel}} \qquad \text{Eq. 5.3}$$

where $\dot{m}_{PG}$ represents the mass flow of the product gas, LHV_{PG} the lower heating value of the product gas, $\dot{m}_{fuel}$ the mass flow into the gasification reactor, and LHV_{fuel} the lower heating value of the feedstock. Moreover, the overall cold gas efficiency takes into account the chemical energy in the fuel that is introduced into the combustion reactor and the overall efficiency for industrial plants is heat loss compensated and therefore, it is significantly higher than in pilot plants.

Table 27 summarizes main operational data of the plant in Güssing and Table 28 shows the composition of the product gas once it exits the scrubber.

Operation parameter	Unit	Value	Data source
Fuel power	MW	8	[20]
Operation hours per year	h/a	7 400	[79]
Overall cold gas efficiency	%	70.3	[79]
Subsequent data	**Unit**	**Value***	**Data source**
Plant input			
Biomass fuel (wood chips) dry	kg/h	1 650	[79]
Electricity consumption	MW	0.2	[79]
Scrubber solvent (RME)	kg/h	17	[79]
Nitrogen (N_2) purge	Nm^3/h	75	[79]
Limestone/burnt limestone	kg/h	10	[79]
Fresh bed material (olivine)	kg/h	40	[79]
Water	kg/h	500	[79]
Plant output			
Product gas volume	Nm^3/h	1 600	Eq. 5.3
Ash	kg/h	16	Table 26

**Operation point: 11.12.2003*

Table 27. Operational data of the DFB gasification plant in Güssing

Component	Unit	Value
Hydrogen (H_2)	vol%$_{db}$	38-42
Carbon monoxide (CO)	vol%$_{db}$	23-27
Carbon dioxide (CO_2)	vol%$_{db}$	20-22
Methane (CH_4)	vol%$_{db}$	9-11
Nitrogen (N_2)	vol%$_{db}$	~2
Tar	g/Nm^3	~1
LHV	MJ/Nm^3	12-14

Table 28. Product gas composition of Güssing [79,53]

5.3. Gasification of wood chips for co-firing and firing applications

Indirect co-firing allows the replacement of fossil fuels with biomass at existing large-scale power plants as well as in industrial boilers [80], some of its advantages are listed below [81]:

- Less strict requirements in product gas as compared to other applications
- Reduction of CO_2 emissions
- Usage of existing infrastructure
- No significant impact on the performance of boiler (capacity, stability, and availability)
- Better fuel flexibility
- Possibility of keeping biomass ash separated from that from fossil fuels

Indirect co-firing and firing in dedicated boilers or kilns are the simplest way to take advantage of the gas obtained from the gasification process due to the less strict requirements for gas quality. Gasification as gas generator for indirect co-firing in existing power plants and for fuelling lime or cement kilns, and in this way, for substituting fossil fuels, has been proven to be a technology that can be applied on a commercial basis in an industrial setting. Specially, the most acceptable idea of co-firing is to burn a mix of biomass and coal in power plants. Co-firing has been considered as the first step to enhance biomass use in power generation due to the possibility of reducing technical and economic risks [80]. Table 29 shows some examples of commercial plants.

Location	Fuel power (MW_{th})	Application
Norrsundet, Sweden	25	Lime kiln
Karlsborg, Sweden	27	Lime kiln
Värö, Sweden	30	Lime kiln
Pietersaari, Finland	34	Lime kiln
Jakobstad, Finland	35	Lime kiln
Grève-in-Chianti, Italy	30	Cement and boiler
Rüdersdorf, Germany	100	Cement
Zeltweg, Austria	10	Co-firing in power plant (3% of the total heat input to boiler)
Ruien, Belgium	40-80	Co-firing in power plant
Lathi, Finland	45-70	Co-firing in power plant (15% of the total heat input to boiler)
Geertruidenberg, The Netherlands	83	Co-firing in power plant (5% of the total heat input to boiler)
Vaasa, Finland	140	Co-firing in power plant

Table 29. Commercial plants for indirect co-firing and for heat production to lime and cement kilns [80,20]

An important aspect to consider when determining the layout of the plant is the cleaning process that should be installed depending on the end-use application of the product gas and in turn, depending on the requirements of the product gas quality. Although applications such as kilns or co-firing systems allow the product gas to be used without strict clean-up process, problems might arise related to emission requirements, fouling in the gas cooler, difficulties to burn tars or corrosion and erosion. In this way, the plant in Grève-in-Chianti was originally designed with only simple gas cleaning in the form of a cyclone solids separator and no product gas cooling. However, the plant modified its layout and incorporated a second combustion line and a product gas cleaning system with a new cyclone solids separator, a high temperature acid gas/dichlorination unit, a second cyclone solids separator, a gas cooler and ceramic filters. Moreover, the plant in Geertruidenberg included a complete product gas cleaning prior to the gas entering the coal-fired boiler with a cyclone solids separator, a steam/gas cooler, a bag filter operating at 200°C and an ammonia stripping section [20].

In view of the above and for the present economic study, it is considered that the plant in Güssing sells the product gas once it has been cleaned. In other words, the study is based on the option to conduct the product gas to a boiler instead to a gas engine. The idea of the present section is to analyse the feasibility of building a DFB gasification plant near to an existing lime kiln, cement industry or power plant to replace a certain amount of fossil fuel used. Figure 46 illustrates the flow chart of the biomass gasification process which is considered to be carried out in the present economic evaluation, paying special attention to the inputs and outputs of the process.

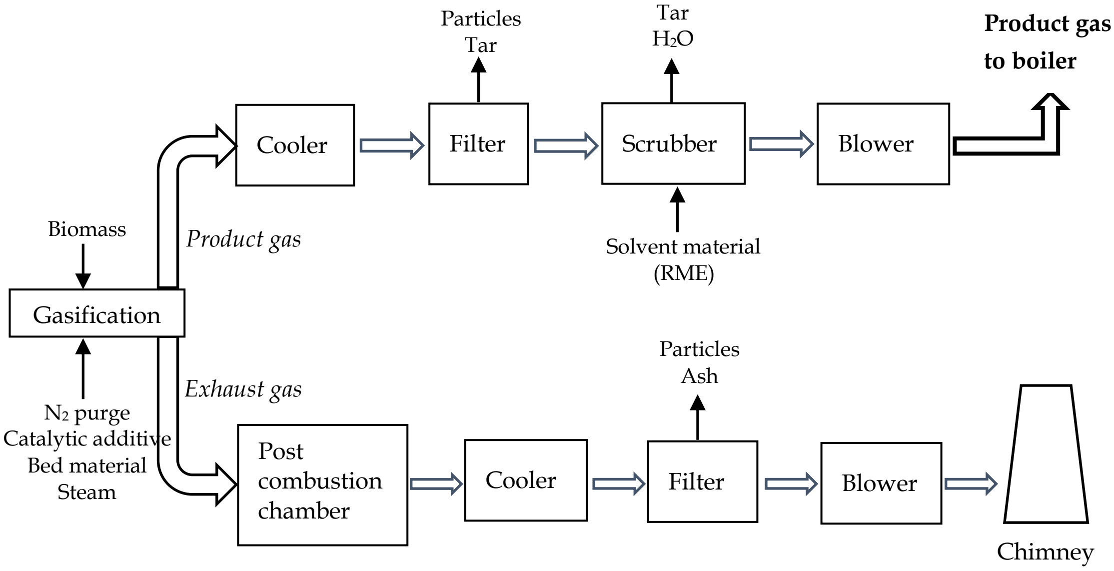


Figure 46. Flow chart of the gasification process considered in the present economic study. Adapted from [79,82]

Once the technical data of the plant have been defined and inputs and outputs have been set, the next step is to determine the financial data of the plant which include both investment and production costs.

Costs for cash flow analysis are usually grouped in several categories. Capital costs have to do with the initial investment and usually include costs related to buildings and facilities, equipment, engineering, construction, and contingency. As the useful life of the plant extends more than a year, this expenditure is expensed using depreciation to spread its cost over its designed useful life as determined by tax regulation [83].

Operating costs are related to the generation of the product gas and depend on the structure and organization of the plant as well as on the production volume. Operational expenses are fully tax-deductible in the year they are made and include categories such as direct production costs (fuel cost, operating supplies, labour cost, utility cost, and maintenance) and fixed costs (insurance and administration, and plant overhead) [84].

No incentives are considered and earnings come from the sale of product gas as it has been previously mentioned, therefore, the aim of this study is to determine the selling price of the product gas at which the breakeven point is reached (NPV=0). Required cost rates for all further investigations are listed in Table 30.

Parameter	Unit	Value	Data source
Capital expenditures (CAPEX)			
Investment cost	€	12 000 000	[20]
Operating expenses (OPEX)			
Direct production costs			
Wood chip costs (per dry ton)	€/t	100	[79]
Fresh bed material (olivine)	€/t	156	[82]
Limestone/burnt limestone	€/t	30	[79]
Nitrogen	€/Nm^3	0.09	[82]
Scrubber solvent (RME)	€/t	1 100	[79]
Fresh water	€/t	2.17	[79]
Number of employees	pers.	7	[79]
Cost of one employee per year	€/a	70 000	[79]
Electricity costs	€/kWh	0.12	[85]
Costs for ash disposal	€/t	90	[79]
Maintenance	% (CAPEX)/a	2.0	[20]
Fixed costs			
Insurance and administration	% (CAPEX)/a	2.5	[79]
Plant overhead	% (CAPEX)/a	0.75	[20]
Earnings			
Selling price of product gas	€/Nm^3	??	

Table 30. Cost rates for economic calculations

Parameters used in the present value calculations are explained in the following paragraphs. Firstly, the expected lifetime of the equipment is considered as 20 years according to similar projects [79,82]. The method used to depreciate is the straight-line method, which allows for a uniform amount to be deducted from revenues each year [84]. Straight-line depreciation can be calculated by using the following formula:

$$Annual\ depreciation = \frac{Capital\ investment}{Equipment\ life} \quad \text{Eq. 5.4}$$

Another important aspect to consider when the NPV calculations are made is the discount rate, which is the interest rate at which future cash flows are discounted to convert them into present values [84]. The discount rate is chosen in conformity with other economical assessments at 8% [79,82]. Inflation cannot be neglected since it measures the general evolution of prices, concretely, it is a reduction in the value of money (monetary depreciation). Consumer price index (CPI) is usually viewed as a country's most important inflation figure and it is defined as the change in the prices of a basket of goods and services that are typically purchased by households. According to the Austrian inflation forecast provided by the OECD Data, inflation for the present economic evaluation is considered as 2% [86]. Inflation rate should be used to calculate the operating expenses that will take place from the second year once the plant has been built. Finally, tax is fixed as 25% according to the Austrian taxation of corporations [87].

All these parameters used to calculate the NPV are summarised in Table 31.

Parameter	Value	Data source
Expected lifetime (N)	20 years	[79,82]
Discount rate (r)	8%	[79,82]
Inflation rate (r_i)	2%	[86]
Tax (t)	25%	[87]

Table 31. Parameter for the NPV calculation

When performing calculations, costs related to raw materials, labour, utilities, maintenance, and administration are adjusted every year in accordance to the inflation rate (2%), which is measured in terms of the CPI. Additionally, the expected costs in each future period during the expected lifetime are discounted and brought to the present time (year 0) at the appropriate rate (8%), yielding the results that are shown in Table 32.

Expected costs (CAPEX and OPEX) in million € along the expected life time of the commercial gasification plant, whose operational data are obtained from Güssing and wood chips are used as biomass feedstocks.

YEAR (n)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
CAPEX	12.00																				
OPEX		2.82	2.88	2.94	2.99	3.05	3.11	3.18	3.24	3.31	3.37	3.44	3.51	3.58	3.65	3.72	3.80	3.87	3.95	4.03	4.11
Fuel cost (wood chips)		1.25	1.27	1.30	1.32	1.35	1.38	1.40	1.43	1.46	1.49	1.52	1.55	1.58	1.61	1.64	1.68	1.71	1.74	1.78	1.81
Operating supplies		0.24	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.30	0.31	0.31	0.32	0.32	0.33	0.34	0.34	0.35
Labour costs		0.50	0.51	0.52	0.53	0.54	0.55	0.56	0.57	0.59	0.60	0.61	0.62	0.63	0.65	0.66	0.67	0.69	0.70	0.71	0.73
Utility costs		0.19	0.20	0.20	0.20	0.21	0.21	0.22	0.22	0.22	0.23	0.23	0.24	0.24	0.25	0.25	0.26	0.26	0.27	0.27	0.28
Maintenance		0.24	0.25	0.25	0.26	0.26	0.27	0.28	0.28	0.29	0.29	0.30	0.30	0.31	0.32	0.32	0.33	0.34	0.34	0.35	0.36
Insurance & admin		0.31	0.31	0.32	0.32	0.33	0.34	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.40	0.40	0.41	0.42	0.43	0.44	0.45
Plant overhead		0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13
Accumulated OPEX		2.61	5.08	7.41	9.61	11.69	13.65	15.51	17.26	18.91	20.47	21.95	23.34	24.66	25.90	27.07	28.18	29.23	30.22	31.15	32.03

Table 32. Cost flows of the gasification plant along its expected lifetime (Millions €)

According to the Eq. 5.1 and taking into account the effect in price change due to inflation, operating cash flows in each year can be calculated as:

$$OCF_n = [E_0(1+r_i)^n - OPEX_0(1+r_i)^n](1-tax) + Dep \cdot tax \qquad \text{Eq. 5.5}$$

where E_0 and $OPEX_0$ are the earnings and operating expenses, respectively, considered when the gasification plant is projected, and r_i is the inflation rate.

Combining both Eq. 5.2 and Eq. 5.5 and then splitting the expression into four terms regarding earnings, OPEX, depreciation and CAPEX, the resulting expression is as follows:

$$NPV = E_0(1-tax)\sum_{n=1}^{N}\frac{(1+r_i)^n}{(1+r)^n} - OPEX_0(1-tax)\sum_{n=1}^{N}\frac{(1+r_i)^n}{(1+r)^n} + Dep \cdot tax \cdot \sum_{n=1}^{N}\frac{1}{(1+r)^n} - CAPEX \qquad \text{Eq. 5.6}$$

Where $\sum_{n=1}^{N}\frac{(1+r_i)^n}{(1+r)^n}$ is calculated as $\frac{k(1-k^n)}{1-k}$, being $k = \frac{1+r_i}{1+r}$.

Considering the breakeven point where NPV=0, it is possible to calculate the earnings from selling product gas (E_0). As the earlier equation leads the earnings obtained in €/a, it is required to consider the amount of product gas obtained as well as the operating hours in order to calculate the price of each cubic meter of product gas.

$$Selling\ price\ product\ gas\left[\frac{€}{Nm^3}\right] = \frac{E_0\,[\frac{€}{a}]}{Amount\ of\ product\ gas\left[\frac{Nm^3}{h}\right]\cdot Operating\ hours\,[\frac{h}{a}]} \qquad \text{Eq. 5.7}$$

Finally, stating the selling price in terms of €/MWh requires to take into account the lower heating value of the product gas. In this case, 13 MJ/Nm^3 as gas heating value is considered.

$$Selling\ price\ product\ gas\left[\frac{€}{MWh}\right] = Selling\ price\ product\ gas\,[\frac{€}{Nm^3}]\cdot LHV_{PG}[\frac{Nm^3}{MJ}]\cdot 3600[\frac{s}{h}] \qquad \text{Eq. 5.8}$$

Once the price of selling the product gas for the base case has been calculated, the next step is to increase the capacity of the gasification plant and see if economies of scale can turn the process more profitable. When the capacity is enlarged, operating expenses increase at the same rate as the capacity does; however, the investment costs follow the relationship shown in Eq. 5.9.

$$\frac{Cost_{size\ 2}}{Cost_{size\ 1}} = \left(\frac{Capacity_{size\ 2}}{Capacity_{size\ 1}}\right)^m \qquad \text{Eq. 5.9}$$

Where m is the size exponent and when a plant size exponent is unknown, one should use the average 2/3 [84].

Table 33 shows the selling price of the product gas both in €/Nm^3 and €/MWh not only for the base case (8 MW) but also for plants with similar characteristics but with more fuel power capacity. Further information about the values regarding operational data, cost rates and expected costs that lead to the results shown in Table 33 is given in Appendix.

Capacity of the gasification plant (MW)	Selling price product gas (€/Nm^3)	Selling price product gas (€/MWh)
8	0.34	93.04
16	0.30	81.70
32	0.26	72.60
64	0.24	65.77
96	0.22	62.23
128	0.22	60.10

Table 33. Selling price of the product gas when comparing different capacities based on the base case

The aim of this part of the economic study is to determine the profitability of substituting a certain percentage of the fossil fuels used by boilers or kilns. Hence, it is important to consider the current fossil fuel prices as it is shown in Table 34.

Fuel	Price (€/MWh)	Data source
Natural gas	16	[88]
Coal	8*	[88,89]
Oil	29*	[89,90]

* *Reference rate USD/EUR=0.91; t hard coal/WMh=8.141; 1 boe/MWh=1.628*

Table 34. Fossil fuel prices

Finally, the previous considerations and assumptions lead to the following graph where a comparison between the price of the product gas obtained when gasifying wood chips and the price of fossil fuels is done. In Figure 47, blue line corresponds to the trendline which gives a measure of how the selling price of the product gas reduces if capacity increases; on the other hand, grey, orange, and green lines correspond to the price of fossil fuels (oil, natural gas, and coal, respectively) according to the current market activity (mid-May 2017).

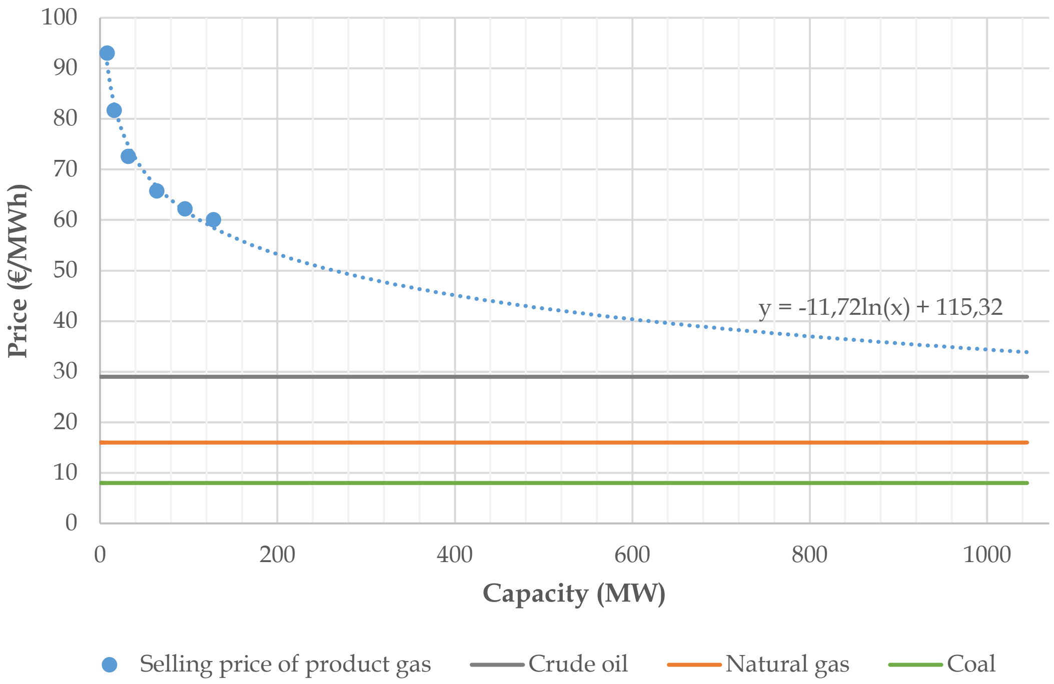


Figure 47. Selling price of product gas depending on the capacity vs fossil fuel prices (€/MWh)

Figure 47 leads to the fact that the selling price of product gas is highly dependent on the fuel power capacity of the gasification plant, in this way, an 8MW gasification plant generating gas obtained from wood chips and selling it for firing or co-firing applications needs to set its price above 93 €/MWh with the purpose of reaching the breakeven point. If the capacity of the plant is increased up to 1000 MW, the selling price goes down to 34€/MWh. However, it is not enough to equal the price of fossil fuels due to its collapse in the late 2014 [91].

As it has been mentioned, the end-use application of the product gas in this case is to be burned in dedicated boilers and kilns, being the purpose to substitute some amount of fossil fuels and therefore, Figure 48 depicts the fuel costs (in million €) of covering the energy demand of the boiler or kiln. When using product gas, it is possible to take advantage of economies of scale and hence, fuel costs decrease as the energy demand increases.

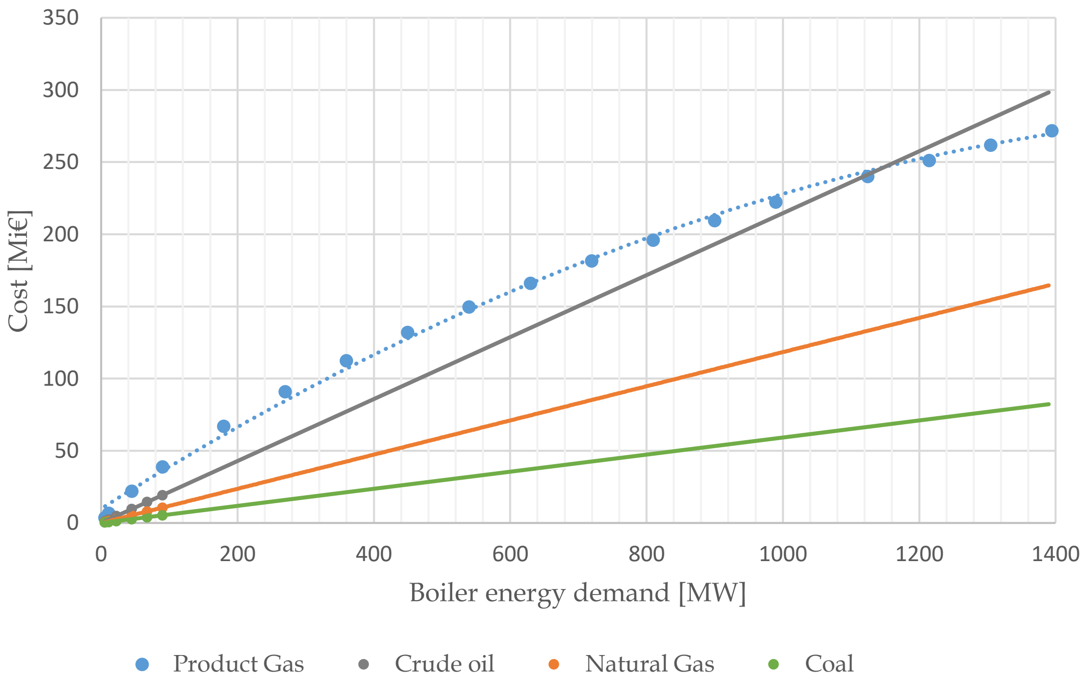


Figure 48. Fuel costs (Mi€) of meeting the boiler energy demand (MW)

As it can be seen in Figure 48, the trendline which represents the fuel costs of supplying the boiler energy demand with the burnt product gas intersects the costs of supplying it with fuel oil when 1120 MW are demanded. Due to the low coal and natural gas prices, it is complicated for product gas to compete against them when talking about economic benefits. Considering the chemical efficiency of the plant (70.3%) and the LHV of the biomass fuel (18.178 MJ/kg$_{dry}$), if the goal is to cover a demand of 1120 MW, the required amount of wood chips to feed the gasifier would be 315 t/h, and in turn, it would mean 2.3 Mt/year (million tonnes or teragram per year). This value is extremely high due to the low LHV of the wood chips and it would imply large forests and large quantity of extracted wood that not only would question the sustainability of the biomass as energy source but also would mean considerable costs when handling and transporting the woody biomass feedstock.

5.4. Gasification of different biomass feedstocks

As it has been demonstrated in the previous section, establishing a business model within which competition among fossil fuels and biomass is analyzed, is not beneficial for biomass as a source of energy. It is true that biomass is the only "greenhouse gas neutral" and the only carbon carrier among the renewable energy sources, and hence, the only that can substitute fossil fuels, but also it is true that this substitution will take time because nowadays, the fossil fuel prices have hit rock-bottom. Moreover, initial capital costs of renewable energy based technologies are 3-7 times higher than those for conventional fossil fuel generation, and private sector investors still consider them as too risky and therefore unattractive due to the longer repayment periods [92]. Therefore, the expectation for biomass gasification is to continue improving in techniques and raw materials that allow costs to go down.

The present section tries to compare the costs of gasifying different feedstocks and therefore, compiled data from the pilot plant at TU Wien are:

- Gasification of traditional woody feedstocks with olivine as bed material.
- Gasification of wood and alternative feedstocks with K-feldspar as bed material, which is exhibited by the three test runs that are presented in the experimental and result chapters.
- Additionally, gasification of exhausted olive pomace (EOP) and olivine is included since the potentials of the EOP were analyzed at TU Wien and represented the core of the European project *Phenolive* [56]. EOP is an interesting biomass fuel for studying its economic feasibility because is an abundant source of biomass in Spain.

It is important to say that the following calculations mean a rough estimation of what would be the cost of gasifying different biomass feedstocks with different bed materials in a gasification plant on an industrial scale. Hence, explaining the assumptions taken is essential.

- Regarding the main operation parameters, it is considered that the different biomass fuels are gasified in a plant like Güssing, on the grounds that TU Wien has a wide knowledge of the performance of the plant since a significant number of research and improvements have been carried out there.
- With respect to the plant input, the diagram followed is similar as the shown in Figure 46. Electricity consumption as well as the amounts of scrubber solvent, nitrogen purge, and water that are demanded by the plant are considered as the same that in the base case of the previous section. These quantities could vary depending on the characteristics of the fuel, but the aim of this estimation is to give an overall idea, not to go deeply through an energy and mass balance or

project portfolios. The feedstock mass flow varies depending on the LHV of the fuel since the thermal power of the fuel should remain unchanged (8 $MW_{th,fuel}$). In addition, the amount of fresh bed material, as well as the one of limestone, changes according to the inventory that is registered at the TU Wien when the bed material is shifted.

Finally, and concerning the plant output, the emitted ash is calculated by taking into account the ash content from the fuel analysis, as well as the feedstock mass flow that enters the plant. The product gas is considered as unchanged for all types of feedstocks since the product gas composition and the LHV_{PG} do not present many variations when changing the fuel. Therefore, the product gas composition is set as the one shown in Table 28. Moreover, it should be remined that for co-firing and firing applications the gas product composition is not crucial, only it is important the thermal power, which keeps around 12 MJ/kg for all the feedstocks. Even though it is possible to get rid of the scrubber due to the low requirements regarding the product gas composition, it is assumed that the operation is done with scrubber to remove tar and avoid problems in the downstream equipment.

Table 35 lists data regarding biomass feedstock and bed materials, which are important to determine the plant input. Once the main properties of feedstocks and bed materials are shown, the plant input and outputs can be set and displayed in Table 36. Finally, the operating expenses are compiled in Table 37, since the aim of this section is to compare the economic opportunities of different feedstocks, only the operating expenses are shown (once technical aspects concerning alternative feedstock are deeply researched, it will have sense to establish a business case competing against fossil fuels). The capital expenditures are considered to be the same no matter the fuel chosen; and concerning the net present value and earnings, it has been demonstrated in the previous section that it is difficult to compete against fossil fuels nowadays when their prices have plummeted.

Properties	Unit	Softwood + olivine	Softwood + K- feldspar	Chicken manure/bark + K-feldspar	Chicken manure + K-feldspar	EOP + olivine
Bed material	%	73 (olivine 200-300µm), 16 (olivine 100-200µm), 11 (calcite 300-600µm)	89 (K-feldspar 287µm), 11 (calcite 480µm)	89 (K-feldspar 287µm), 11 (calcite 480µm)	89 (K-feldspar 370µm), 11 (calcite 480µm)	78 (olivine 100-300µm), 22 (calcite 240-600µm)
Initial bed material inventory	kg	93	80	80	80	85
Feedstock type	-	Softwood pellets	Softwood pellets	Chicken manure/bark pellets	Chicken manure pellets	EOP pellets
Water content	wt %	7.2	7.2	9.5	9.1	-
Volatile matter	wt $\%_{db}$	85.4	85.4	68.8	67.7	75.8
Ash content	wt $\%_{db}$	0.2	0.2	13.0	25.4	4.7
LHV_{fuel}	kJ/kg_{db}	18 940	18 940	17 100	13 900	18 983

Table 35. Main properties of the different biomass feedstocks and bed materials that are compared

Operation parameter	Unit	Softwood + olivine	Softwood + K- feldspar	Chicken manure/bark +K- feldspar	Chicken manure + K-feldspar	EOP + olivine
Fuel power	MW	8	8	8	8	8
Operation hours/year	h/a	7 400	7 400	7 400	7 400	7 400
Cold gas efficiency	%	70.3	70.3	70.3	70.3	70.3
Subsequent data						
Plant input						
Biomass fuel dry	kg/h	1 500	1 500	1 700	2 000	1 500
Electricity consumption	MW	0.2	0.2	0.2	0.2	0.2
Scrubber solvent (RME)	kg/h	17	17	17	17	17
Nitrogen (N_2) purge	Nm^3/h	75	75	75	75	75
Limestone	kg/h	5.5	4.7	4.7	4.7	10
Fresh bed material	kg/h	44.5	38.3	38.3	38.3	35
Water	kg/h	500	500	500	500	500
Plant output						
Product gas	Nm^3/h	1 600	1 600	1 600	1 600	1 600
Ash	kg/h	3	3	221	508	70

Table 36. Operational data for a plant when gasifying different feedstock with distinct bed materials

Parameter	Unit	Softwood + olivine	Softwood + K-feldspar	Chicken manure/bark + K-feldspar	Chicken manure +K- feldspar	EOP + olivine
Operating expenses (OPEX)						
Direct production costs						
Biomass pellets costs (per dry ton)	€/t	100	100	50	0	50
Fresh bed material	€/t	156	156	156	156	156
Limestone/burnt limestone	€/t	30	30	30	30	30
Nitrogen	€/Nm³	0.09	0.09	0.09	0.09	0.09
Scrubber solvent (RME)	€/t	1 100	1 100	1 100	1 100	1 100
Fresh water	€/t	2.17	2.17	2.17	2.17	2.17
Number of employees	pers.	7	7	7	7	7
Cost of one employee per year	€/a	70 000	70 000	70 000	70 000	70 000
Electricity costs	€/kWh	0.12	0.12	0.12	0.12	0.12
Costs for ash disposal	€/t	90	45	45	45	90
Maintenance	% (CAPEX)/a	240 000	240 000	240 000	240 000	240 000
Fixed costs						
Insurance and administration	% (CAPEX)/a	300 000	300 000	300 000	300 000	300 000
Plant overhead	% (CAPEX)/a	90 000	90 000	90 000	90 000	90 000

Table 37. Unit operating costs of the different alternative

Considering all the earlier assumptions and input parameters for calculations, the results standing for the operating costs when gasifying different biomass feedstocks with different bed materials are shown in Figure 49. Additionally, Table 38 provides numerical data to supplement the figure.

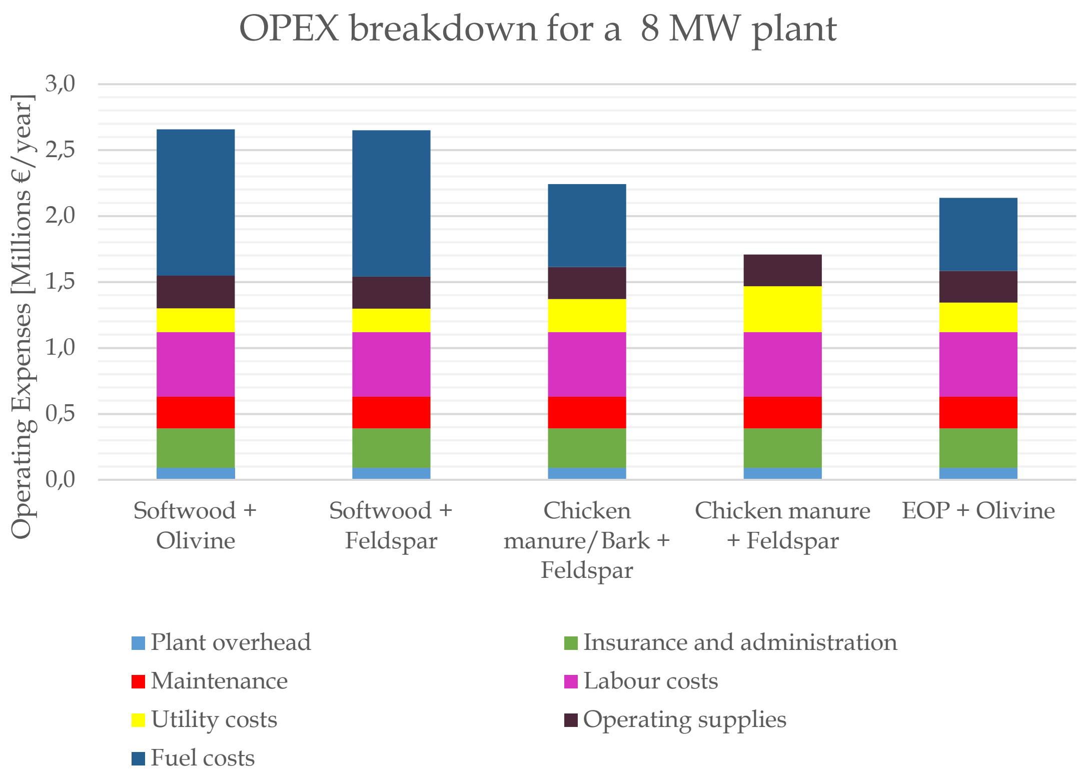


Figure 49. Breakdown of the OPEX for each of the five considered alternatives (Mi€/year)

OPEX (Mi€)	Softwood + Olivine	Softwood + K-feldspar	Chicken manure/Bark + K-feldspar	Chicken manure + K-feldspar	EOP + Olivine
Plant overhead	90 000	90 000	90 000	90 000	90 000
Ins. & Adm.	300 000	300 000	300 000	300 000	300 000
Maintenance	240 000	240 000	240 000	240 000	240 000
Labour costs	490 000	490 000	490 000	490 000	490 000
Utility costs	179 598	178 599	251 193	346 764	224 220
Operating supplies	248 951	241 616	241 616	241 616	238 983
Fuel costs	1 110 000	1 100 000	629 000	0	555 000
TOTAL	2 658 549	2 650 215	2 241 809	1 708 380	2 138 203

Table 38. Operating expenses for each of the five considered alternatives (Mi€/year)

Costs concerning plant overhead (light blue), insurance and administration (green), and maintenance (red) remain unchanged because their value do not depend on the operating conditions or raw materials, but are tied to the characteristics of the plant because are defined as a percentage of the capital expenditure. Additionally, labour costs (pink) do not vary when plant inputs are changed.

Regarding utility costs (yellow), electricity consumption and costs for ash disposal are included in this category. Electricity consumption is considered unchanged for the five studied cases, unlike ash disposal costs that are expected to change. As it can be seen in Table 37, ash disposal costs when gasifying with K-feldspar are estimated as the half of those when gasifying with olivine due to the absence of ash deposition, as no problematic compounds (such as heavy metals, as it is the case for olivine) are brought into the ash. However, this advantage linked to use of K-feldspar is not enough to compensate the huge ash content in chicken manure and bark, especially in the case of chicken manure. Since softwood pellets are nearly ash-free feedstocks, the ash disposal costs when using wood as biomass feedstocks are the lowest one. On the other hand, gasifying only with chicken manure means a problem when getting rid of the ash due to the high ash content in the fuel (Figure 39).

No remarkable differences are noticed when looking at the operating supplies (black) in Figure 49 and Table 38. This cost category includes the expenses concerning the supply of RME, N_2, water and bed materials. The amount of bed material needed, limestone (rock composed mainly of calcite) as well as olivine or K-feldspar, is estimated according to the data obtained from the experiments at TU Wien and thus, the gasification of EOP with olivine leads to the lowest operating supplies, as the percentage of calcite used is bigger than for the other cases and its price cheaper.

Finally, it should be analysed the fuel costs (dark blue), as the expense on biomass fuels represents a large share of the operating expenses. In this way, softwood pellets mean 41.75% and 41.88% of the total OPEX for the first two cases respectively; bark amounts a share of 28.06% for the third case; and finally, 25.96% of the OPEX for the last case corresponds to the acquisition of the EOP feedstock. Since chicken manure is a waste stream, it is possible to get the fuel for free, it is mostly a solution where there is already chicken manure (chicken farms). Furthermore, the gasification of EOP is also a solution for industries involved in the production of olive and vegetable oils where the disposal of the residues from that production is a problem. These wastes and sub-products are associated with dangerous pollutants for the environment but also are characterized by an excellent energy content. Therefore, gasification process stands for a way of getting rid of these residues while obtaining a gas useful for different applications.

6. CONCLUSION

Biomass gasification is a promising technology for energy production from a technical point of view. The gasification process of alternative feedstocks with new forms of bed materials has been proven to be technically feasible and test runs in the 100 kW pilot plant at TU Wien were successfully carried out. From an economic point of view, it is different, and even though biomass is the only way to reach a future energy generation based on fossil carbon-free production, it has no economic sense to establish markets where there is direct competition with fossil fuels such as coal, natural gas and oil. The future of biomass gasification will depend a lot on success or failure of new technological developments with cheaper feedstocks. And furthermore, governments will play a crucial role with the chance of granting incentives that make investments more attractive, resulting finally in cost reduction because of investment and research aids, increased adoption, and economies of scale.

The gasification of woody feedstocks with olivine has meant the basis of several researches carried out at TU Wien and later demonstrated in Güssing (Austria), which has been operated since 2001. The fuel flexibility of the pilot plant allows to research in new and challenging biomass feedstocks to further industrial scale-ups. Three test runs with three different biomass feedstocks, which are:

- softwood pellets,
- 70% bark and 30% chicken manure pellets, and
- pure chicken manure pellets

and K-feldspar as bed material, were successfully completed at the novel DFB pilot plant.

Main results obtained from the experiment and comparison with the traditional gasification of wood and olivine can be summarized as follows:

- Quick changes in biomass fuels did not influence the process at all and stationary operation was possible to be reached over a period of hours. Additionally, process parameters were set to similar values in order to allow equal comparisons among different fuels.

- Ash content in the alternative feedstocks (both mixture of chicken manure/bark and pure chicken manure) is significantly high, which can cause agglomeration and inhibit continuous operation. Although the presence of alkali metals such as potassium or sodium is a problem regarding low ash softening/melting temperature, this is compensated by the important amount of phosphor and magnesium, which are able to mitigate low ash melting behaviour.

- Despite the diversity in chemical composition of fuels, the product gas composition is not remarkably affected. Main points found out regarding the product gas obtained from the different feedstocks are:
    - The gasification of chicken manure leads to a high product gas volume and power, which means an advantage when using the product gas for applications such as the production of heat due to the low requirements concerning the quality of product gas composition.
    - It is also chicken manure which produces the high content of ammonia in the product gas, as its N content is the highest when comparing with the rest of the feedstocks. Therefore, ammonia reduction treatment would be required because emissions of this compound into the atmosphere are not allowed by regulations.
    - Dust content in product gas is influenced by the ash content in the biomass feedstock, being the high share of dust in the product gas from chicken manure correlated with the high ash content in the feedstock.
    - Regarding tar content of the product gases obtained from different feedstocks, the comparison should be done among the test runs carried out with the same type of bed material (K-feldspar in this case). The gasification of the mixture of chicken manure and bark yields the least tar content. It can be explained by the higher hydrogen content and thus, the enhancement of water-gas shift reaction that takes place; the potential of char content to act as a catalyst, as the char content in the product gas produced from chicken manure/bark is the highest; and finally, the chance of ash and alkalis to act also as catalysts, since catalytic reactions occur when tars and ash particles enter in contact.
- In relation to the comparison between both types of bed materials (olivine and K-feldspar), the heat transfer capacity of olivine is higher than the one of K-feldspar because with olivine it is possible to keep gasification and combustion temperatures closer than with K-feldspar, and moreover, more additional fuel is need when gasifying with K-feldspar. Finally, it has also been proven the higher catalytic activity of olivine.

Although biomass gasification has been proven to be technically feasible and can represent a clean alternative for energy production, it seems that the role of fossil fuels will remain large and will stay dominant unless radical changes are made. The economic evaluation of the present work leads to the conclusion that it is not possible to compete directly against fossil fuels because fossil fuel prices are plummeting due to the discovery of oil reserves and new technologies (as it is the case for fracking). If a plant like Güssing would sell the product gas directly for heat production in boilers or kilns, the selling price of the product gas would be above 93€/MWh to reach the breakeven point. Even taking advantages of scale-ups and economies of scale would not be sufficient to beat fossil fuel prices. Thus, the product gas price would go down to 34€/MWh for a 1000 MW power plant whose purpose would be to produce product gas and sell it for firing or co-firing applications, an evident lowering but not enough if fossil fuel prices are considered in a project portfolio (16€/MWh natural gas, 8€/MWh coal, and 29€/MWh oil). Moreover, plants characterized by a large capacity not only are technically unfeasible, but also represent in themselves an environmental threat because they involve extraction of enormous quantities of biomass, which would be environmentally unsustainable if that is not correctly regulated. In any case, large amounts of biomass lead to handling and transportation costs extremely high.

Researching in new raw materials is a way to cut operating costs from biomass gasification, as fuel costs represent a large share of the total operating expenses. Buying wood for biomass gasification amounts more than 40% of the total process cost. Therefore, taking advantage of chicken manure from chicken farms or EOP from industries involved in the production of vegetable oils means not only a solution for polluting waste streams but also a manner of reducing operating cost in the gasification process.

Despite biomass cannot be part of market where competition with fossil fuels is established, it should be realised that the harmful and potential dangerous long-term effects of fossil fuels are not included or at least insufficiently taken into account in the economies. A range of incentives or government subsidies in the form of feed-in tariffs, quotas, green certificates, or carbon taxation will be required to shift the economic statistics. That is the most important factor for the future of biomass as well as for many other renewable and sustainable energy sources because is the only way to turn an ethically and environmentally attractive project into one where profits and commercial rewards justify the risks and attract new investors.

REFERENCES

[1] International Energy Agency, IEA (2016). "World Energy Outlook", Executive Summary. Paris, France.

[2] Kopetz, H. (2015). "The Future Role of Bioenergy in the Global Energy System", *Biomass Power for the World*, Pan Stanford, pp. 141–162.

[3] New CO_2 Fuels. "CO_2 Emissions". Retrieved from:
http://www.newco2fuels.co.il/challenge/15/co2-emissions, 03.2017

[4] Paris Agreement and United Nations (2015). "Paris Agreement".

[5] European Commission (2016). "EU Energy in Figures". Belgium.

[6] Hofbauer, H.; Rauch, R.; Loeffler, G.; Kaiser, S.; Fercher, E.; Tremmel, H. (1998). "Six Years Experience with the FICFB-Gasification Process". Vienna, Austria.

[7] Palz, W. (2015). "Bioenergy: Global Potentials and Markets", *Biomass Power for the World*, Pan Stanford, pp. 117–139.

[8] Pfeifer, C.; Koppatz, C.; Hofbauer, H. (2011). "Steam gasification of various feedstocks at a dual fluidized bed gasifier: Impacts of operation conditions and bed materials", *Biomass Convers Biorefinery*, pp. 39–53.

[9] Wilk, V.; Kitzler, H.; Koppatz, S.; Pfeifer, C.; Hofbauer, H. (2011). "Gasification of waste wood and bark in a dual fluidized bed steam gasifier", *Biomass Convers,* pp. 91–97

[10] Schmid, J. C.; Wolfesberger, U.; Koppatz, S.; Pfeifer, C.; Hofbauer, H. (2012). "Variation of Feedstock in a Dual Fluidized Bed Steam Gasifier — Influence on Product Gas, Tar Content, and Composition", *Biorefinery*, pp. 91–97.

[11] Kitzler, H.; Pfeifer, C.; Hofbauer, H. (2011). "Gasification of reed in a 100kW dual fluidized bed steam gasifier". European biomass conf, Berlin, Germany.

[12] Kern, S.; Pfeifer, C.; Hofbauer, H. (2011). "Dual fluidized-bed steam gasification of solid feedstock: Matching syngas requirements with fuel mixtures". Vienna, Austria.

[13] Kern, S.; Pfeifer, C.; Hofbauer, H. (2012). "Synergetic Utilization of Renewable and Fossil Fuels: Dual Fluidized Bed Steam Co-gasification of Coal and Wood", vol. 1, no. January, pp. 136–140.

[14] Wilk, V.; Hofbauer, H. (2013). "Conversion of mixed plastic wastes in a dual fluidized bed steam gasifier", *Fuel*, vol. 107, pp. 787–799.

[15] Kirnbauer, F.; Hofbauer, H. (2011). "Investigations on Bed Material Changes in a Dual Fluidized Bed Steam Güssing, Austria", *Gasification Plant in Güssing*, pp. 3793–3798.

[16] Kuba, M.; He, H.; Kirnbauer, F.; Boström, D.; Öhman, M.; Hofbauer, H. (2015). "Deposit build-up and ash behavior in dual fluid bed steam gasification of logging residues in an industrial power plant", *Fuel Process. Technol.*, vol. 139, pp. 33–41.

[17] Basu, P. (2010). *Biomass Gasification and Pyrolysis, Practical Design and Theory*. First Edition, 2010 Elsevier Inc.

[18] Swaaij, W.; Kersten, S. (2015). "Overview of Energy from Biomass for Nonexperts", *Biomass Power for the World*, Pan Stanford, pp. 1–116.

[19] IEA Bioenergy Task 33 (2014). "Biomass as gasification feedstock".

[20] Knoef, H.A.M. (2005). *Handbook Biomass Gasification*. BTG biomass technology group BV, The Netherlands.

[21] Howes, T. (2010). "The EU's New Renewable Energy Directive (2009/28/EC), The New Climate Policies of the European Union: Internal Legislation and Climate Diplomacy".

[22] Palz, W.; Zibetta, H. (2015). "EU Biomass R&D: The Beginnings (Laying the Ground for Biomass Becoming Mainstream in Sustainable Energy Supply in Europe)". *Biomass Power for the World*, Pan Stanford, pp. 163–189.

[23] Bridgwater, A.V. (1995). "The technical and economic feasibility of biomass gasification for power generation", vol. 14, no. 5.

[24] Bridgwater, A. V.; Hofbauer, H.; Van, L. S. (2009). *Thermal biomass conversion*. Newbury: CPL Press.

[25] Reed, T. B.; Gaur, S. (2001). *Gasifier projects and manufactures around the world*. The National Renewable Energy Laboratory and The Biomass Energy Foundation.

[26] Hrbek, J. (2016). "Status report on thermal biomass gasification in countries participating in IEA Bioenergy Task 33".

[27] Kaltschmitt, M.; Hartmann, H.; Hofbauer, H. (2009). *Energie aus Biomasse*. Vienna.

[28] Schmid, J.C.; Hofbauer, H. (2014). "Development of a novel dual fluidized bed gasification system for increased fuel flexibility", Doctoral Thesis, Vienna University of Technology.

[29] Salomonsson, J. (2015). "Catalytic Performance of Coated and Non-Coated Bed Materials in Fluidized Bed Steam Gasification of Biomass", Master's Thesis, Luleå University of Technology.

[30] Zainal, Z.A.; Rifau, A.; Quadir, G.A.; Seetharamu, K.N. (2002). "Experimental investigation of a downdraft biomass gasifier", *Biomass Bioenergy* 23, 283–289.

[31] Rapagna, S.; Jand, N.; Kiennemann, A.; Foscolo, P.U. (2000). "Steam-gasification of biomass in a fluidized-bed of olivine particles", *Biomass Bioenerg*y 19, 187–197.

[32] Molina, A.; Mondragón, F. (1998). "Reactivity of coal gasification with steam and CO_2", *Fuel* 77, 1831–1839.

[33] Kern, S.; Pfeifer, C.; Hofbauer, H. (2013). "Gasification of wood in a dual fluidized bed gasifier: Influence of fuel feeding on process performance", *Chem. Eng. Sci.*, vol. 90, pp. 284–298.

[34] Havlik, H.; Hofbauer, H. (2015). "Catalytic Investigations Regarding Alternative Bed Materials for Dual Fluidized Bed Gasification of Biomass", Master's Thesis, Vienna University of Technology.

[35] Phillips, J. (2004). "Different Types of Gasifiers and their Integration with Gas Turbines 1.2.1-1 Introduction", pp. 67–77.

[36] Kuba, M.; Hofbauer, H. (2013). "Product gas cleaning for biomass gasification with focus on catalytic tar decomposition and operation of a downstream reformer", Master's Thesis, Vienna University of Technology.

[37] IEA Bioenergy Task 33 (2014). "Gasification technologies".

[38] Drift, A. van der; Boerrigter, H.; Coda, B.; Cieplik, M.K.; Hemmes, K. (2004). "Entrained flow gasification of biomass - Ash behaviour, feeding issues, system analyses". Energy research Centre of the Netherlands (ECN), Petten, The Netherlands.

[39] Basu, P. (2006). *Combustion and Gasification in Fluidized Beds*. Taylor & Francis Group.

[40] Stevens, D.J. (2001). "Hot Gas Conditioning: Recent Progress with Larger-Scale Biomass Gasification Systems Update and Summary of Recent Progress". National Renewable Energy Laboratory, Golden, Colorado.

[41] Baker, E.G.; Brown, M.D.; Moore, R.H.; Mudge, L.K.; Elliott, D.C. (1986). "Engineering Analysis of Biomass Gasifier Product Gas Cleaning Technology". Pacific Northwest National Laboratory, Richland, Washington.

[42] Kiel, J.H.A. (2002). "Gas cleaning: the Achilles heel of biomass gasification". Energy Research Centre of The Netherlands, Amsterdam, The Netherlands.

[43] Devi, L.; Ptasinski, K.J.; Janssen, F.J.J.G. (2003). "A review of the primary measures for tar elimination in biomass gasification processes", *Biomass and Bioenergy* 24 (2), 125–140.

[44] Neeft, J.P.A.; Knoef, H.A.M.; Zielke, U.; Sjöström, K.; Hasler, P.; Simell, P.A.; Dorrington, M.A.; Abatzoglou, N.; Deutch, S.; Greil, C.; Buffinga, G.J.; Brage, C.; Soumalainen, M. (1999). "Guideline for Sampling an Analysis of Tar and Particles in Biomass Producer Gas", Version 3.1; Energy project EEN5-1999-00507 (tar protocol).

[45] IEA Bioenergy Task 33 (2014). "Contaminants in producer gas".

[46] Milne, T.A.; Evans, R.J.; Abatzoglou, N. (1998). "Tars: Their Nature, Formation and Conversion". Technical report, National Renewable Energy Laboratory, Golden, Colorado.

[47] Evans, R.J.; Milne, T.A. (1997). "Chemistry of tar formation and maturation in the thermochemical conversion of biomass". Springer Netherlands, Dorddrecht, Netherlands.

[48] Evans, R.J.; Milne, T.A. (1987). "Molecular characterization of the pyrolysis of biomass. 1. Fundamentals". *Energy & Fuels*.

[49] Paasen, S.V.B. van; Kiel, J.H.A. (2004). "Tar formation in a fluidized-bed gasifier". ECN Biomass.

[50] Li, C.; Suzuki, K. (2009). "Tar property, analysis, reforming mechanism and model for biomass gasification—An overview". EcoTopia Science Institute, Nagoya University, Nagoya, Japan.

[51] Zwart, R.W.R. (2009). "Gas cleaning downstream biomass gasification Status Report 2009".

[52] Lancee, R. J. (2014). "Characterization and reactivity of olivine and model catalysts for biomass gasification". Technische Universiteit Eindhoven, The Netherlands.

[53] Hofbauer, H.; Veronik, G.; Fleck, T.; Rauch, R.; Mackinger, H.; Fercher, E. (1996). "The FICFB – Gasification Process". Vienna University of Technology, Austria and Austrian Energy & Environment, Graz, Austria.

[54] Diem, R.; Hofbauer, H. (2015). "Design, Construction and Start-up of an Advanced 100 kW Dual Fluidized Bed System for Thermal Gasification", Doctoral Thesis, Vienna University of Technology.

[55] Hofbauer, H. (2015). "Energy from Biomass via Gasification in Güssing", *Biomass Power for the World*, Pan Stanford, pp. 343–373.

[56] Schmid, J.C.; Kolbitsch, M.; Fuchs, J.; Mueller, S.; Benedikt, F.; Hofbauer, H. (2016). "Technical Report of Scientific Experimental Research for the EU project PHENOLIVE. Steam gasification of EXHAUSTED OLIVE POMACE with the dual fluidized bed pilot plant". Technical report, Institute of Chemical Engineering, Vienna University of Technology.

[57] Mauerhofer, A.M.; Fuchs, J.; Benedikt, F.; Martin, M.; Schmid, J.C.; Hofbauer, H. (2017). "Dual fluidized bed steam gasification of softwood, chicken manure-bark blend and pure chicken manure with a 100kW pilot plant at TU Wien and a mixture of potassium feldspar and calcite as bed material". Technical report, Institute of Chemical Engineering, Vienna University of Technology.

[58] Schmid, J.C.; Mueller, S.; Hofbauer, H. (2016). "Technical Report of Scientific Experimental Research for the Department of Chemical Engineering, Lund University. Dual fluidized bed steam gasification of wood with the novel pilot plant at TU Wien". Technical report, Institute of Chemical Engineering, Vienna University of Technology.

[59] Pasteiner, H.A.; Hofbauer, H. (2015). "Cold Flow Investigations on a Novel Dual Fluidized Bed Steam Gasification Test Plant", Diplomarbeit, Vienna University of Technology.

[60] Kern, S.; Pfeifer, C.; Hofbauer, H. (2013). "Co-Gasification of Wood and Lignite in a Dual Fluidized Bed Gasifier".

[61] Kolbitsch, M.; Hofbauer, H. (2016). "First Fuel Tests at a Novel 100 kWth Dual Fluidized Bed Steam Gasification Pilot Plant", Doctoral Thesis, Vienna University of Technology.

[62] Good, J.; Ventress, H.; Knoef, U.; Zielke, P.; Lyck, H. P.; van de Kamp, W.; de Wild, P; Coda, B.; van Paasen, S.; Kiel, J.; Sjoestroem, K.; Liliedahl, T.; Unger, C.; Neeft, J.; Suomalainen, M.; Simell, P. (2005). "Sampling and analysis of tar and particles in biomass producer gases: Technical Report".

[63] Wolfesberger, U.; Aigner, I.; Hofbauer, H. (2009). "Tar composition in producer gas of fluidized bed gasification of wood – influence of temperature and pressure". Environmental Progress & Sustainable Energy, pages 372-379.

[64] Hofbauer, H.; Rauch, R.; Siefert, I. (2003). "Endbericht Analytik III. Renet". Technical report.

[65] CEN/TS 15439:2006. "Biomass gasification. Tar and particles in product gas. Sampling and analysis". Technical report.

[66] Kitzler, H.; Pfeifer, C.; Hofbauer, H. (2011). "Proceedings of the 19th European biomass conference and exhibition". Berlin, Germany; pp 1101-1105.

[67] Koppatz, S.; Hofbauer, H. (2012). "Outlining active bed materials for dual fluidized bed biomass gasification – in-bed catalysts and oxygen/carbonate looping behaviour". PhD Thesis, Institute of Chemical Engineering, Vienna University of Technology.

[68] Devi, L.; Craje, M.; Thüne, P..; Ptasinski, K.J.; Janssen, F. J. J. G. (2005). "Olivine as tar removal catalyst for biomass gasifiers: Catalyst characterization".

[69] Rauch, R.; Pfeifer, C.; Bosch, K.; Hofbauer, H.; Świerczyński, D.; Courson, C. (2004). "Comparison of different olivines for biomass steam gasification". Proceedings of the Conference for Science in Thermal and Chemical Biomass Conversion, Victoria, Canada, vol. 1, pp. 799–809.

[70] El-Rub, Z.A.; Bramer, E.A.; Brem, G. (2008) "Experimental comparison of biomass chars with other catalysts for tar reduction," *Fuel*, vol. 87, no. 10, pp. 2243–2252.

[71] Kern, S.; Pfeifer. C.; Hofbauer, H. (2013). "Gasification of lignite in a dual fluidized bed gasifier — Influence of bed material particle size and the amount of steam," vol. 111, pp. 1–13, 2013.

[72] Hein, D.; Wiedmann, F.; Schneider, A.; Kappes, M.; Krumm, W. (2011). "Gasification of miscanthus – Influence of ash on tar content and gas quality". Proceedings of the International Conference of Polygeneration Strategies (ICPS11), Vienna, Austria.

[73] International Energy Agency, IEA (2014). "Energy policies of IEA countries: Austria". Paris, France.

[74] International Energy Agency, IEA (2015). "Energy policies of IEA countries: Spain". Paris, France.

[75] Ross, S. A.; Westerfield, R. W.; Jaffe, J. F.; Jordan, B. D. (2011). *Corporate Finance: core principles & applications*. The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY, 10020.

[76] Centre for Management Technology (2009). "4th BTLtec (Biomass to Liquids)". Retrieved from:
http://www.cmtevents.com/aboutevent.aspx?ev=090939, 05.2017

[77] Bolhàr-Nordenkampf, M.; Rauch, R.; Bosch, R.; Aichernig, C.; Hofbauer, H. (2002). "Biomass CHP Plant Güssing – Using Gasification for Power Generation," vol. 3.

[78] Bolhàr-Nordenkampf, M.; Hofbauer, H. (2004). "Techno-economic assessment on the gasification of biomass on the large scale for heat and power production", Doctoral Thesis, Vienna University of Technology.

[79] Müller, S.; Hofbauer, H. (2013). "Hydrogen from biomass for industry – Industrial application of hydrogen production based on dual fluid gasification", Doctoral Thesis, Vienna University of Technology.

[80] Rodrigues, M.; Walter, A.; Faaij, A. (2003). "Co-firing of natural gas and biomass gas in biomass integrated gasification / combined cycle systems," vol. 28, pp. 1115–1131.

[81] IEA Bioenergy Task 33 (2014). "Indirect co-firing".

[82] Kasapoglu, Z.; Hofbauer, H. (2016). "Technical and economic evaluation of the carbon dioxide neutral production technologies of hydrogen", Bachelor's Thesis, Vienna University of Technology.

[83] Maverick J.B. (2017). "What is the difference between CPAEX and OPEX?". Investopedia. Retrieved from: http://www.investopedia.com/ask/answers/020915/what-difference-between-capex-and-opex.asp, 05.2017

[84] Brown, T. (2006). "Economics and economic design for process engineers". CRC Press, Taylor & Francis Group.

[85] Eurostat. "Electricity prices for industrial consumers - bi-annual data (from 2007 onwards)". Retrieved from: http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do, 04.2017

[86] OECD (2017). "Inflation forecast (indicator)". Doi: 10.1787/598f4aa4-en (Accessed on 02 May 2017).

[87] Austrian Business Agency (2016). "Invest in Austria: Tax aspects". Compiled by Deloitte.

[88] EEX, European Energy Exchange AG. Retrieved from: https://www.eex.com/en/, 05.2017

[89] Unit Juggler, unit converter: https://www.unitjuggler.com/, 05.2017

[90] Oil price: http://oilprice.com/, 05.2017

[91] Krauss, C. (2017, May 15). "Oil Prices: What to Make of the Volatility". *The New York Times*. Retrieved from: https://www.nytimes.com/interactive/2017/business/energy-environment/oil-prices.html, 05.2017

[92] Commission of the European Communities, COM (2006). "Mobilising public and private finance towards global access to climate-friendly, affordable and secure energy services: The Global Energy Efficiency and Renewable Energy Fund". *Communication from the commission to the council and the European Parliament*, Brussels.

APPENDIX

Operation parameter	Unit	Value
Fuel power	MW	16
Operation hours per year	h/a	7 400
Overall cold gas efficiency	%	70.3
Subsequent data	**Unit**	**Value**
Plant input		
Biomass fuel (wood chips) dry	kg/h	3 300
Electricity consumption	MW	0.4
Scrubber solvent (RME)	kg/h	34
Nitrogen (N_2) purge	Nm^3/h	150
Limestone/burnt limestone	kg/h	20
Fresh bed material (olivine)	kg/h	80
Water	kg/h	1 000
Plant output		
Product gas volume	Nm^3/h	3 200
Ash	kg/h	32

Table A- 1. Operational data of a 16 MW DFB gasification plant

Parameter	Unit	Value
Capital expenditures (CAPEX)		
Investment cost	€	19 048 812.62
Operating expenses (OPEX)		
Direct production costs		
Wood chip costs (per dry ton)	€/t	100
Fresh bed material (olivine)	€/t	156
Limestone/burnt limestone	€/t	30
Nitrogen	€/Nm^3	0.09
Scrubber solvent (RME)	€/t	1 100
Fresh water	€/t	2.17
Number of employees	pers.	11
Cost of one employee per year	€/a	70 000
Electricity costs	€/kWh	0.12
Costs for ash disposal	€/t	90
Maintenance	% (CAPEX)/a	2.0
Fixed costs		
Insurance and administration	% (CAPEX)/a	2.5
Plant overhead	% (CAPEX)/a	0.75

Table A- 2. Cost rates for economic calculations of a 16 MW plant

YEAR (n)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
CAPEX	19.05																				
OPEX		5.16	5.27	5.37	5.48	5.59	5.70	5.81	5.93	6.05	6.17	6.29	6.42	6.55	6.68	6.81	6.95	7.09	7.23	7.37	7.52
Fuel cost (wood chips)		2.49	2.54	2.59	2.64	2.70	2.75	2.81	2.86	2.92	2.98	3.04	3.10	3.16	3.22	3.29	3.35	3.42	3.49	3.56	3.63
Operating supplies		0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.55	0.57	0.58	0.59	0.60	0.61	0.62	0.64	0.65	0.66	0.68	0.69	0.70
Labour costs		0.79	0.80	0.82	0.83	0.85	0.87	0.88	0.90	0.92	0.94	0.96	0.98	1.00	1.02	1.04	1.06	1.08	1.10	1.12	1.14
Utility costs		0.38	0.39	0.40	0.41	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.55	0.56
Maintenance		0.39	0.40	0.40	0.41	0.42	0.43	0.44	0.45	0.46	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.56	0.57
Insurance & admin		0.49	0.50	0.51	0.52	0.53	0.54	0.55	0.56	0.57	0.58	0.59	0.60	0.62	0.63	0.64	0.65	0.67	0.68	0.69	0.71
Plant overhead		0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.20	0.21	0.21
Accumulated OPEX		4.78	9.30	13.56	17.59	21.39	24.98	28.38	31.58	34.61	37.47	40.16	42.71	45.12	47.40	49.54	51.57	53.49	55.30	57.01	59.62

Table A- 3. Cost flows of a 16 MW gasification plant along its expected lifetime (Millions €)

Operation parameter	Unit	Value
Fuel power	MW	32
Operation hours per year	h/a	7 400
Overall cold gas efficiency	%	70.3
Subsequent data	**Unit**	**Value**
Plant input		
Biomass fuel (wood chips) dry	kg/h	6 600
Electricity consumption	MW	0.8
Scrubber solvent (RME)	kg/h	68
Nitrogen (N_2) purge	Nm^3/h	300
Limestone/burnt limestone	kg/h	40
Fresh bed material (olivine)	kg/h	160
Water	kg/h	2 000
Plant output		
Product gas volume	Nm^3/h	6 400
Ash	kg/h	64

Table A- 4. Operational data of a 32 MW DFB gasification plant

Parameter	Unit	Value
Capital expenditures (CAPEX)		
Investment cost	€	30 238 105.20
Operating expenses (OPEX)		
Direct production costs		
Wood chip costs (per dry ton)	€/t	100
Fresh bed material (olivine)	€/t	156
Limestone/burnt limestone	€/t	30
Nitrogen	$€/Nm^3$	0.09
Scrubber solvent (RME)	€/t	1 100
Fresh water	€/t	2.17
Number of employees	pers.	17
Cost of one employee per year	€/a	70 000
Electricity costs	€/kWh	0.12
Costs for ash disposal	€/t	90
Maintenance	% (CAPEX)/a	2.0
Fixed costs		
Insurance and administration	% (CAPEX)/a	2.5
Plant overhead	% (CAPEX)/a	0.75

Table A- 5. Cost rates for economic calculations of a 32 MW plant

YEAR (n)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
CAPEX	30.24																				
OPEX		9.55	9.74	9.93	10.13	10.34	10.54	10.75	10.97	11.19	11.41	11.64	11.87	12.11	12.35	12.60	12.85	13.11	13.37	13.64	13.91
Fuel cost (wood chips)		4.98	5.08	5.18	5.29	5.39	5.50	5.61	5.72	5.84	5.95	6.07	6.19	6.32	6.44	6.57	6.70	6.84	6.98	7.12	7.26
Operating supplies		0.97	0.99	1.00	1.02	1.05	1.07	1.09	1.11	1.13	1.15	1.18	1.20	1.22	1.25	1.27	1.30	1.33	1.35	1.38	1.41
Labour costs		1.21	1.24	1.26	1.29	1.31	1.34	1.37	1.39	1.42	1.45	1.48	1.51	1.54	1.57	1.60	1.63	1.67	1.70	1.73	1.77
Utility costs		0.77	0.78	0.80	0.82	0.83	0.85	0.86	0.88	0.90	0.92	0.94	0.96	0.97	0.99	1.01	1.03	1.05	1.08	1.10	1.12
Maintenance		0.62	0.63	0.64	0.65	0.67	0.68	0.69	0.71	0.72	0.74	0.75	0.77	0.78	0.80	0.81	0.83	0.85	0.86	0.88	0.90
Insurance & admin		0.77	0.79	0.80	0.82	0.83	0.85	0.87	0.89	0.90	0.92	0.94	0.96	0.98	1.00	1.02	1.04	1.06	1.08	1.10	1.12
Plant overhead		0.23	0.24	0.24	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.30	0.31	0.31	0.32	0.32	0.33	0.34
Accumulated OPEX		8.84	17.19	25.08	32.53	39.56	46.20	52.48	58.40	64.00	69.29	74.28	78.99	83.45	87.65	91.62	95.37	98.92	102.26	105.42	108.41

Table A- 6. Cost flows of a 32 MW gasification plant along its expected lifetime (Millions €)

Operation parameter	Unit	Value
Fuel power	MW	64
Operation hours per year	h/a	7 400
Overall cold gas efficiency	%	70.3
Subsequent data	**Unit**	**Value**
Plant input		
Biomass fuel (wood chips) dry	kg/h	13 200
Electricity consumption	MW	1.6
Scrubber solvent (RME)	kg/h	136
Nitrogen (N_2) purge	Nm³/h	600
Limestone/burnt limestone	kg/h	80
Fresh bed material (olivine)	kg/h	320
Water	kg/h	4 000
Plant output		
Product gas volume	Nm³/h	12 800
Ash	kg/h	128

Table A- 7. Operational data of a 64 MW DFB gasification plant

Parameter	Unit	Value
Capital expenditures (CAPEX)		
Investment cost	€	48 000 000
Operating expenses (OPEX)		
Direct production costs		
Wood chip costs (per dry ton)	€/t	100
Fresh bed material (olivine)	€/t	156
Limestone/burnt limestone	€/t	30
Nitrogen	€/Nm³	0.09
Scrubber solvent (RME)	€/t	1 100
Fresh water	€/t	2.17
Number of employees	pers.	28
Cost of one employee per year	€/a	70 000
Electricity costs	€/kWh	0.12
Costs for ash disposal	€/t	90
Maintenance	% (CAPEX)/a	2.0
Fixed costs		
Insurance and administration	% (CAPEX)/a	2.5
Plant overhead	% (CAPEX)/a	0.75

Table A- 8. Cost rates for economic calculations of a 64 MW plant

YEAR (n)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
CAPEX	48.00																				
OPEX		18.00	18.36	18.73	19.10	19.48	19.87	20.27	20.68	21.09	21.51	21.94	22.38	22.83	23.29	23.75	24.23	24.71	25.21	25.71	26.22
Fuel cost (wood chips)		9.96	10.16	10.37	10.57	10.78	11.00	11.22	11.44	11.67	11.91	12.15	12.39	12.64	12.89	13.15	13.41	13.68	13.95	14.23	14.51
Operating supplies		1.93	1.97	2.01	2.05	2.09	2.13	2.18	2.22	2.26	2.31	2.35	2.40	2.45	2.50	2.55	2.60	2.65	2.70	2.76	2.81
Labour costs		2.00	2.04	2.08	2.12	2.16	2.21	2.25	2.30	2.34	2.39	2.44	2.49	2.54	2.59	2.64	2.69	2.74	2.80	2.86	2.91
Utility costs		1.54	1.57	1.60	1.63	1.66	1.70	1.73	1.76	1.80	1.84	1.87	1.91	1.95	1.99	2.03	2.07	2.11	2.15	2.19	2.24
Maintenance		0.98	1.00	1.02	1.04	1.06	1.08	1.10	1.12	1.15	1.17	1.19	1.22	1.24	1.27	1.29	1.32	1.34	1.37	1.40	1.43
Insurance & admin		1.22	1.25	1.27	1.30	1.32	1.35	1.38	1.41	1.43	1.46	1.49	1.52	1.55	1.58	1.62	1.65	1.68	1.71	1.75	1.78
Plant overhead		0.37	0.37	0.38	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.48	0.49	0.50	0.51	0.52	0.53
Accumulated OPEX		16.67	32.41	47.28	61.32	74.58	87.10	98.93	110.10	120.65	130.62	140.03	148.92	157.31	165.24	172.73	179.80	186.48	192.78	198.74	204.37

Table A- 9. Cost flows of a 64 MW gasification plant along its expected lifetime (Millions €)

Operation parameter	Unit	Value
Fuel power	MW	96
Operation hours per year	h/a	7 400
Overall cold gas efficiency	%	70.3
Subsequent data	**Unit**	**Value**
Plant input		
Biomass fuel (wood chips) dry	kg/h	19 800
Electricity consumption	MW	2.4
Scrubber solvent (RME)	kg/h	204
Nitrogen (N_2) purge	Nm^3/h	900
Limestone/burnt limestone	kg/h	120
Fresh bed material (olivine)	kg/h	480
Water	kg/h	6 000
Plant output		
Product gas volume	Nm^3/h	19 200
Ash	kg/h	192

Table A- 10. Operational data of a 96 MW DFB gasification plant

Parameter	Unit	Value
Capital expenditures (CAPEX)		
Investment cost	€	62 897 793.46
Operating expenses (OPEX)		
Direct production costs		
Wood chip costs (per dry ton)	€/t	100
Fresh bed material (olivine)	€/t	156
Limestone/burnt limestone	€/t	30
Nitrogen	$€/Nm^3$	0.09
Scrubber solvent (RME)	€/t	1 100
Fresh water	€/t	2.17
Number of employees	pers.	36
Cost of one employee per year	€/a	70 000
Electricity costs	€/kWh	0.12
Costs for ash disposal	€/t	90
Maintenance	% (CAPEX)/a	2.0
Fixed costs		
Insurance and administration	% (CAPEX)/a	2.5
Plant overhead	% (CAPEX)/a	0.75

Table A- 11. Cost rates for economic calculations of a 96 MW plant

YEAR (n)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
CAPEX	62.90																				
OPEX		26.09	26.61	27.14	27.68	28.24	28.80	29.38	29.96	30.56	31.17	31.80	32.43	33.08	33.74	34.42	35.11	35.81	36.53	37.26	38.00
Fuel cost (wood chips)		14.95	15.24	15.55	15.86	16.18	16.50	16.83	17.17	17.51	17.86	18.22	18.58	18.95	19.33	19.72	20.11	20.52	20.93	21.35	21.77
Operating supplies		2.90	2.96	3.01	3.07	3.14	3.20	3.26	3.33	3.39	3.46	3.53	3.60	3.67	3.75	3.82	3.90	3.98	4.06	4.14	4.22
Labour costs		2.57	2.62	2.67	2.73	2.78	2.84	2.89	2.95	3.01	3.07	3.13	3.20	3.26	3.33	3.39	3.46	3.53	3.60	3.67	3.74
Utility costs		2.30	2.35	2.40	2.45	2.49	2.54	2.59	2.65	2.70	2.75	2.81	2.87	2.92	2.98	3.04	3.10	3.16	3.23	3.29	3.36
Maintenance		1.28	1.31	1.33	1.36	1.39	1.42	1.44	1.47	1.50	1.53	1.56	1.60	1.63	1.66	1.69	1.73	1.76	1.80	1.83	1.87
Insurance & admin		1.60	1.64	1.67	1.70	1.74	1.77	1.81	1.84	1.88	1.92	1.96	1.99	2.03	2.07	2.12	2.16	2.20	2.25	2.29	2.34
Plant overhead		0.48	0.49	0.50	0.51	0.52	0.53	0.54	0.55	0.56	0.58	0.59	0.60	0.61	0.62	0.63	0.65	0.66	0.67	0.69	0.70
Accumulated OPEX		4.00	26.81	48.36	68.70	87.92	106.07	123.21	139.40	154.69	169.13	182.76	195.64	207.81	219.30	230.15	240.40	250.07	259.21	267.85	276.00

Table A- 12. Cost flows of a 96 MW gasification plant along its expected lifetime (Millions €)

Operation parameter	Unit	Value
Fuel power	MW	128
Operation hours per year	h/a	7 400
Overall cold gas efficiency	%	70.3
Subsequent data	**Unit**	**Value**
Plant input		
Biomass fuel (wood chips) dry	kg/h	26 400
Electricity consumption	MW	3.2
Scrubber solvent (RME)	kg/h	272
Nitrogen (N_2) purge	Nm^3/h	1 200
Limestone/burnt limestone	kg/h	160
Fresh bed material (olivine)	kg/h	640
Water	kg/h	8 000
Plant output		
Product gas volume	Nm^3/h	25 600
Ash	kg/h	256

Table A- 13. Operational data of a 128 MW DFB gasification plant

Parameter	Unit	Value
Capital expenditures (CAPEX)		
Investment cost	€	76 195 250.49
Operating expenses (OPEX)		
Direct production costs		
Wood chip costs (per dry ton)	€/t	100
Fresh bed material (olivine)	€/t	156
Limestone/burnt limestone	€/t	30
Nitrogen	$€/Nm^3$	0.09
Scrubber solvent (RME)	€/t	1 100
Fresh water	€/t	2.17
Number of employees	pers.	44
Cost of one employee per year	€/a	70 000
Electricity costs	€/kWh	0.12
Costs for ash disposal	€/t	90
Maintenance	% (CAPEX)/a	2.0
Fixed costs		
Insurance and administration	% (CAPEX)/a	2.5
Plant overhead	% (CAPEX)/a	0.75

Table A- 14. Cost rates for economic calculations of a 128 MW plant

YEAR (n)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
CAPEX	76.20																				
OPEX		34.08	34.77	35.46	36.17	36.89	37.63	38.38	39.15	39.94	40.73	41.55	42.38	43.23	44.09	44.97	45.87	46.79	47.73	48.68	49.65
Fuel cost (wood chips)		19.93	20.33	20.73	21.15	21.57	22.00	22.44	22.89	23.65	23.81	24.29	24.78	25.27	25.78	26.29	26.82	27.36	27.90	28.46	29.03
Operating supplies		3.86	3.94	4.02	4.10	4.18	4.27	4.35	4.44	4.53	4.62	4.71	4.80	4.90	5.00	5.10	5.20	5.30	5.41	5.52	5.63
Labour costs		3.14	3.20	3.27	3.33	3.40	3.47	3.54	3.61	3.68	3.75	3.83	3.91	3.98	4.06	4.15	4.23	4.31	4.40	4.49	4.58
Utility costs		3.07	3.13	3.20	3.26	3.33	3.39	3.46	3.53	3.60	3.67	3.75	3.82	3.90	3.97	4.05	4.13	4.22	4.30	4.39	4.48
Maintenance		1.55	1.59	1.62	1.65	1.68	1.72	1.75	1.79	1.82	1.86	1.89	1.93	1.97	2.01	2.05	2.09	2.13	2.18	2.22	2.26
Insurance & admin		1.94	1.98	2.02	2.06	2.10	2.15	2.19	2.23	2.28	2.32	2.37	2.42	2.46	2.51	2.56	2.61	2.67	2.72	2.78	2.83
Plant overhead		0.58	0.59	0.61	0.62	0.63	0.64	0.66	0.67	0.68	0.70	0.71	0.72	0.74	0.75	0.77	0.78	0.80	0.82	0.83	0.85
Accumulated OPEX		31.56	61.37	89.52	116.10	141.21	164.93	187.32	208.48	228.45	247.32	265.14	281.97	297.86	312.88	327.05	340.44	353.09	365.03	376.31	386.97

Table A- 15. Cost flows of a 128 MW gasification plant along its expected lifetime (Millions €)