unibz junior researcher

# Use of Biomass in South Tyrol

## Energy Conversion and Distribution to the End User

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bu,press
bozen
bolzano
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Cover design: doc.bz / bu,press
Printer: Druckstudio Leo, Frangart/o


www.unibz.it/universitypress

ISBN 978-88-6046-087-5 (pdf/print)

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# The *unibz junior researcher* series

Especially at a time when universities are increasingly expected to produce tangible results, it is clear that one of their main tasks is to promote the work of their young scientists. The decision by the Free University of Bozen-Bolzano to publish the new series *unibz junior researcher,* enabling PhD students to present their research to a wider readership, is designed not so much to promote the work of individual scholars but rather to foster a common university culture. The idea is to publish studies which are exemplary, not just within the standards of the individual discipline, but also because of the wider significance of the issues they deal with and the way they are dealt with.

Due to the ever-increasing pressure in the academic world to publish papers in internationally-renowned journals, there is a danger that a lot of research reaches out to only a narrow field of specialists. But we maintain that it is precisely the role of the university to ensure that knowledge is transmitted to a wider audience, that discussion between different areas of research is stimulated and that a dialogue with a wider readership beyond the university is established. This promotes a public sphere that is better informed and more competent in debating. The studies which are published in the *unibz junior researcher* series will serve future PhD students as reference points for participation in such a culture of research. Engaging in research in isolation from the general public simply ignores the requirements of our times: Universities need to open up and academics need to learn to transmit their knowledge at various levels—all the more so considering the increasing complexity of research topics and the higher demands of research methods. This is the only way to justify public investment in universities, only in this way can universities fulfil their public mandate and contribute to a competent dialogue over impending societal issues.

The first issues of this series convincingly fulfil these criteria. They present PhD research projects judged as excellent by the examining commissions. The Free University of Bozen-Bolzano’s excellent research environment has contributed greatly to these results: The authors were able to approach their research topics in a measured way, under the close supervision of members of the respective PhD advisory commission, who were able to offer a range of perspectives on the relevant research methodology. Furthermore, the university's generous bursary scheme gives PhD students the opportunity to spend periods of study and research abroad, and to thereby gain experience of how other universities conduct research on related topics. They could also present their research methodology and preliminary findings at international congresses – a valuable experience in improving communicative competences. Finally, the regional setting of our university gave them access to a rich variety of empirical data which shows that South Tyrol, while being an alpine region, is by no means represents “periphery”. Instead, the research projects demonstrate that regional study objects can have international relevance because the condensed dimensions allow processes to be brought into focus more readily and changes to be monitored more precisely. The region of South Tyrol is indeed affected by global change, as witnessed for instance in the environmental field, where its sensitive alpine landscape is particularly susceptible to harmful developments. So it is possible to see South Tyrol as a sort of laboratory where we can register warning signs earlier and experiment with appropriate counter measures. A greater density of transformation processes can equally be seen in the social field. As a traditional border area, South Tyrol has always been at the crossroads of different cultures. Its historical experience with multilingualism, with different political and legal frameworks and with the cultural interaction of very different reference points for identity, makes for a background against which some of today’s major social challenges such as migration or the globalised economy, can be analysed and interpreted.

These chances for new socially-relevant scientific insights find expression in the PhD studies selected for this series. The university authorities hope that these publications will allow the wider public to gain insights into the quality of the work of these young researchers, and to recognize that the fruits of the financial investment in this university have direct beneficial effects on the local society. I congratulate the authors chosen for this series and wish them every success in their scientific career hoping they will remain intellectually and emotionally linked to their university and to South Tyrol.

Walter Lorenz
Rector – Free University of Bozen-Bolzano

# Acknowledgements

This research work was financially supported by the Autonomous Province of Bolzano in the main framework of the project "Sustainable use of biomass in South Tyrol: from production to technology". I thank Prof. Zerbe, who coordinated the project.
A special thanks goes to my supervisors Prof. Gasparella, Prof. Baratieri and Prof. Dasappa for teaching me the secrets of research and making me feel at home, both in Italy and in India. I am also grateful to Prof. Righetto, Prof. Zaffani and Prof. Longo, who lit my way from the middle school up to university.
I would like to thank all the friends who accompany me on my journey, in particular, the biomass guys, the buildings guys, the PhD guys and the CGPL guys.
Last but not least, my gratitude goes to my family, and to my wife Stefy in particular, for her constant support and for her enormous commitment for our new family.

# Preface

This book is the result of a PhD research, based on both modelling and experimental studies in the area of renewable energy. The research was conducted in Italy at the Free University of Bolzano and complemented with research at the Indian Institute of Science in Bangalore (India). This collaboration was established through the SAHYOG project, which aims at strengthening the network between Europe and India. In addition, other cooperation initiatives with national and international scientific partners have been established, such as with the University of Florence, the University of Trento, the University of Innsbruck, and with companies such as Bioenergy 2020+, Bioenergie Renon, EcoResearch, Re-Cord, SIBE and Tis Innovation Park. This research was financially supported by the Autonomous Province of Bozen-Bolzano within the main framework of the project "Sustainable use of biomass in South Tyrol: from production to technology" coordinated by Stefan Zerbe.

Renewable energy and energy efficiency is at the top of the political agenda both in Europe and worldwide. The European Union has issued various directives for the promotion of the use of renewable energy and the energy efficiency of both buildings and energy conversion systems. All these measures are considered viable options to reduce both greenhouse gas emissions as well as the dependence on imported fossil fuels. Moreover, when referring to the efficiency of a system, it is imperative not to refer only to the nominal efficiency of each single component but to the global efficiency of the entire system. This aspect is a key point to develop efficient systems, and it requires tools and skills to identify the optimal solution for a specific application.

With this volume the author aims at providing an insight into the above-mentioned issues by presenting an integrated assessment of the performance of energy conversion systems based on lignocellulosic biomass. On the one hand, it focuses on the conversion of biomass into energy, on the other hand, on the distribution and matching of the generated heat to the demand, i.e. the final uses, considering the respective efficiencies. These two elements are complementary and both their efficiencies contribute to the overall performance of the whole system.

One of the challenges of this topic involves the improvement of biomass-to-energy systems identifying possible upgrading measures and—in particular for the gasification-based plants—the enhancement of the operational reliability. Nonetheless, the subsidy mechanism for the promotion of renewable energy should be revised since it strongly favours the profitability of electricity production compared to heat production. In this perspective, the first part of the work deals with the detailed monitoring of two commercially available plants—one based on combustion and one on gasification—in order to define the current energy performance achievable in practical applications. The experimentation has been supplemented with the modelling of the main components in order to identify potential improvements. Since the operational reliability of gasification systems is threatened by the presence of tar compounds in the producer gas, a base study on tar characterisation was carried out during the research at the Indian Institute of Science in Bangalore. In fact, tar is considered the main barrier for the development of gasification technology. However, the research has shown that technology packages do exist to meet the demand.

Another challenge that needs to be met is the prediction of the impact of building refurbishment on the energy performance of the systems. Nowadays, both subsidies and minimum requirements are set by the governments to promote improvements in building energy performance. This rapidly changes the building scenario and it also requires a constant update of the energy systems to be efficient in real operation. Furthermore, when considering the installation of small scale combined heat and power (CHP) systems based on biomass, there is a limit on the minimum scale available in the market. In this perspective, the CHP installation is rarely suitable for a single building and the use of district heating (DH) networks is required to justify this application. Nonetheless, the DH network should not compromise the heat distribution efficiency that would affect the global efficiency of the system. In this framework, the second part of this work deals with the energy and economic assessment of the distribution and use of the heat generated by a plant. A numerical model, developed for the purpose, enables the simulation of both centralised users (building, flat) and distributed users (district heating). The impact on the whole system of both the refurbishment of the buildings and the potential improvement of the DH network has been investigated exploiting the prediction capabilities of the developed model.

The main results of this research highlight that, in most of the CHP plants, a considerable share of the heat is discharged into the environment because the subsidisation mechanism makes heat generation less profitable than electricity. Moreover, gasification systems have shown higher electrical efficiency than Organic Rankine Cycle (ORC) systems, however the latter could increase the performance if operated with a heat sink at low temperature. Therefore, the conversion of the current district heating networks to low temperature systems could considerably improve the heat distribution efficiency and, consequently, the efficiency of the whole system. The future refurbishment of buildings will be a great challenge for the DH networks, which will need to consider improvement measures, such as low temperature distribution and CHP system installation, to be competitive against alternative solutions.

This study is undoubtedly a tangible contribution to spread the know-how acquired from an extensive investigation into the sustainable use of lignocellulosic biomass and it paves the way for the implementation of efficient energy systems from a global perspective.

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# 1. Introduction and literature review

Biomass, wood in particular, is the oldest source of energy used by mankind. It still represents roughly 9 % of the world's primary energy consumption and 65 % of the world's renewable primary energy consumption (Lauri et al. 2014). Nowadays, this renewable energy resource is considered as an option to reduce both greenhouse gas emissions and the dependence on imported fossil fuels (The European Parliament and the Council of the European Union 2009). The process involving growth and combustion of biomass is carbon neutral because $CO_2$, emitted during combustion, is sequestered by process of photosynthesis from the atmosphere during the growth of the plant. Furthermore, the emitted $CO_2$ is twenty times less active as greenhouse gas than methane which would be produced from the natural decomposition of biomass (Demirbas 2001). Nevertheless, biomass usually needs pre-processing to become a suitable fuel and has to be transported to the energy generation plant; all these steps negatively impact on the greenhouse gas emissions.

Cogeneration is defined as the combined production of heat and power and allows a primary energy saving compared to the separate production of the two energy streams. With regard to the limited availability of renewable resources, among them especially biomass resources, efficiency in terms of consumption and utilization becomes vital. Heat is the energy stream with lower quality and it is generated in most of the conversion processes. Thermodynamically, the lower the exit temperature of the flue gases from the process plant, the higher the efficiency of the polygeneration system. For this reason, a polygeneration system is suitable to be coupled to a DH system which enables exploiting heat at quite low temperature (i.e. < 100 °C). Furthermore, future implementation of the fourth generation DH (i.e. return/supply temperatures at 30/70 °C) will allow exploiting heat share that until now has usually been discharged into the environment .

The first part of this chapter deals with the main technologies for cogeneration based on biomass. CHP generation technologies are then compared; combustion-based systems (i.e. steam turbine, organic Rankine cycle and Stirling engine) and gasification-based systems (i.e. internal combustion engine and biomass integrated gasification combined cycle). Capacity (power level), efficiency, operation flexibility and field experience at the current state of the art have been reported for each technology.

The second part of the chapter deals with the implementation of biomass technologies in DH systems. A brief introduction about the architecture of DH systems has been complemented by an analysis of the potential benefits deriving from the use of biomass. The CHP systems, presented in the previous section, are analysed focusing on their application to DH networks. The discussion has been extended including the determination of the cost-optimal size, the role of thermal energy storage and the impact of biomass transportation on the energy chain. Moreover, the influence of extensive refurbishment on the buildings connected to DH grids is extensively analysed. The possible solutions that allow the DH systems to be competitive in the future are presented in accordance with the scientific literature. Finally, the smart grid concept has been introduced and its applicability to thermal networks is discussed highlighting the potential benefits for the thermal sector as well as for the entire energy system.

## 1.1 Biomass for CHP generation

In the past few years, there has been a great interest in renewable energy sources. On the one hand, energy demand has been constantly growing, strictly correlated to the increase of global population and to expansion of developing countries' economies (Nelson 2011). This aspect, combined with the depletion of fossil fuels, has in the last few years caused a considerable increase in the prices for fossil fuel energy on the global energy markets. On the other hand, industrialized societies are currently becoming more aware of the impacts of fossil fuel utilization on the environment and on human health, making the search for environmentally and socially acceptable alternatives increasingly important (Kaltschmitt et al. 2007). If compared to other renewable sources (e.g., wind or solar energy) biomass has the main advantage that, if well managed, it can ensure a constant supply of energy, its availability not being dependent on climatic conditions in the short and medium term. This is an essential aspect in the design of an integrated exploitation of different renewable sources.

Sustainable biomass feedstock should have no impact on the food chain. In particular, lignocellulosics biomass, as woody biomass, energy crops—that are cultivated for the purpose of energy generation—or even algae are some examples of them. In Fig. 1.1 a rough distinction between crops, residues, by-products and waste has been made to consider a wide spectrum of feedstock for polygeneration. After the harvesting or collection, biomass has to be subjected to different pre-treatments, which usually have the common purpose of energy densification. The biomass chain is then characterized by transportation and storage to the first stage of conversion, i.e. thermo-, physical- and bio-chemical. Intermediate fuels and chemicals (solid, liquid and gaseous) can be obtained starting from the original feedstock, which can be valorised through combustion in boilers and, prime movers or fuel cell stacks for heat and electricity generation both for stationary and automotive applications.

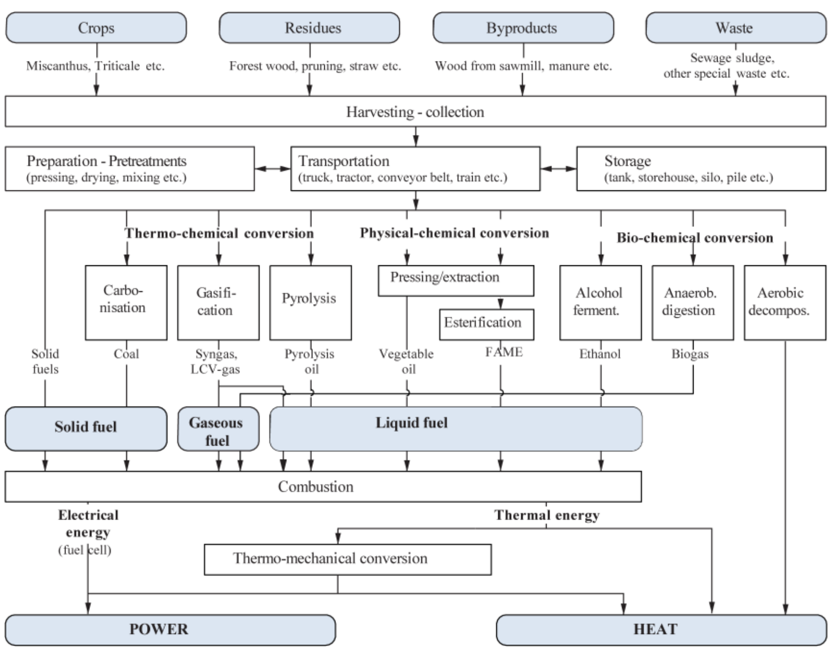


Fig. 1.1 – Schematic representation of different biomass-to-energy pathways (rounded boxes: energy carriers; boxes: conversion processes); Kaltschmitt et al. (2007).

The main technologies developed for converting biomass into thermal energy and electricity usually include a primary conversion stage that produces hot water, steam, gaseous or liquid products and a secondary conversion stage that transforms these intermediate products to heat and power. In the present section, the thermochemical processes are considered in detail and the different technologies are presented according to the following classification:

- combustion-based technologies producing steam or hot water, coupled to steam engines, steam turbines, Organic Rankine Cycle (ORC) and Stirling engines;
- gasification-based technologies producing gaseous fuels, coupled to internal combustion engines (ICEs), gas turbines (GTs), fuel cell stacks and micro-turbines.

### 1.1.1 Combustion-based technologies

The direct combustion of lignocellulosic biomass is a process mostly applied for the pure generation of heat by means of boilers. The boilers can be based on fixed bed combustion, fluidized bed combustion and pulverized bed combustion (Saidur et al. 2011). The fixed bed combustion boilers include grate furnaces, for large scale systems up to 20 $MW_{th}$, and underfeed stokers, for small-medium scale systems up to 6 $MW_{th}$. The former are suitable for biomass with high water content, high ash content, and irregular particle size since the grate allows a smooth transportation of the material and facilitates the drying phase. The latter, due to a simpler fuel load system, requires water content smaller than 35 %, homogeneous material and small ash content. The fixed bed combustion boiler can reach combustion efficiency up to 90 % at nominal thermal output (Van Loo and Koppejan 2008). The fluidized bed combustion boilers are typically used for large scale applications, more than 30 $MW_{th}$. These boilers have high fuel flexibility due to a mixed suspension of fuel and solid bed material that promotes a complete combustion with a lower excess of air. Thanks to the homogeneous combustion and the low excess of air, the fluidized bed boilers can reach a combustion efficiency of 95 % and low NOx emissions (Saidur et al. 2011). The pulverized combustion bed boilers are mostly used for large scale applications.

The fuel, small dried particles such as wood powder, are transported by air, which is also used as primary air for combustion. Combustion is then completed with the addition of secondary air. Low excess of air is required for a complete combustion because the suspended fuel and the combustive air are perfectly mixed. This results in high combustion efficiency and low $NO_x$ emissions.

The direct combustion of lignocellulosic biomass can be coupled with different prime movers for cogeneration of heat and power. The most common prime movers consist of steam turbines, Organic Rankine Cycle generators and Stirling engines.

Steam turbines are typically used for applications with size in the range 0.5–500 $MW_{el}$. Turbines smaller than 0.5 $MW_{el}$ are available but they have a niche market (Van Loo and Koppejan 2008). This technology is based on a thermodynamic direct cycle (i.e. Rankine cycle) that allows converting heat into mechanical work using water as working fluid. In the specific case, a steam boiler based on biomass generates high-pressure steam that is converted into mechanical work by means of a turbine. The mechanical work usually drives a generator to produce electrical power. The steam, after its expansion, is condensed at constant pressure and the saturated liquid is pumped from low to high pressure. The water at high pressure enters the steam boiler and repeats the cycle. The steam turbines, used for CHP generation, can be classified into two main typologies: non-condensing (or back pressure) turbines and extraction turbines. Non-condensing turbines exhaust the entire flow of steam to provide heat to the DH network. The network temperature level at the condenser determines the condensing temperature; lower temperatures increase the capacity of the turbine to generate work. Extraction turbines have different steam extractions from intermediate portions of the turbine to satisfy the requirements of the DH grid. The steam extractions are designed depending on the required pressure/temperature of the DH network. The extraction turbine enables a higher steam flow to the turbine, generating additional electricity, during the periods of reduced thermal power. The steam turbines benefit from the usability of a wide variety of biomass (i.e. forest wood, sawmill by-product and agricultural residues) because the combustion of biomass and the production of steam occur in different sys-

tems. This technology has also some drawbacks. The steam boiler requires a super-heater to avoid liquid drops in the turbine that would erode the turbine blades. This is an obstacle for the scaling down of the system to a simplified design. Furthermore, the use of steam required qualified personnel to operate the plant (Duvia and Guercio 2009). The scaling-down of this technology below 30 $kW_{el}$ encounters some obstacles such as low electrical efficiency and high specific investment costs (Alanne et al. 2012).
The ORC generators are available for small-medium CHP applications, from 500 $kW_{el}$ up to 10 $MW_{el}$ (Duvia and Guercio 2009; Quoilin et al. 2013). The technology is based on the Rankine cycle, similar to a conventional steam turbine, but it operates with a high molecular mass organic fluid. The operation with this fluid is particularly suitable for low temperature heat sources. Other benefits are related to the use of the organic fluid. The coupled boiler does not require a super-heater due to the absence of liquid drops in the turbine. The organic fluid is not corrosive and thermal oil is used as a thermal medium, therefore offering high reliability and requiring little maintenance.. Furthermore, no licensed operators are necessary for the maintenance. The turbine has a large diameter, due to the large flow rate of the organic fluid, and low peripheral speed enabling the direct drive of the electrical generator without reduction gear. The ORC generators can reach an electrical efficiency up to 20 % at nominal load, but the efficiency is satisfactory also at partial load (Bini and Manciana 1996; Dong, Liu and Riffat 2009; Duvia and Guercio 2009). This technology is well established and commercially available from various manufacturers (Rentizelas et al. 2009). Nevertheless, ORC generators are considered less prominent for micro-scale application due to high specific investment cost and limited electrical efficiency (Dong et al. 2009; Quoilin et al. 2013).
The Stirling engine is a reciprocated engine externally heated. In the specific case, it is an external combustion engine because the heat is provided by means of biomass combustion. The cycle is closed in a loop with a gaseous working fluid (i.e. usually air, hydrogen or helium) that is compressed in the cold portion and expanded in the hot portion. These cyclic compressions and expansions convert heat into mechanical work. The reciprocating motion is then converted to circular motion by means of a crankshaft that turns a gen-