Freie Universität Bozen
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GAST project

"Gasification Experiences in South Tyrol: energy and environmental assessment"

Final report

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Part I

Executive summary

The gasification technology represents a viable and promising route to convert lignocellulosic biomass - an important resource for South Tyrol - into energy. Thanks to the high feed-in tariff and incentives for electricity from renewable sources, several biomass-based gasification plants have been built up and authorized in the last years in South Tyrol.
The main aim of GAST project is the assessment of small scale gasification plants under real operation, providing an overview of the actual state-of-the-art of this technology in South Tyrol. The outcomes of the GAST project provide a unique overview of the local situation, in terms of efficiency of the plants, effectiveness of the adopted solutions, characteristics of the products and by-products.
This research project has a significant impact on the scientific field, as confirmed by the interest arose in the international scientific conferences on which the project has been presented. In fact, even if biomass gasification is being studied since decades, only in the recent time reliable small-scale technologies entered the market. The technologies investigated in this project represent the first examples of reliable solutions in the market and such kind of comparative analysis has been never performed before.
The monitoring of mass and energy fluxes on real scale gasification systems allowed the assessment of the actual performance and the identification of possible efficiency improvement and reduction of maintenance costs.
Furthermore, the byproducts characterization (i.e., tar and char) enabled to implement and put into practice a reference methodology developed for the purpose of such analysis. The obtained results contribute to enrich the scientific literature and, together with the results of other similar studies, to provide useful information for further developments of the current sampling and analysis methodologies.
In addition, the monitoring activity supported the owners of the investigated plants in the management, with awareness on several aspects such as tar issue and comprehensive efficiency of the system. The experience of the manager, supported by measurements of the system, can considerably increase the know-how for an optimal operation of gasification systems.

A short description of the performed activities and of the main results is here reported, while further details can be found in the attached comprehensive report.
A detailed screening of small scale biomass-gasification-based CHP plants located in South Tyrol has been carried out in collaboration with TIS Innovation Park. The major characteristics of each plant have been collected; plant localization, gasification technology, type of gasifier, biomass used as feedstock and its characteristics, feeding configuration (batch or continuous), gasifier agent, gas cleaning and conditioning system and type of engine for electricity generation.
According to the survey, a total of 70 projects concerning small scale biomass gasification have been presented since 2009; among them, 36 plants have been authorized and are actually in operation (June 2015).
Three representative plants have been selected for the monitoring campaign, considering the designs of the gasifiers, the types of biomass used, the market share and the different engine technologies. In addition, another representative technology has been selected, on which the characterization of the products and by-products has been performed but not the energy and mass balances. Here after, the different technologies will be named from A to D.
The monitoring procedure has been designed in accordance with the “Raccomandazione CTI 13”, a draft guideline published by the “Comitato Termotecnico Italiano” for plants which produce and utilize producer gas obtained by gasification of ligno-cellulosic biomass.
The measurement of the mass and energy fluxes has been done on a 5-hour continuous operation basis. Therefore, it has been possible to characterize and quantify all the mass and

energy fluxes of the different investigated plants. In addition, feedstock and gasification products and by-products have been characterized as follow:

- feedstock: calorific value, composition, ash and moisture content;
- producer gas: composition, tar content;
- char: calorific value, composition, ash content, phytotoxicity levels.

This allowed evaluating the actual performance of the plants in operation. The three investigated technologies showed similar overall efficiency (electric and thermal efficiency summed together), slightly lower than 70 %. However, technology B enables a higher electrical efficiency (25.3 %) compared to technology A (18.3 %) and C (16.8 %). This is due to the fact that technology B generates a producer gas with higher heating value thanks to a more refined input feedstock to the gasifier, i.e. pellets. In addition, the engine is a dual-fuel therefore colza oil prompts the combustion reactions inside the cylinder and contribute to further increase the heating value of the fuel.

According to the energy balances, the gasifier thermal loss is the main loss for all the three investigated technologies. An exergy analysis (i.e., a balance in terms of exergy, which is an indicator of the “quality” of the energy streams) shows that the contribution of this loss is particularly enhanced by the high temperature of the discharged heat. A proper insulation of the reactor should be implemented to reduce this loss. Moreover, the exergy loss in the CHP engine is also a considerable share. Heat available at high temperature could be used for industrial applications which require high temperature or in an organic Rankine cycle to produce a further share of electricity. The utilization of heat at high temperature to satisfy heat demand at low temperature should be avoided from an exergetic point of view.

Additional interesting results are related to the by-products characterization. Phytotoxicity tests have been performed on char samples according to UNI 10780. For the germination test, cress seeds (Lepidium sativum L.) have been used. For each tested char, the germination index has been calculated. The germination index (GI) is an indicator of phytotoxicity in soils and takes into account the number of germinated seeds and the mean root length of seedlings occurring during test conditions and during reference control conditions. During the tests, the germination of cress seeds was very low, seedlings had necrotic brownish root tips indicating high char toxicity. The char of technology C lead to the lowest germination index, followed by the chars of technology A, B and D. Yet GI of < 20 % are very low and do not suggest that these extraction ratios might be used as soil amendment and do certainly not increase soil fertility nor have plant growth promoting effects. A correlation between GI and ash content can be observed, a higher amount of ash content leads to a lower germination index. This can be explained by the fact that a higher amount of ash corresponds to a lower carbon fraction, which usually promotes the germination. At the same time, heavy metals and salts in the ashes can contribute to create osmotic stress.

As far as the tar analysis is concerned, for all the technologies the compound with the highest concentration is naphthalene that is the one with the lowest molecular weight (128.17 g/mol), among the detected tar. Naphthalene concentration is 64 %, 53 %, 29 % and 58 % for technology A, B, C and D, respectively. The lighter tars, up to fluoranthene (202.26 g/mol), account for 99 % of the total ones if we consider technologies A, B and D. As far as concern technology C, apart for naphthalene, there are no dominant compounds and light and heavy compounds have comparable concentration. Lighter tars are less detrimental that the heavier ones, therefore technologies A and B have a producer gas that is more suitable for use in prime movers. High contents of tar can be compatible with the engine operation but requiring higher maintenance.

Part II

Technical report

Introduction

Biomass is one of the most interesting and promising renewable resources for energy production. If compared to other renewable sources (e.g., wind or solar energy) biomass has the main advantage that, if well managed, can ensure a constant supply of energy, being its availability not dependent on climatic conditions on the short and medium term. This is an essential aspect in the design of an integrated exploitation model of different renewable sources.

On the one hand, biomass can be considered as a potential substitute of traditional fossil fuels and, on the other hand, the biomass availability in alpine regions (e.g., forestry wood, agricultural tree pruning residues) makes the development of those technologies strategically important for the future supply, generation and distribution of energy in South Tyrol.

Biomass gasification in South Tyrol

The Province of Bolzano there are experiences of cogeneration (combined heat and power generation, CHP) plants for the generation of heat and electricity through small scale biomass gasifiers ($<50kW_{el}$). In the last years, several entrepreneurs have decided to invest in the gasification conversion technology, even if it is not completely consolidated for the market. The plant owners are both private subjects (i.e., local farmers) and companies (i.e., sawmill) that have access to large amounts of low cost local woody biomass. The situation is quite complex and variegated. On the one hand, biomass – if well managed – can represent a keystone for the energy generation in the Province of Bolzano. The management of the forests (e.g. removal of pruning, dead branches, small plants, plants attacked by pathogens, etc.) can be transformed from a cost to a resource, giving work to local labor and making the forests even more attractive from a touristic point of view. On the other hand, at the moment, the potential of the local forests is not well suited and the collected biomass is not enough for the working of the district heating plants, as it has been highlighted by an awareness campaign of the Südtiroler Bauernbund in collaboration with the Consorzio Biomassa Alto Adige.

Small scale biomass plants for cogeneration

Gasification process is the thermal conversion of a solid fuel into a combustible gas, mainly consisting of carbon monoxide, carbon dioxide, hydrogen, methane, water, nitrogen. It contains also contaminants such as sulfur and nitrogen compounds, particles and tars (the organic fraction of condensable products). A small part of the initial solid feedstock remains as char and ash.

The gasifiers classification can be made with different criteria [1]: according to the gasification agent (air-blown gasifiers, oxygen gasifiers and steam gasifiers), according to the heat for gasification (autothermal or direct gasifiers, where heat is provided by partial combustion of the biomass and allothermal or indirect gasifiers, where heat is supplied from an external source through heat exchangers or indirect processes, i.e. separation of gasification and combustion zone), according to the process pressure (atmospheric and pressurized) and according to the reactor design (updraft, downdraft or crossdraft fixed bed, bubbling or circulating fluidized bed, entrained flow and twin-bed).

After proper cleaning and conditioning, the gas can be used to produce heat and power in CHP systems. Suitable technologies for this purpose are boilers, internal combustion engines or gas turbines. For low power plants (50 kW to 1-10 MW) with internal combustion engines, a gasification-based CHP system can potentially have higher electricity efficiency than a direct combustion-based CHP system [2]. For higher power (1-10 MW to 50-100 MW) combustion systems with steam turbines are more efficient than gasification systems. For very large-scale power plants (50-100 MW) gasification can reach exceptionally high levels of efficiency through a combined gas turbine-steam turbine system [3].

There is an increasing interest in CHP plants with small/pilot scale biomass gasifiers. On the one hand there is a clear economic interest; according to the Italian Law 23/07/2009, n.99, operators can obtain incentives for the selling of electricity produced by biomass and for the direct use of heat. On the other hand, there is a scientific interest on the evaluation of the energetic efficiency, environmental performance, reliability and optimization of this technology. The selection and analysis of a representative set (referring also to different types of technology) of small scale gasification-based CHP plants located in South Tyrol can respond to this type of scientific interest but also be supportive to the authorization procedures by the public administration. In this context, indeed, it is important to provide the local decision-makers with the tools to develop suitable and appropriate strategies for the development of this sector, giving an overview of the performance of the local plants and identifying possible ways of improvement. These are the main reasons which drove the implementation of the GAST project.

Utilization of gasification by-products

To further increase the sustainability of energy production from biomass, the residuals (e.g. char) might be applied to agricultural soils. For instance, char application to soil is also considered to improve several physical and chemical soil characteristics fundamental for preserving soil quality. Soil degradation is becoming in fact a more and more relevant issue and has negative consequences on both natural ecosystems and agricultural productivity [4]. Char application to soils might thereby enhance its water holding capacity, build up organic matter, enhance nutrient cycling, lower bulk density, counteract soil acidity and reduce leaching of both pesticides and nutrients to surface and groundwater [5]. Laird (2008) defined such an integrated biomass-bioenergy system as the charcoal vision: gasification of biomass produces besides syngas hydrocarbon liquids (oils, bio-oils or tar) which might displace fossil fuels and char which might be returned to soil enhancing soil and water quality, increase agricultural productivity and strengthen local rural economics. On a larger global scale, this integrated biomass-energy system might even mitigate the effects of climate change and give a substantial contribution to the energy supply. Nevertheless, several issues regarding the compatibility of gasification char with agricultural soil are nowadays under investigation and need further critical research.

1. The GAST project

GAST stands for "GAsification experiences in South Tyrol: energy and environmental assessment". In the peculiar context of South Tyrol, characterized by a widespread diffusion of small scale CHP pants based on biomass gasification, this project has given the opportunity to monitor and assess some representative gasification units. Due to the lack of a common international standard, the monitoring campaign is following the Italian test methodology proposed by the "Raccomandazione CTI 13" document, i.e. a guideline about the contracting and commissioning of gasification systems published by the Italian Thermotechnical Committee Energy & Environment (CTI).

1.1. Aims

Aim of the GAST project is to perform a survey of the actual spreading and development in South Tyrol of small scale biomass-gasification-based CHP plant, selecting some representative plant and monitoring them. The expected result is the understanding the state of the art of the gasification technology in South Tyrol, to give an overview of the performances of the local plants and to identify possible ways of improvement.
The present project is aimed to fulfill the needs of the local territory. In fact, in the last years several South Tyrolean entrepreneurs have decided to invest in the gasification conversion technology, even if it is still not consolidated for the market.
The answer to this need will help to reinforce previous results obtained from previous research projects on biomass gasification. The present project is in fact complementary to them and, in particular, the activities carried out on full-scale plants will provide useful information for the comparison and improvement of the results obtained through the modeling approach used in a already completed project ("Sustainable use of biomass in South Tyrol: from production to technology"), also funded by the Province of Bolzano in 2009.
A further focus of the present project is the valorization of the process by-products in order to close the gasification energy production chain in a sustainable way.
To our knowledge, this kind of survey is, at the moment, unique in Italy. In addition, it can support the local public administration, providing useful tools for the authorization procedures of small biomass plants, which are becoming more and more diffused in South Tyrol.

1.2. Work packages structure

In order to achieve all the expected results, the project has been clustered in four major work packages:

- WP1: Analysis of the local situation and selection of the plant to be monitored
- WP2: Plant monitoring
- WP3: Energy balance and optimization of the plants
- WP4: Characterization and management of the reaction products and byproducts.

In addition, a specific work package (WP5) has been devoted to the management of the project, including the awareness and the dissemination of the achieved results.
The structure of the project and the interactions between the different work packages are outlined in Figure 1.

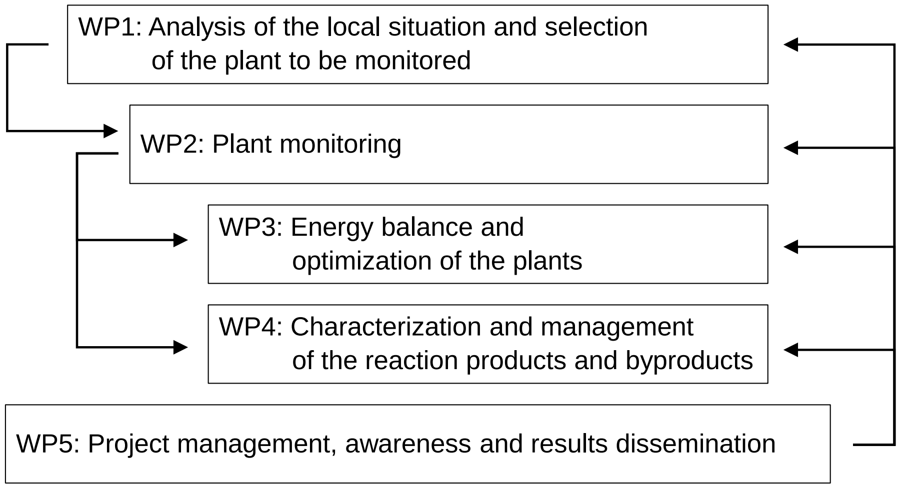

Figure 1: Structure of the GAST project and interactions between the different work-packages.

1.3. Research team members

The GAST project has been coordinated by the Free University of Bozen-Bolzano (FUB). Through the funding from the Autonomous province of South Tyrol, the GAST project has been carried out with the cooperation of local partners, Eco-research and TIS-Innovation Park, and national scientific partners, i.e. RE-CORD (Firenze).

Free University of Bozen-Bolzano (FUB)

The Technical Physics Research Group, and in particular the branch of the group dealing with bioenergy, led the GAST project.
The research group of Technical Physics at the Free University of Bolzano is active since 2009 on the topics of thermochemical conversion process from biomass. The activities and the aims of the group are manifold. At the process scale, the group has developed both numerical models and experimental methods to evaluate the energy performance and environmental impacts of innovative biomass-to-energy pathways. At the plant scale, the research has been focused on the system performance assessment, considering the energy generation stage, but also taking into account the relation between the generator and the distribution/utilization systems.

Eco-Research

Eco-Research is an analytical laboratory with a solid experience in environmental research. The team of chemists, biologists, laboratory technicians and engineers is specialized in the detection and determination of environmental pollutants.
Eco-Research has been involved in the monitoring activity, in particular in the analysis of the collected tar samples. Their expertise in environmental measurement has been suited also for the assessment of the pollutants emissions and the characterization of tar content in the collected char.

TIS innovation park

TIS provides an area for economic development and stability through innovation, cooperation and transfer of technologies, it is a center for those pioneering innovation and links the economy with science.

It serves as a gateway to the latest technological trends, as an institution for translating academic and international knowledge into economic exploitation and concrete applications, and promotes innovative projects within small and medium-sized companies.
The Energy & Environment Area of the TIS innovation park is responsible for renewable energy and energy efficiency. Technical expertise, positioning within the provincial park for innovation and the network of companies it works with, make this area a benchmark for the territory.
TIS innovation park has been involved in the analysis of plant distribution in South Tyrol and in the selection of the representative plants to be monitored, setting the basis for the fruitful professional relationship between plant owners and university researchers.

RE-CORD

The RE-CORD Consortium develops scientific and technological research in the field of Renewable Energies and in particular Bioenergy. RE-CORD is a no-profit independent research body established in 2010, which merges competences and resources in the field of basic and applied research, engineering, and sustainable land planning and development.
Funding members of RE-CORD are the University of Florence (through the Interdepartmental Research Center for Alternative Energy and Renewable - CREAR, and the Azienda Agricola Montepaldi Srl), Pianvallico SpA, and Spike Renewables Ltd.
RE-CORD has been involved in the monitoring activity of the plants, in particular in the tar sampling and analysis and in the characterization of the producer gas. In this way, it has been possible to perform parallel sampling from different institutions applying similar methodologies (i.e., Round Robin tests), enhancing the reliability of the obtained results.

2. Census of the small scale gasification plants in South Tyrol

A detailed screening of small scale biomass-gasification-based CHP plants located in South Tyrol has been carried out in collaboration with TIS Innovation Park. The main characteristics of each plant have been collected; plant localization, gasification technology, type of gasifier, biomass used as feedstock and its characteristics, feeding configuration (batch or continuous), gasifier agent, gas cleaning and conditioning system and type of engine for the electricity production.

According to the survey, a total of 70 projects concerning small scale biomass gasification have been presented since 2009. Among these, 36 plants have been authorized and are presently in operation (June 2015).

It is worth noticing how a new market sector has grown in South Tyrol since 2008. The number of presented projects has gradually increased in the years between 2008 and 2012 (Figure 2), with a peak of 30 new projects in the year 2012, surely caused by the adoption of the Italian law for the promotion of renewable energies sources other than photovoltaic technologies, named “Decreto Ministeriale 6 luglio 2012”. After that, this number has decreased gradually in the years from 2013 to 2015, due to the uncertainty of the incentives system. From the same Figure, it can be also observed that, even if the interest for this technology grew up since the year 2008, the first plants were authorized only in 2012. This demonstrates that almost 5 years were necessary to reach the minimum requirements to obtain the authorization by the Air and Noise Office of the Province of Bolzano. The number of authorized plants is more constant through the years, from 2012 to 2014 (around 10 to 13 per year), reaching the actual cumulated total number of 36 plants. The data for 2015 are updated to the end of May. It must be noticed that just 50% of the presented projects have been realized and authorized. Often the detected problems are connected with pollutants emission exceeding the legislative limits. This shows that the technology is still on an initial state and cannot always guarantee a high degree of reliability, even if, actually, an increasingly number of companies have products that are ready for the market.

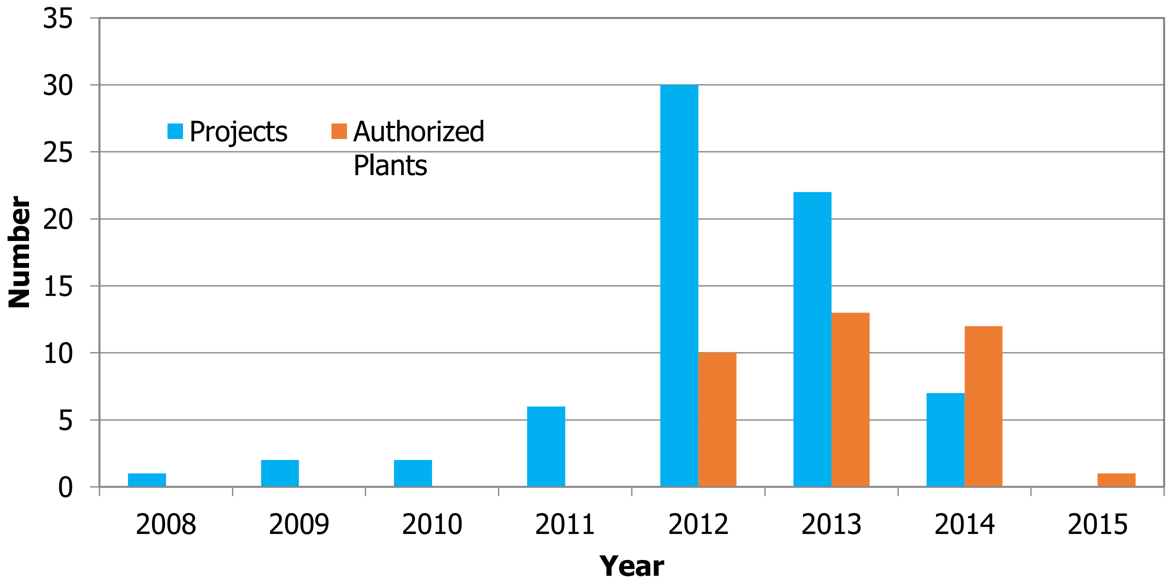

Figure 2: Presented projects and authorized gasification plants in the Autonomous Province of South Tyrol in the years from 2008 to 2015.

An estimation of the most important figures of the diffusion of small scale biomass gasification plants has been performed.
From an economic perspective, it has been evaluated that:

- approximately 35.5 M€ were invested for the plants construction;
- 6.5 M€/year is the average cost for the 53 000 tons of biomass used for supplying these plants.

As far as the environmental aspects are concerned, it can be said that:

- the 36 plants can produce 53 GWh/year of electric energy;
- they can also produce 103 GWh/year of thermic energy;
- this corresponds to 18.800 toe/year of avoided fossil fuels consumptions;
- this also corresponds to 78.000 ton/year of avoided CO_2 emissions;

Considering both environmental and economic aspects:

- an amount of about 2 600 ton/year of char are disposed off as a waste, with a cost of approximately 373 k€; there is therefore a considerable interest in finding alternatives for the valorization of this by-product.

Finally, it is worth pointing out that South Tyrol has seen the growth of an interesting new market in the last 7 years, with a significant amount of money involved in its satellite activities (biomass production and handling, gasification plants' construction, designing & engineering, etc.). The peculiar characteristic of the area is that a high number of different technologies are installed in a small territory, offering a unique opportunity for a comparative analysis. For this reason, the present study has been of particular interest, allowing the monitoring and comparison of the different technological solutions.

2.1. Main technologies in the areas

The 36 authorized plants include 10 different technologies (plus one which is present but not authorized for issues related to the engine emissions), with electric power for the single modules ranging from 30 to 850 kW. The technologies differ from each other for the used biomass too. Most of them use wood chips of different qualities and dimensions, but there is also a technology supplied with wood pellets and another one supplied with wood logs. All the technologies have an automatic loading system, except one: the smallest gasifier produced by Hans Gräbner requires a manual loading of the wood logs. Table I reports the 11 different technologies, with the year of first authorization, the reactor type, the biomass type, the electric and the thermal power of each single module. As it can be seen, the variation in the size (i.e., output power) of the different technologies is high. The fixed bed reactor is the most used at these scales, but also fluidized bed reactors are applied on two different technologies.
A diffused application for this kind of cogeneration systems, especially for the smallest ones, is the electric and thermic energy supply of farms. South Tyrolean farms are perfect users for small scale gasification plants, since they often have woody biomass available and necessity of both electric and thermic energy.
Another diffused application for this kind of cogeneration systems is the operation in district heating plants besides the standard biomass boiler. In fact, during summertime the required thermal energy is much lower than during wintertime. For this reason, the district heating systems usually have a small secondary boiler to supply the summer thermic energy. In this case, for economic reasons, an interesting option is the installation of a cogeneration system

like a small scale gasifier, since the produced electrical energy receives state incentives or can in any case be sold to the national grid.
Figure 3 shows the geographical distribution of the authorized plants in the South Tyrolean territory. The widespread diffusion of small scale gasification plants in the local territory can be easily recognized.

Table I: Different gasification technologies present in South Tyrol and their characteristics.

Tecnology	First Authorization Year	Reactor type	Biomass type	Electric Power [kW / module]	Thermic Power [kW / module]
Burkhardt GmbH	2012	Fixed bed, updraft	Pellets & bio oil	180	270
Hans Gräbner	2014	Fixed bed, downdraft	Logs or chips G40-G70	30	60
Holzenergie Wegscheid GmbH	2013	Fixed bed, downdraft,	Chips G50-G100 or briquettes	140	270
Kuntschar Energieerzeugung GmbH	2014	Fixed bed, downdraft	Chips G30-G70	150	260
Pyrox GmbH	2013	Fixed bed, downdraft	Chips G50-G100	850	1060
Revogas GmbH	2015	Circulating fluidized bed	Chips G30-G50	500	1150
Spanner Re² GmbH	2012	Fixed bed, downdraft	Chips G30-G40	45	105
Syncraft Engineering GmbH	2012	Fluidized bed, 3 separate stages	Chips G30-G50	250	990
Urbas Maschinenfabrik GmbH	2014	Fixed bed, downdraft	Chips G50-G100	296	550
Xylogas & EAF	2014	Fixed bed, downdraft	Chips G40-G80	440	880
Agnion Technologies GmbH	Not authorized	Heatpipe reformer©	Chips or pellets	400	630

Figure 3: Authorized gasification plants' distribution in South Tyrol: the plants are distinguished by year of authorization.

2.2. New South Tyrolean Companies

The birth of a new market always keeps new opportunities for the local territory. This is what is happening for the gasification market in South Tyrol. Six new companies were founded until today. They are specialized in the field of wood gasification systems, with a total amount of 19 new employees. Table II reports the details about these new companies. There are new Italian locations of foreign companies involved in the wood gasification field as well as new companies that are developing their own technology.

Table II: New companies founded in South Tyrol in the field of wood gasification systems.

Company	Office	Date of foundation	Technology	Service	Nr. of employees	Market
Burkhardt Italia Srl	VIA NICOLO' COPERNICO , 13/A 39100 BOLZANO P.IVA. 02682200213	2010	Burkhardt GmbH	Service	7	Italy
Forest Power Srl	BREITBACH , 29 39040 CORTACCIA s.s.d.V. P.IVA. 02753830211	2013	Kuntschar Energieerzeugung GmbH	Engineering Selling	3	South Tyrol
Grünenergy Srl	VIA MARIE CURIE , 17 39100 BOLZANO P.IVA. 02713730212	2011	Agnion Technologies GmbH	Engineering Selling Service	2	South Tyrol
GTS Syngas Srl	VIA SAN LORENZO , 34 39031 BRUNICO P.IVA. 02598280218	2012	GTS Syngas Srl	Development	0	-
Revogas GmbH	BURGUSIO , 191 - 39024 MALLES VENOSTA P.IVA. 02726180215	2011	Revogas GmbH	Development	4	-
Spanner Re² Italia Srl	VIA ISOLA DI SOPRA , 17 - 39044 EGNA P.IVA. 02841660216	2014	Spanner Re² GmbH	Selling Service	3	Italy

For foreign companies (most of them come from Austria and Germany) South Tyrol is a perfect access for the Italian market, because of its proximity to the boundary and the presence of bilingualism (Italian and German languages).
Moreover, according to an evaluation of TIS innovation park, more than other 10 South Tyrolean companies are involved in this new market, in different steps of the supply chain, even if it is not their only business. It is evident that, even if wood gasification still requires technological developments, an interesting new market is growing in South Tyrol, where the territory is particularly suited for the diffusion of this kind of cogeneration systems. This also can explain why South Tyrol is a perfect location where to study and compare different technologies.

2.3. Selection of the representative plants to be monitored

Three representative plants have been selected for the monitoring campaign, considering the design of the gasifiers, the types of used biomass, the market share and the different engine technologies. In addition, another representative technology has been selected, on which the characterization of the products and by-products has been performed but not the energy and mass balances. Here after, the different technologies will be named from A to D (see Table III).

Table III: Main characteristics of the investigated technologies.

Technology	**A**	**B**	**C**	**D (*)**
Fuel	wood chips	pellet	wood chips	wood chips
Feeding	from the top	from the bottom	from the top	from the top
Nominal power	45 kW_{el} / 120 kW_{th}	180-190 kW_{el} / 220-240 kW_{th}	100-150 kW_{el} / 200-250 kW_{th}	300 kW_{el} / 600 kW_{th}
Reactor	downdraft	rising co-current	downdraft	downdraft
Gas cleaning	dry, on the cold gas	dry, on the cold gas	dry, on the hot gas	wet, on the hot gas
Engine	turbo-compressed Otto cycle	dual-fuel Diesel cycle	Otto cycle	modified Diesel cycle
Peculiarity	The (already quite dry) biomass is first dried in a separated vessel and then transported to the main reactor	The biomass feeding from the bottom creates a vortex above the combustion zone The engine is co-fed with colza oil for the auto-ignition	The wet wood chips are dried in an external drier suiting the excess of heat	The wet wood chips are dried in a external drier suiting the excess of heat

(*) On technology D only the characterization of the products and by-products has been performed, but not the whole balance of plant.

Technology A represents a downdraft biomass gasifier that operates in a scale smaller than 50 kW_{el}. It has a nominal electrical efficiency of 23 % and a nominal thermal efficiency of 52 %. The technology is input-specific, meaning that its performance is optimal for a specific range of biomass. Specifically, wood chips with a corresponding size range G30-G40 are utilized. Moreover, the fine matter should be less than 30 %.
The type of gasifier is called Joos gasifier, from the name of the inventor of this design (Bernhard Joos). The concept is that the input is first dried in a separated vessel and then transported to the main reactor – gasifier with a loading screw. The whole process is air tight and fully automated. The output hot producer gas exits the gasifier together with char and ash. The gas cools down as it passes from a counter-current heat exchanger. A bag filter removes the soot and the dust particles and a cyclone removes the char and ash fraction. The cooled and filtered producer gas is then fed to a gas engine (8V) which produces electricity and heat (CHP).

The peculiarity of technology B is the design of the gasifier, which is called “rising co-current”. It has the exact zone distribution like a downdraft gasifier. Nonetheless, the input biomass (pellets) is fed from the bottom by means of a loading auger and the producer gas exits the gasifier from the top. Additionally, the way that the air is fed in the gasifier creates a vortex above the combustion zone, a behavior similar to the term commonly known as fluidized bed. Although other reports have used the term updraft to define this type of technology, such a term is not sufficient to describe its nature. The definition that is more accurate and describes the full range of this technology is in fact the term ‘rising co-current’.
Like in the previous technology, the heat is recovered both from the hot producer gas and from the CHP engine. The difference lies in two aspects of the processes downstream of the gasifier. On the one hand the fact that this technology utilizes a wet scrubber and thus produces also a liquid by-product output and on the other hand the operation of the engine, which works on a dual-fuel mode and is fed by bio-oil along with the producer gas.

In technology C the gasifier is a downdraft gasifier very similar to the technology A. Nonetheless, the operating conditions of technology C allow the development of hot char bed inside the gasifier that enforces the surface char – gas reactions. Moreover this design has a special feature (steel filters) that makes possible the filtering of the hot gas. The heat is recovered downstream from the filter and at the engine. The engine is also a reciprocate gas engine, like technology A, but with the additional feature of operating under higher compression ratio (14.5:1) than the typical Otto-engine (10:1). This optimizes the thermal efficiency in the engine and thus the thermal and electrical output.

Technology D follows the concept of a combined gasification system rather than simply relying on the innovative design of the gasifier, thus it could be defined as a ‘Hot coated filter gasifier’. Concerning the type of the reactor, the patented design is referring to several options, i.e. a fixed-bed, entrained-flow or fluidized bed gasifier but it is stated that the preferable choice is direct current fixed bed gasifier which basically refers to a downdraft gasifier. The invention further relates to a method for purifying the gas from wood gasification. Due to scarcity of raw materials and energy resources, there is considerable interest in supplying residual wood. These residues may contain high concentrations of fine matter (i.e. coarse and fine dust) which may result to high dust concentrations and inefficiencies in combustion, which may result to high tar concentrations. These issues may prevent the direct use of the gas to internal combustion engines.
The gasifier is supplied by means of a conveyor belt and the air is preheated at a level of 250 °C. The gas exits the gasifier at a temperature of approx. 480 °C and drops to 300 °C after the filtering system. Thus, the gas passes from a filter, which has a ceramic surface, of high temperature of up to 500 °C, where the condensing of tar compounds is substantially avoided. It is of high importance the repeated coating of the filter with $Ca(OH)_2$ which acts as a filter-aid. After the filter, the gas temperature drops to 300 °C and a pressure drop of 72 mbar are observed. Then by means of a heat exchanger, thermal energy is captured and the gas temperature drops to 105 – 110 °C, a temperature that is maintained until the internal combustion engine, which is a modified diesel engine. The total pressure drop for the process is below the level of 145 mbar.

3. Plant monitoring

3.1. Raccomandazione CTI 13

The technology behind small scale gasification represents a concrete opportunity for the deployment of distributed power and heat generation systems, because offers the possibility to produce a fuel gas from solid biomasses, which can be converted in adapted internal combustion engines to generate electricity and heat from renewable sources.
Several plant layouts have been proposed since the ‘40s, and large amount of experience has been collectively accumulated by the scientific community. Nonetheless, the development and deployment of many small scale biomass gasification systems has been hystorically hindered by a common set of issues, e.g. inconsistent plant performance, poor gas quality, large amount of tar in the producer gas. Some of the aforementioned problems are connected to the feedstock properties (physical and chemical), some to the plant design, some to the actual operation by the end user, but also to the very limited number of mature technological alternatives.
While plant reliability is still a business of technology supplier and R&D, and very few of them can actually exhibit a proven track record or (successfully) operating installations, it can be noticed that the legislative framework for biomass gasification plant is still vague and uneven on the national territory at both local and regional level. This uncertain structure of laws and governamental bodies, which are involved in the plant erection, each for the respective area of competence, is partly a consequence of the limited number of running installations, but has a direct implication on the risk perception of investors and on the bankability of the investment.
In order to tackle the non-technical barriers that prevents the market introduction of biomass gasification technologies, the Italian Thermotechnical Committee led a standardization initiative, namely the “Raccomandazione CTI13”, aimed at establishing a common ground between all those personalities involved in the set-up of a biomass gasification facility, i.e. technology providers, investors, banks, public officers.
The Recommendation CTI 13 is an intermediate step to a regulatory path, which aims to provide a technical standard for small scale gasification plants. It is intended to be used as a reference document for the process of procurement and implementation of a gasification plant fueled with lignocellulosic biomass. The involved parties may be the technology developers, the engineering companies, the operators and even the financial institutions. The Recommendation CTI 13 will be likely converted to a technical standard, which will complement that of the UNI 10458 on plants producing biogas from anaerobic digestion. In addition, the Recommendation CTI 13 includes the best practices that should be applied between the operator and the manufacturer, the minimum technical specifications that the developer must provide to the manufacturer, the final contents of the offer that the manufacturer should provide to the purchaser and the set of procedures, checks and tests to which the facility is subjected. Finally, the correspondence between the actual and the nominal performance of the equipment and devices should be declared.

3.2. Applied methodologies

The basis for the monitoring activity have been set through surveys performed on the selected plants. In particular, contact have been taken with the owners of the plants in order to explain them the purpose of the project. The involvement and agreement with the owners is in fact a basic requirement for the success of the monitoring activity. With their collaboration, some non-invasive interventions to be performed on the plant have been planned, in order to allow the sampling of the producer gas and the measurement of the other terms involved in the mass and energy balances. All the measurements on the mass and energy fluxes have been performed on a minimum basis of 5 hours continuous operation.

Mass fluxes

For a correct assessment of the actual performance of the plant, a key parameter is the measurement of the energy input, i.e. the biomass entering into the reactor. Depending on the plant configuration, the input biomass has been weighted and manually fed to the reactor or, alternatively where this method was not applicable, the amount of fed biomass has been determined applying inverse strategies, e.g. using the maximum level of the storage as reference for understanding how much biomass were fed to the reactor during the monitored time span. In addition, samples of the fed biomass have been collected and characterized. In particular, moisture and ash content have been determined according to UNI EN 14774 and UNI EN 14775 respectively, while elemental and calorimetric analysis have been performed according to UNI 15104 and UNI EN 14918, respectively.
The gasifying agent flow rate, i.e. the mass of air entering into the reactor, has been derived measuring the velocity, by means of a Pitot tube, in a known dimensions tube connected to the air inlet (Figure 4).

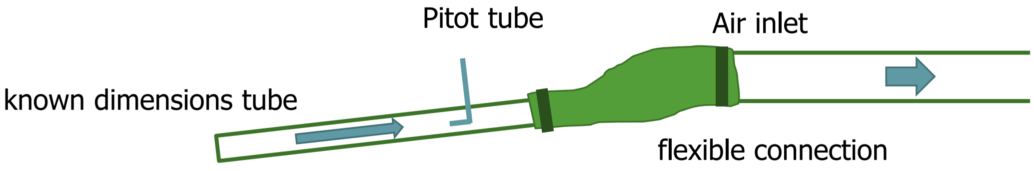

Figure 4: Set up for the measurement of the gasifying agent flow rate.

The producer gas flow rate has been determined once measured the gas composition (as described in the next section) and the input air flow rate, assuming negligible the nitrogen content in the fuel. The applied relation is:

$$\dot{V}_{gas} = \frac{x_{N_2}}{0.21} \dot{V}_{air} \quad (1)$$

where $\dot{V}$ represents the volumetric flow rates and x_{N_2} is the molar fraction of nitrogen in the producer gas.
Finally, the char flow rate has been determined collecting and weighting the char during the whole monitoring period.

Energy Fluxes

The energy flux related to the input biomass has been determined on the basis of the biomass flow rate and of its Lower Heating Value:

$$P_{biom} = \dot{m}_{biom} \cdot LHV_{biom} / 3.6 \quad (2)$$

where P_{biom} is the power associated to the input biomass expressed in kW, $\dot{m}_{biom}$ is the biomass flow rate in kg/h and LHV_{biom} is its Lower Heating Value in MJ/kg on as received basis.
The LHV is obtained measuring the Higher Heating Value (HHV) by means of a calorimetric bomb and considering the elemental analysis of the analyzed sample:

$$LHV_{biom} = HHV_{ar} - 2.443 \cdot 8.936\ H \quad (3)$$

where HHV_{ar} is the Higher Heating Value (i.e., the heating value considering also the amount of energy that can be recovered condensing the water vapor produced during the thermal conversion reactions) expressed on as received basis and H is the hydrogen content of the analyzed sample on a dry basis.

Similarly, the producer gas LHV has been calculated on the basis of its dry composition, measured by means of a portable gas chromatography system, and then used for the evaluation of the power associated to the producer gas mass flow rate $\dot{m}_{gas}$:

$$P_{gas} = \dot{m}_{gas} \cdot LHV_{gas} \quad (4)$$

Finally, the electrical power produced by the plant has been measured by means of a power analyzer and/or the integrated meter of the plant, while the thermal power has been estimated measuring the flow rate of the heat-carrying fluid by means of an ultrasonic meter and the supply and return temperatures by means of PT100 resistance thermometers.

Finally, in order to summarize the energy performance of the investigated plants, the electric and thermal efficiencies have been calculated as ratio between input and output energy during the time span of the monitoring. The electric and thermal efficiencies are computed as:

$$\eta_e = \frac{E_e - E_{aux}}{m_{biom} \cdot LHV_{biom}} \quad (5)$$

$$\eta_t = \frac{E_t}{m_{biom} \cdot LHV_{biom}} \quad (6)$$

where E_e is the electric energy, E_{aux} is the electric self-consumption of the auxiliary equipment, E_t is the thermal energy, m_{biom} is the amount of biomass, LHV_{biom} is the lower heating value of the input biomass calculated on “as receive” basis.

The overall efficiency of the gasification plant can be simply calculated as sum of electric and thermal efficiency.

Exergy assessment

Exergy concept could be used to assess the quality of energy. In the present case, exergy is a good indicator for the maximum amount of work that can be exploited from a stream [7]. There are two main different types of exergy, physical and chemical (potential and kinetic exergy are almost negligible in this case). The former depends on the difference of the temperature and the pressure between the system and the environment. The latter is related to the type of the substances and their composition. As the different processes propagate, irreversibilities take place and decrease the maximum work that the system is able to exploit. A valid term of comparison could also be exergy degradation. The general equation for exergy calculation is the following:

$$B = h - h_0 - T_0 \cdot (s - s_0) \quad (8)$$

where B is exergy, h is enthalpy, s is entropy and T is temperature. The values h_0, s_0, T_0 are the relevant values at standard conditions. Physical exergy is highly dependent not only on the relative temperature and pressure of a stream, but also on the physical state of matter, i.e. for a perfect gas with a constant C_p the physical exergy is:

$$B_{ph} = C_p \cdot \left[(T - T_0) - T_0 \cdot \ln\left(\frac{T}{T_0}\right) \right] + R \cdot T_0 \cdot \ln\left(\frac{p}{p_0}\right) \quad (9)$$

As mentioned above, chemical exergy is dependent on the composition. Relations developed by Morris and Szargut [8], provide straightforward correlations of the substances and their heating value by a factor, known as *β* factor:

$$B_{ch} = \beta \cdot LHV \tag{10}$$

For biomass the *β* factor is:

$$\beta = \frac{1.0414 + 0.0177 \cdot \frac{H}{C} - 0.3328 \cdot \frac{O}{C} \cdot \left(1 + 0.0537 \cdot \frac{H}{C}\right)}{1 - 0.4041 \cdot \frac{O}{C}} \tag{11}$$

For the calculations, char is considered to be graphite. Moreover, the chemical molar exergy of the gaseous compounds are also retrieved from tables available in scientific literature [8]. The molar chemical exergy of these substances are reported in Table IV.

Table IV: Molar chemical exergy of substances.

Substance	Chemical exergy
Carbon Monoxide	275 kJ/mol
Hydrogen	236 kJ/mol
Methane	831 kJ/mol
Carbon (graphite)	410 kJ/mol
Carbon Dioxide	20 kJ/mol

The sum of chemical and physical exergy gives the overall exergy (if kinetic and potential exergy values are negligible).

$$B = B_{ph} + B_{ch} \tag{12}$$

Products and by-products characterization

The main product of a gasification process is the producer gas, mainly consisting of hydrogen, methane, carbon monoxide and carbon dioxide, diluted in nitrogen. This definition applies typically to air gasifier, in order to distinguish the produced “producer gas” from syngas, which is obtained in steam gasification (i.e., using water vapor as oxidizing agent) and which is for this reason less diluted in nitrogen.
Beside the combustible gases, which are the “valuable” products of gasification, the conversion of biomass through gasification produces also a solid and a liquid by-product, i.e. char and tar respectively.
In the practice, an effective gasification technology should try to minimize the yields of both these by-products. A high yield of char means that the conversion of the initial feedstock should be improved, since a high amount of the energy initially “stored” in the biomass has not been made available through the producer gas. A high content of condensable tar in the producer gas could have detrimental effects on the engine leading to an intensive maintenance of the plant.

Producer gas
The producer gas, after filtration in the tar sampling system as described below, has been analyzed by means of a portable gas chromatograph (3000 microGC, SRA Instruments), equipped with two columns, a Molsieve column able to detect H_2, O_2, N_2, CH_4 and CO and a Plot-U column able to detect CO_2, C_2H_4, C_2H_6 and C_3H_6/C_3H_8 (C3’s). The microGC device has been calibrated with calibration blends characterized by compositions very similar to that of the producer gas of the investigated plants.

Tar

Tar is a bituminous oil present in the producer gas in vapor phase that is difficult to remove with a simple condensation, resulting in the clogging of filter, exchanger and valves, and corrosion of the metallic components [9]. For this reason, the analysis of tar, present in the producer gas, is one of the key aspect to be investigated in a gasification system in order to assess its reliability of operation. The tar in the producer gas, after clean-up and cooling sections, has been collected by means of a tar sampling system. This system is equipped with six impinger bottles, in accordance with the technical specification UNI CEN/TS 15439; all the bottles, exception for the last one, are filled with isopropanol that is an organic solvent suitable for tar capture. The first, the second and the fourth bottle are kept at 35/40 °C with water as cooling liquid, while the others are cooled at -15/-20 °C with a mixture of salt/ice/water. The producer gas has been bubbled in the impinger bottle for a total volume of at least 0.7 m^3 in a time span of 1-2 h.
The sample of tar diluted in the solvent has been then analyzed by means of GC-MS technique. The tar compounds have been separated on a DB5 MS column (J&W Scientific) and detected by a mass spectrometer (GC–HRMS, MAT95XL, Thermo Scientific). The detected compounds have been identified by the addition of deuterated internal standards.

Char
Char is a solid by-product with a high concentration of carbon and the remaining fraction is mainly ash. This by-product is extracted from the gasifier by means of a screw and separated from the producer gas in the filtration section. Three samples have been collected for each technology during the monitoring period. In accordance to the reference European normative, ash content (EN 14775:2010), elemental composition (EN 15104:2005) and heating value (EN 14918:2010) have been measured for each sample. These analyses enable to estimate the residual energy content of char and give an indication on the proper approach to dispose such a residue.
In addition, phytotoxicity tests have been performed on char samples according to UNI 10780. For the germination test, cress seeds (*Lepidium sativum* L.) have been used. Seeds have been soaked in distilled water for 1 hour. Ten seeds have been placed on one layer of filter paper (8 cm, Whatman 41) in 9 cm Petri dishes and 1.2 mL of either distilled water or char extracts have been added. The Petri dishes have been sealed with parafilm, covered with aluminium foil and incubated for 24 hours at 25 °C. Char have been extracted with water (1:10 m/v) for 2 hours, centrifuged at 5000 g and filtered at 0.45 μm. After the incubation time, number and length of seeds have been assessed. Each treatment has been replicated 10 times. The germination index (GI, expressed in percentage) has been calculated as follows:

$$GI = NGS_{sample} \times MRL_{sample} / (NGS_{control} \times MRL_{control}) \times 100 \qquad (13)$$

where NGS is the number of germinated seeds and MRL is the mean root length of seedlings in millimeters.

3.3. Results

3.3.1. Feedstock characterization

Moisture and ash content, elemental analysis and heating value for the collected biomass samples are reported in Figure 5. From the graphical representation, it can be clearly observed how the characteristics in terms of ash content, composition and heating value of the different biomasses are quite similar. This is quite expected for technologies A, C and D since they use wood chips as input biomass, which is locally produced. On the contrary, technology B is fed by pellets, thus the raw material has a different structure with respect to the material used by the other technology. Nonetheless, the chemical and calorimetric characteristics are comparable.

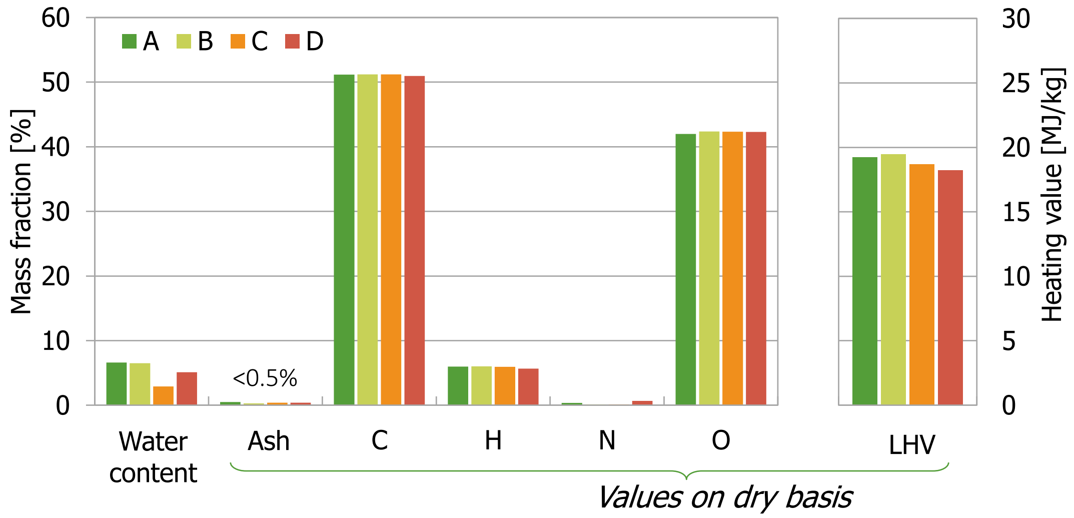

Figure 5: Water, ash content, elemental analysis and heating value of the feedstock used by the different technologies.

3.3.2. Mass and energy balance

As an example, Figure 6 shows the main terms involved in the mass and energy balances which has been measured during the monitoring campaigns for the different technologies. The energy content of biomass is converted in the gasifier into a form of energy easier to be suited, i.e. the energy stored in the producer gas. Some of the biomass energy content is lost in the conversion process, both as heat – which can be partially recovered in the heat exchanger – and as energy “trapped” in the char. The energy content in the producer gas is then converted in the engine into “useful” electrical energy and heat, which can be partially recovered from the exhaust gases and from the engine (oil and cooling water).

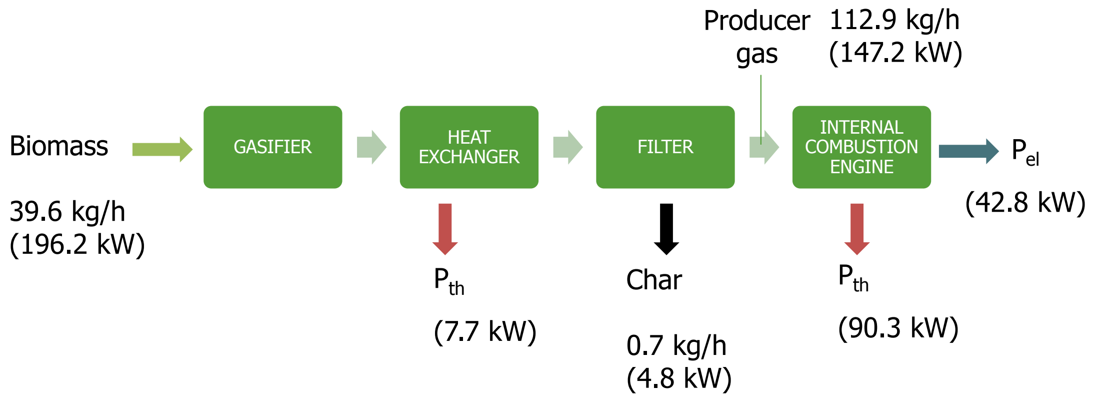

Figure 6: Block scheme representation of the typical components of a (small scale) gasification plant and main terms involved in the mass and energy balances. The exemplifying values, refers to technology A.

Thanks to the measurements performed during the monitoring activity, it has been possible to characterize and quantify all the mass and energy fluxes of the different investigated plants. A detailed representation of the energy balances for the different technologies is shown in Figure 7 by means of Sankey diagrams, a specific type of flow diagram in which the width of the arrows is proportional to the flow quantity, used to visualize energy transfers between processes. At first glance, the gasifier thermal loss is the dominant one for the three investigated technologies. This loss is even more important to be recovered if we consider that it occurs at high temperature (300-500 °C); this aspect will be discussed below in the chapter about the possible optimization strategies in the section "heat valorization". Technology B is based on a dual-fuel engine and the corresponding Sankey diagram shows a second input on the ICE section; this share contributes for the 5 % of the input energy to the ICE. The detailed percentage values with respect to the input energy of the feedstock have been reported in Table V for losses, useful fractions and electric self-consumptions of the investigated technologies. Finally, Figure 8 summarizes the key performance indicators of biomass-to-energy plants. The three investigated technologies have similar overall efficiency (electric and thermal efficiency summed together). However, technology B enables a higher fraction of electricity. This is due to the fact that technology B generates a producer gas with higher heating value thanks to a more refined input feedstock to the gasifier, i.e. pellets. In addition, the engine is a dual-fuel, therefore colza oil prompts the combustion reactions inside the cylinder and contribute to further increase the heating value of the fuel.

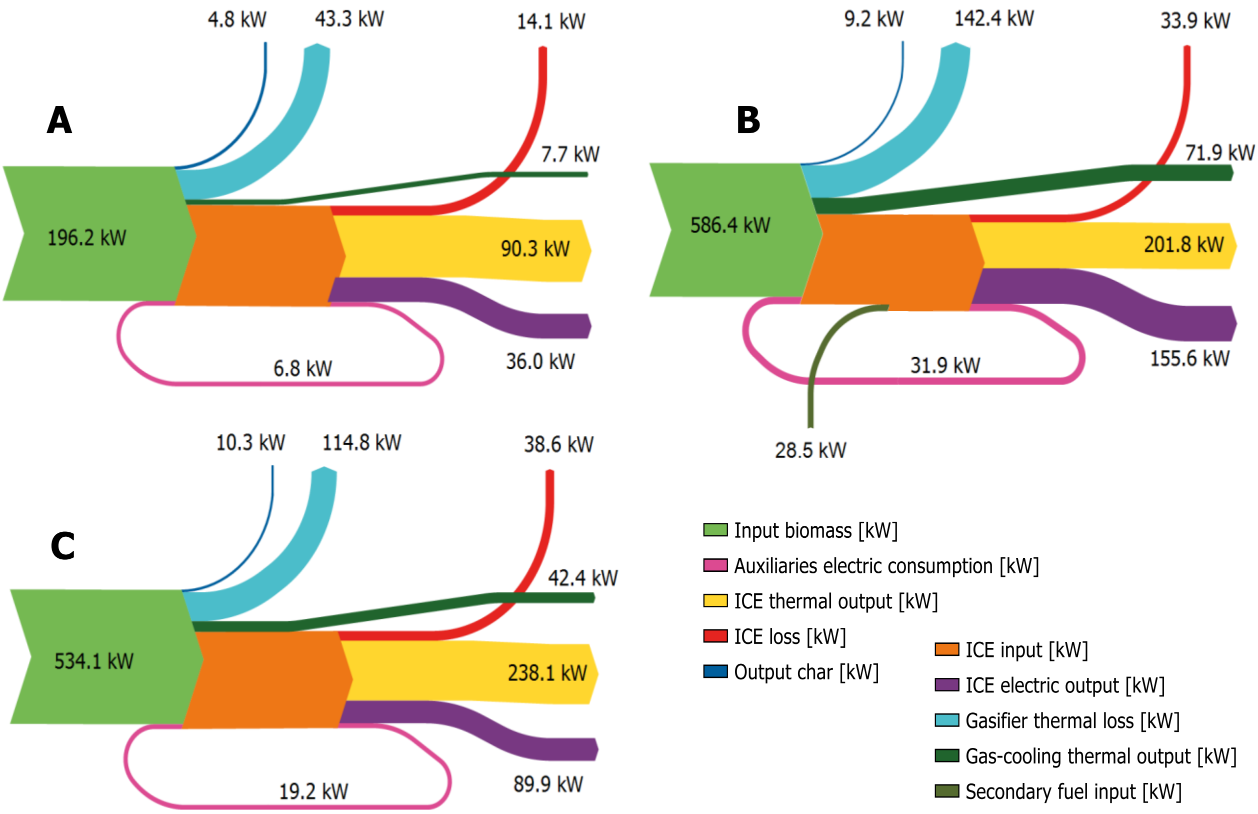

Figure 7: Energy balances for the different investigated technologies.

Table V: Losses, useful fractions and electric self-consumptions for the different technologies.

	Technology

	A	B(*)	C
Losses			
Char	2.4 %	1.5 %	1.9 %
Thermal gasifier	22.1 %	23.9 %	22.3 %
Thermal CHP	7.2 %	4.8 %	6.4 %
Useful			
Thermal gasifier	3.9 %	11.7 %	7.9 %
Net electric CHP	18.3 %	25.3 %	16.8 %
Thermal CHP	46.0 %	32.8 %	44.6 %
Electric self-consumption			
Auxiliary	15.9 %	17.0 %	17.6 %

(*) considers 3 l/h of colza oil as secondary fuel.

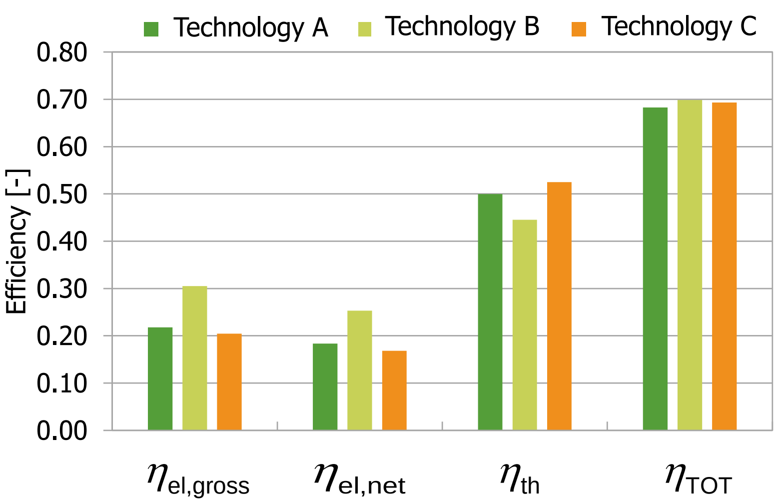

Figure 8: Measured efficiencies of the different investigated technologies during actual operation.

3.3.3. Products and by-products analysis

The composition and heating value of the producer gas is reported for the different investigated technologies in Figure 9. The producer gas of technology B has a slightly higher heating value than that of the other technologies due to the higher hydrogen content. On the contrary, the heating value for technology D is slightly lower due to the higher amount of CO_2 in the producer gas. Nonetheless, all the technologies are characterized by a producer gas with an interesting heating value, in the range of 4 to 5 MJ/kg.

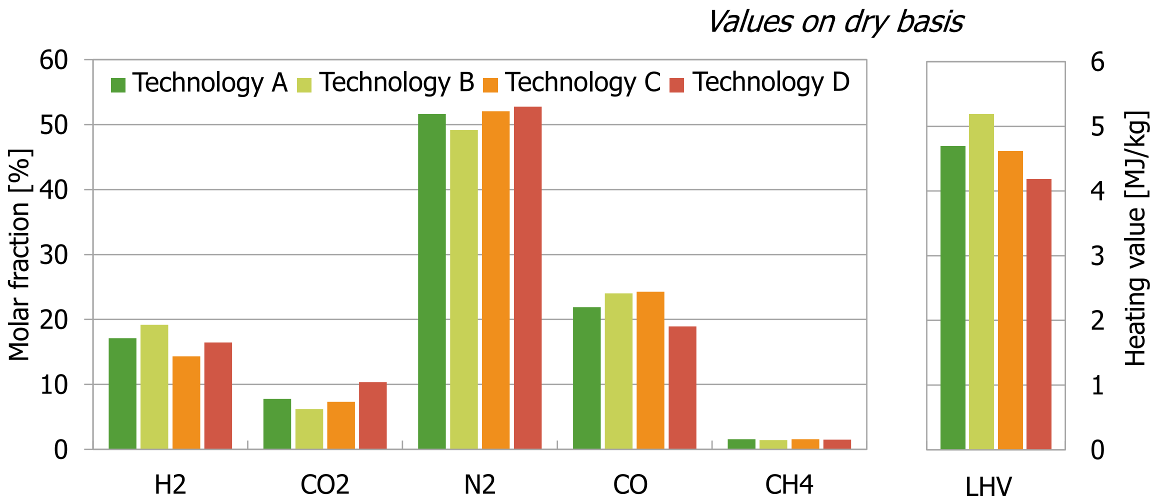

Figure 9: Composition and heating value of the producer gas for the different analyzed technologies.

The main by-products of the investigated gasification systems are char and tar, the results of their characterization are presented and discussed hereinafter.
Ash content, elemental analysis and heating value for the collected chars are reported in Table VI. The chars of all the investigated technologies are mainly composed of carbon and ash with fractions that depends on the conditions in the reactor. Technology C has a lower amount of carbon in the solid by-product, compared with the other technologies; this means that a larger fraction of carbon has been converted into gaseous components. The char characteristics can be compared among the different technologies because the initial feedstock have similar characteristics (see Figure 5).

Table VI: Ash content, elemental analysis and heating value for the collected chars.

Technology	A	B	C	D
Ash [%]	27.84	13.54	49.52	8.68
C [%]	68.63	83.39	48.03	87.58
H [%]	0.33	0.98	0.89	0.98
N [%]	0.83	0.23	0.25	1.98
O [%]	2.37	1.86	1.31	0.78
LHV [MJ/kg]	23.04	31.26	35.73	25.95

The results of phytotoxicity tests are reported in Table VII. Germination of cress seeds was very low, seedlings had necrotic brownish root tips indicating high char toxicity. The char of technology C lead to the lowest germination index followed by the chars of technology A, B and D. Yet GI of less than 20 % are very low and do not suggest that these extraction ratios might be used as soil amendment and do certainly not increase soil fertility nor have plant growth promoting effects. A correlation between GI and ash content can be observed, a higher amount of ash content leads to a lower germination index. This can be explained by the fact that a higher amount of ash corresponds to a lower carbon fraction, which usually promotes the germination. At the same time, heavy metals and salts in the ashes can contribute to create osmotic stress.
It is worth pointing out that most likely char extracts were too concentrated, probably more diluted extracts should be tested to verify the toxicity. Extraction ratios of 1:10 or 1:20 are usually used for the test of biosolids but do not seem to be appropriate for char studies.

Table VII: Germination index for the different chars.

Technology	GI [%]
A	7.38
B	14.42
C	1.13
D	18.99

The tar present in the producer gas is reported in Figure 10 for each investigated technology. The total detected tar involves both aromatic and polycyclic aromatic hydrocarbon (PAH) and it amounts to 0.6 mg/Nm³ (technology A), 0.4 mg/Nm³ (technology B), 1.6 mg/Nm³ (technology C), and 14.5 mg/Nm³ (technology D). For all the technologies the compound with the highest concentration is naphthalene that is the one with the lowest molecular weight (128.17 g/mol), among the detected tar. Naphthalene concentration is 64 %, 53 %, 29 % and 58 % for technology A, B, C and D, respectively. The lighter tars, up to fluoranthene (202.26 g/mol), account for 99 % of the total ones if we consider technologies A, B and D. As far as concern technology C, apart for naphthalene, there are no dominant compounds and light and heavy compounds have comparable concentration. Lighter tars are less detrimental that the heavier ones, therefore technologies A and B have a producer gas that is more suitable for the use in prime movers. A high content of tar usually causes higher maintenance on the engine.
This analysis enables to assess the tar content in the producer gas in order to assess the operating condition of the system and to operate in advance to reduce the maintenance load. A custom assessment has to be carried out to reduce the tar content since it depends on several factors. Some measurements, e.g. quality of the feedstock, water content, condition of the clean-up section, could be operated by the system manager while some others, e.g. modification of the reactor conditions, should be implemented by the manufacturer. For the purpose of this project, the tar measurements have been carried out in order to optimize the system operation.

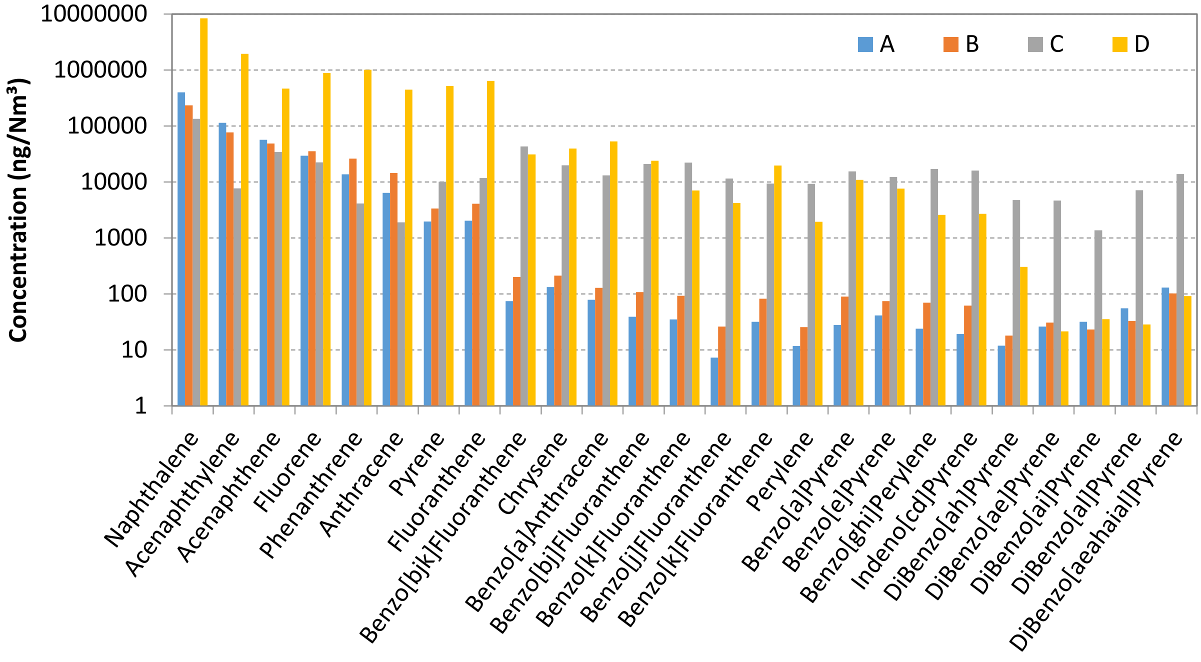

Figure 10: Tar compounds in the producer gas detected by means of GC-MS (the compounds are ordered from the smaller molecular weight to the highest one).

4. Possible optimization strategies

As an alternative to fossil biofuels, biomass valorization in gasification plants is addressed either to generate (1) process heat, (2) power, or a (3) combination of both output. Different end-use pattern of the energy produced in a gasification system can lead to distinct strategies for system optimization, depending on the target: from the system perspective this can translate in increasing the efficiency, decreasing the environmental footprint, diversifying the feedstock. On the other hand, from a different point of view, like a public regulation authority, an optimization objective could increase public acceptance and decreasing effluents production.

The case of sole heat generation is when there is a large availability of inexpensive high-ash biomasses, which could be hardly combusted due to the risk of slags formation during combustion (e.g. ash-melting temperature). In this case, the gas quality is not a major source of concerns, since all the tar content in the producer gas is oxidized to generate heat for the process in the furnace. In this case, the margin for optimization is limited, as the application is already leveraging a residue or low value feedstock.

The case of sole power generation is generally addressed (1) when biomass is more readily available or cheaper than other energy source in off-grid contexts, or (2) when incentives of feed-in tariffs, combined with cheap feedstock, allow a quick investment payoff. Decentralized production facilities, rural areas or remote locations are example of the former, while examples of the latter are more common in developed countries. In both cases, increasing the power output by diverting part of the high-temperature heat generated in the engine to a bottom cycle (e.g. ORC) can result in significant benefits. A further possibility, if there is a need for refrigeration, could be to send a sidestream of medium temperature heat to an absorption cycle.

The case of combined heat and power production (or even CCHP, combined cold, heat and power production) is the most frequently met in EU, especially when the gasification plant is installed in large residential facilities or tertiary-sector buildings.

4.1. Heat valorization

Figure 11 reports the flow of exergy for the technology A. We observe significant exergy losses after each process due to irreversibilities. The low exergy content of generated heat streams is due to their relative low temperature. Thus, although the energy content in the heat streams is significant, its quality can be considered as relatively low. The major factor for the exergy losses is the heat transfer that takes place between the oxidation zone of the gasifier and the surroundings. Its contribution is particularly enhanced by the high temperature of the discharged heat. Moreover, the exergy loss in the CHP engine is also a considerable share. A proper insulation of the reactor should be implemented to reduce this loss. Moreover, heat available at high temperature could be used for industrial applications - which require high temperature - or to feed an organic Rankine cycle to produce a further share of electricity. The utilization of heat at high temperature to satisfy heat demand at low temperature should be avoided from an exergetic point of view.

The overall exergetic efficiency of the gasifier can be estimated dividing the exergy content of the producer gas that exits the gasifier with the total exergy input reaching a value of approx. 63 %. Similarly, the exergetic efficiency of the whole plant can be evaluated at approx. 31 %.

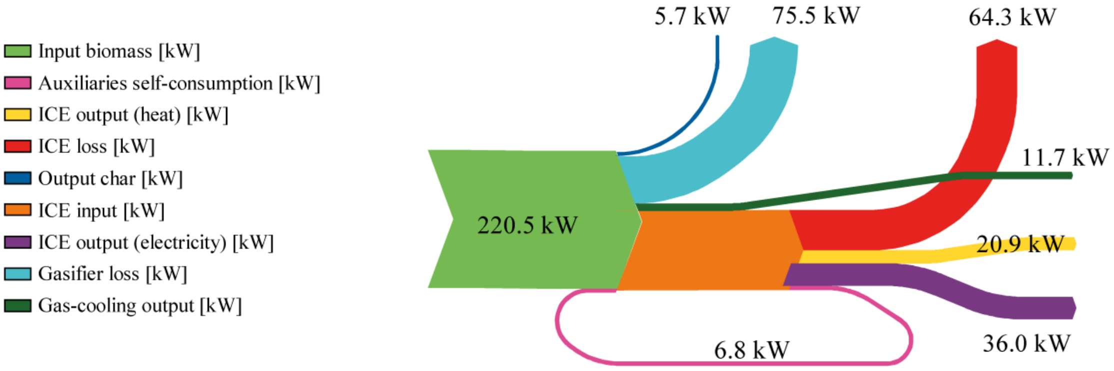

Figure 11: Flow of exergy and exergy losses for technology A.

4.2. By-products management

Biomass gasification systems generate up to three distinct effluents:

1. Fugitive emission of producer gas, which can be originated for example from seal leakage and ports for instrumentation, or as a result of normal operation of plant components (e.g. during biomass loading/unloading or solid discharge, and relief valve opening)
2. Condensates from gas cleaning, for the plant that are equipped with a post-processing section for tar removal from producer gas, or condensate from tar deposits in the gas line. Condensates from gas cleaning can be produced in minimal amount in systems generating very high quality producer gas (less than 10 kg/year for a 50 kWe downdraft plant running 7000 h/year). If wet cleaning systems are employed, the amount of condensates that are produced annually can be in the order of tens of ton per year, depending on the ratio between water and tar in the condensates. Moreover, solid content of the condensates can be variable, depending on the layout of the gas cleaning section.
3. Solid from cyclones, char from discharge port of the gasifier or char from dry filters (ceramic, fabric filter, etc). The solid residue sometimes carries a residual tar content.

With the exception of fugitive emission, which should be addressed in the general safety evaluation of plant or other safety-related analyses (e.g. ATEX, HAZOP), legal classification of condensate and solid residue is still troublesome, and both can be classified as refuse and must be disposed accordingly. The main open issues associated with the classification of solid and liquid by-products lies in their toxicity and eco-compatibility, which is due to the presence of aromatic and organic compounds (e.g. BTEX, naphthalene, anthracene). As an example, in the analyzed chars, a PAH content ranging from 53 to 402 mg/kg has been detected.

A limited number of alternative processes have been proposed for solid and condensate by-products treatment: anaerobic digestion of the condensates to reduce its toxicity, char activation for activated carbon production, char purification for Si recovery; however, in spite of the intense R&D activity on these processes, none of these alternatives have reached technological maturity yet and further research is urgently needed

An additional effluent, which cannot be classify as a by-products being actually a waste, is represented by the emissions from the engine. The admissible emissions of engines fed by producer gas are determined by article 11bis of the Annex C of L.P. n.8 of 16th March 2000. The emission limits are reported in Table VIII.

Table VIII: Emission limits in South Tyrol for internal combustion engines fed by producer gas.

Pollutant	**Limit [mg/Nm^3 @ 5%O_2]**
Particulate matter	30
NOx	500
CO	650
Benzene	5

The standard engines are generally optimized in order to operate with gasoline or diesel, which have different properties with respect to the producer gas. Nonetheless, with a correct engine setting the conformity to legal levels of emissions does not represent a problem, as confirmed by the measurements performed on the plants.

5. Project outcomes

The GAST project has been presented in several international conferences, promoting the peculiarity of the Autonomous Province of Bolzano from the point of view of the widespread utilization of renewable resources (in particular biomass) for the production of heat and power. The list of the published contributions in conference proceedings is reported in Section 5.1.
Beside the relevance from a scientific point of view, as demonstrated by the high interest raised during the international conferences, the project had an important outcome also for the local territory. In fact, the final workshop organized in 2015 the frame of Klimaenergy represented a perfect opportunity to widespread the results of the project to an interested non-scientific audience. The workshop made the population aware of the big potential of gasification technology for the utilization of biomass as a renewable energy source, as well as the importance of an effective operation of the plant for a correct management of the biomass resource and of the relevant products and by-products. Details about the final workshop can be found in Section 5.2.
Other opportunities to present the project to an interested audience (specialized non-scientific public) have been offered by the participation to Klimaenergy in September 2013 in order to promote the starting of the project and by the organization in February 2014 of the workshop "Cogenerazione di piccola scala da biomasse mediante gassificazione e ORC: learning by doing?" in the frame of Progetto Fuoco at the Fair of Verona.

5.1. List of publications

Vakalis, S.; Prando, D.; Patuzzi, F.; Mimmo, T.; Gasparella, A.; Tirler, W.; Dal Savio, S.; Chiaramonti, D.; Prussi, M.; Baratieri, M. Experiences in biomass gasification in South Tyrol: the "GAST" project. In *21st European Biomass Conference & Exhibition*; ETA Florence, Ed.; Copenhagen, Denmark, 2013; pp. 891–901.

Vakalis, S.; Prando, D.; Patuzzi, F.; Mimmo, T.; Gasparella, A.; Tirler, W.; Dal Savio, S.; Chiaramonti, D.; Prussi, M.; Baratieri, M. Measuring the performance of biomass small scale gasification plants by implementing mass and energy balances. In *4th Central European Biomass Conference*; Graz, Austria, 2014.

Vakalis, S.; Baratieri, M. Technological advancements in small scale biomass gasification: case study of South Tyrol. In *2nd International Conference on Sustainable Solid Waste Management*; Athens, Greece, 2014.

Vakalis, S.; Prando, D.; Patuzzi, F.; Mimmo, T.; Gasparella, A.; Tirler, W.; Mair, K.; Voto, G.; Chiaramonti, D.; Rizzo, A.; Pettorali, M.; Prussi, M.; Dal Savio, S.; Andreasi, D.; Baratieri, M. Assessment of a test methodology suitable for small scale gasification systems. In *22nd European Biomass Conference & Exhibition*; ETA Florence, Ed.; Hamburg, Germany, 2014; pp. 579–584.

Prando, D.; Rizzo, A.M.; Vakalis, S.; Patuzzi, F.; Gasparella, A.; Chiaramonti, D.; Baratieri, M. Monitoring of two CHP systems based on biomass in northern Italy: boiler-ORC and gasifier-ICE. In *5th International Conference on Engineering for Waste and Biomass Valorisation*; Nzihou, A., Guerreiro, S., Silva Lora, E., Eds.; Rio de Janeiro, Brazil, 2014; pp. 1108–1118.

Vakalis, S.; Patuzzi, F.; Prando, D.; Mair, K.; Chiaramonti, D.; Dal Savio, S.; Baratieri, M. Monitoring and analysis of representative small scale biomass gasifiers in South Tyrol. In *From Biomass to Power and Heat*; Zittau, Germany, 2015

Vakalis, S.; Prando, D.; Patuzzi, F.; Mimmo, T.; Gasparella, A.; Tirler, W.; Mair, K.; Voto, G.; Chiaramonti, D.; Rizzo, A.; Pettorali, M.; Prussi, M.; Dal Savio, S.; Andreasi, D.; Baratieri, M. Measuring the performance of different small scale biomass gasifiers – Results from the GaST project. In *23rd European Biomass Conference & Exhibition*; ETA Florence, Ed.; Vienna, Austria, 2015.

Prando, D.; Shivananda S.; Mair, K.; Chiaramonti, D.; Dasappa, S.; Baratieri, M. Characterization of tar depositions of three commercial gasification systems. In *23rd European Biomass Conference & Exhibition*; ETA Florence, Ed.; Vienna, Austria, 2015.

5.2. Final dissemination workshop

In order to present the results of the entire GAST project, a final dissemination workshop was organized. It took place on Friday, 27th March 2015 at the Sheraton Hotel in Bolzano, in conjunction with Klimaenergy 2015. The workshop was attended by 48 participants (in addition to the 10 speakers), coming from South Tyrol and from the other Italian regions, demonstrating the high level of interest that this theme arouses among local and non-local actors. This interest was revealed at the end of the workshop too, at the final discussion, when many questions were posed to the speakers.

During the 2 hours lasting workshop, the following topics were covered:

- *Introduction and moderation* – Stefano Dal Savio (TIS innovation park)
- *GAST - "Experiences in biomass Gasification in South Tyrol: energy and environmental assessment" Project presentation* – Marco Baratieri (Free University of Bolzano)
- *Gasification plants' characterization in South Tyrol: geographical diffusion and technologies* – Diego Andreasi (TIS innovation park)
- *The measurement campaign's results and conclusions* – Francesco Patuzzi & Dario Prando (Free University of Bolzano)
- *Emissions and byproducts: equipment and measurement methodology* – Karl Mair (EcoResearch)
- *Small scale plants: testing and contractual issues* – Andrea Rizzo (Re-cord)
- *Corporate presentations*:
    - VIS energy SRL, Spanner Re² Technology
    - Urbas SRL, Urbas Technology
    - Dr. Ing. Norbert Klammsteiner, Burkhardt and Xylogas Technologies

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