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THE IPRP TECHNOLOGY: from concept to demonstration

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Abstract

Biomass and wastes are distributed and renewable energy sources that may contribute effectively to sustainability.

Integrated Pyrolysis Regenerated Plant (IPRP) concept is based on a Gas Turbine (GT) fuelled by pyrogas produced in a rotary kiln slow pyrolysis reactor; waste heat from GT is used to sustain the pyrolysis process. The IPRP plant provides a unique solution for microscale (below 500 kW) power plants, opening a new and competitive possibility for distributed biomass or waste to energy conversion systems. To this aim a IPRP pilot plant, provided with a 80 kW micro-gas turbine, was designed and built, at the Terni facility of the University of Perugia. When used for 6,000 hours per year, electricity production is 400 MWh/year with a biomass consumption of 730 tonnes; the plant would avoid 290 t/year of CO_2 in atmosphere. Data obtained with experimental activity will be used to tune simulation models which are fundamental for process optimization being the key issue for the estimation of pyrolysis product yields (char, tar, and syngas) and LHV (Lower Heating Values). This could give important information about the overall process efficiency and about mass and energy balances that characterize the plant for different operating conditions. A measuring device to determine tar content in syngas is necessary for mass and energy balance and to obtain samples for analytical characterization. To this aim on the basis of technical specification CEN/TS 15439:2006 a sampling line for tar has been designed and realized at the laboratories of the University of Perugia.

Keywords

Biomass, wastes, IPRP, pyrolysis, microturbine, ICE, pyrogas, syngas, tar, char, rotary kiln.

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Introduction

Turning biomass into energy is addressed as one of the key issues for reaching sustainability and to meet the ambitious goals of the Kyoto Protocol [1] because it permits the reduction of fossil fuels utilization with a zero balance between the CO_2 absorbed during the plant's life cycle and the CO_2 reintroduced during energy conversion.
The best available technology for B&W electric energy conversion is still the grate-based incineration with a net electric efficiency lower than 30 % and a minimum plant size for economical feasibility above 2 MWe. Higher efficiencies may be obtained through an intermediate conversion (gasification) that turns B&W into a medium-low calorific fuel gas that can be used in a high efficiency cycle based on Internal Combustion Engine (ICE) or Gas Turbine (GT) but still at a demonstrative stage.
Microscale biomass conversion shows different benefits, decreasing electricity transmission losses and B&W supply costs by taking advantage of the distributed nature of fuels. Nevertheless there are few available technologies for biomass conversion on the microscale mainly based on pyrolysis and gasification [2-5]. Given this background, the authors have proposed, and optimised in previous works, an innovative integrated approach, namely the IPRP (Integrated Pyrolysis Regenerated Plant) [6-7], that combines a rotary kiln pyrolyzer and a gas turbine fuelled by the pyrolysis gas produced from the thermal degradation of biomass. Given the little amount of data available in the Literature on slow rotary kiln pyrolysis a laboratory scale kiln reactor was built to provide experimentally backup to mass and energy balances on different feedstocks.

IPRP Concept and optimization

The IPRP (Integrated Pyrolysis Regenerated Plant) is mainly composed by a Gas Turbine (GT) fuelled by synthesis gas obtained through slow pyrolysis of biomass and/or waste in an externally heated reactor. The energy required to sustain pyrolysis is provided by the exhaust gases of the GT and by combustion of pyrolysis non gaseous products such as tars and char.
Figure 1 shows the flow diagram of the IPRP concept which considers two different heat recovery to increase plant performance by means of regenerating the Joule cycle through air preheating.

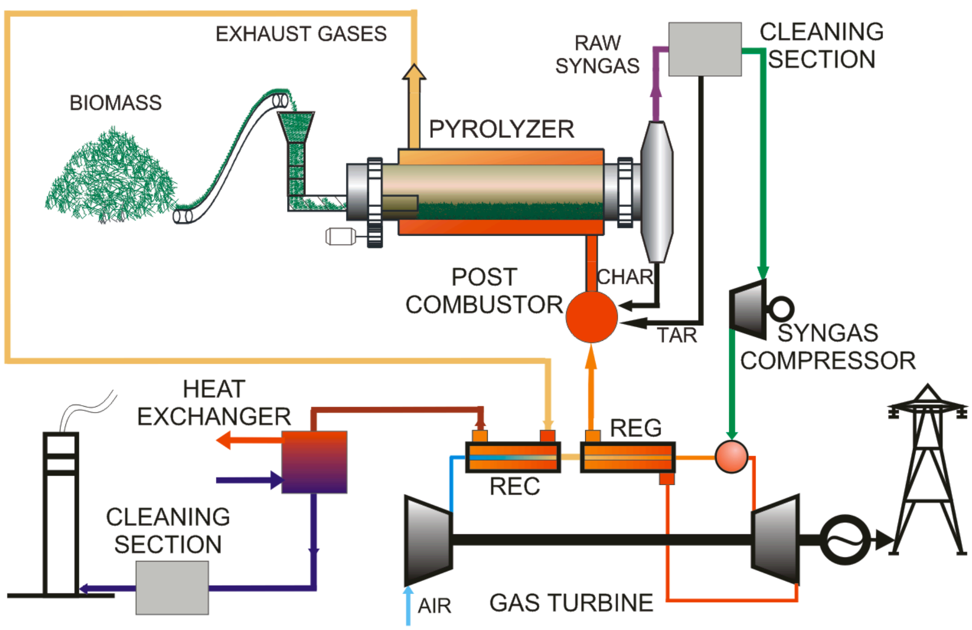


Figure 1 – The IPRP concept

Thermal energy of the exhaust gases out the turbine may be recovered in the regenerator (REG) while thermal energy of exhaust gases out the pyrolyzer may be recovered in the recuperator (REC). Thermodynamic optimisation of the IPRP technology was carried out in previous work [6-7] through a sensibility analysis on main design parameters such as GT β, RR, TIT and pyrolysis temperature. Typical results show that with TIT decreasing, the plant performance decreases because GT efficiency decreases and also because a higher amount of char is needed in the post-combustor. Moreover while decreasing TIT the value of pressure ratio β corresponding to best efficiency points also decreases. IPRP technology appears therefore to be suitable at every GT scale because decreasing the TIT (it is typical when reducing the GT size) the best plant efficiency point moves to lower β (also typical of reduced GT size). This fact shows that IPRP technology is a scalable concept because best efficiency points are obtainable for combinations of operational parameters that are consistent with microturbines (mGT), aero-derivative (AD GT) and heavy duty GTs (HD GT).

Figure 2 shows the main results of the thermodynamic optimization, the graph shows the efficiency of the plant versus the Turbine Inlet Temperature (TIT) for two different plant configuration: heat is recovered both from the gas turbine outlet and the pyrolyzer outlet; no heat recovery is considered.
Different geometric figure outside the points in the graph represent different (optimized) pyrolysis temperature (Tp). Varying the TIT, different manometric compression ratio (β) are considered: for TIT in the range 1000-1200 K, β=4; in the range 1200-1400 K, β =12; in the range 1300-1500 K, β =20. Figure 2 shows that when fuelled with a plastic-behaving residue, results obtained for the simple cycle with no regeneration, show best efficiencies that range from 11% for microscale plants to 23 % for big scale plants. The possibility of regenerating the Joule cycle with the exhaust gases exiting the pyrolyzer strongly enhances plant performance especially on the medium to small scale with results that range between 30 % and 40 %. Using a recuperated GT improves efficiency only at low values of pressure ratio therefore it may be utilized only on the microscale.

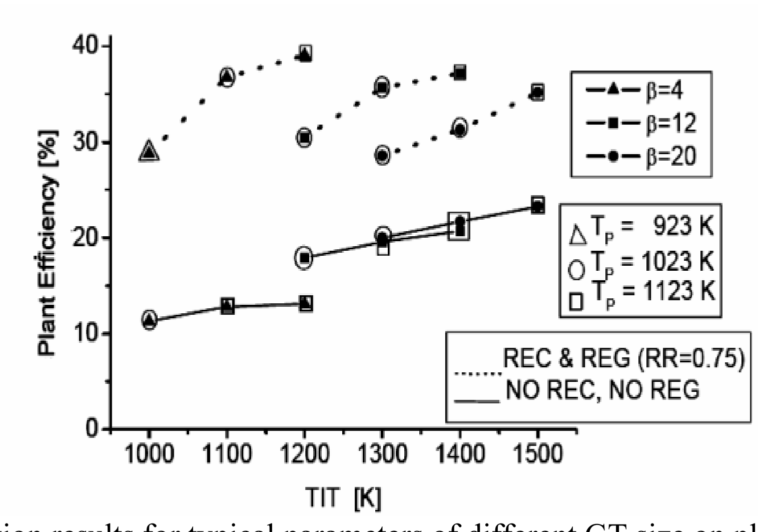


Figure 2: Simulation results for typical parameters of different GT size on plastic behaving residue [8]

When fuelled with a wood-behaving residue the results obtained show similar trends but the efficiencies are halved due to the lower energetic content of the pyrolysis gas and the use of only char in post-combustion.

IPRP Performance on different fuels

Previous work [9-11] showed that for plants fuelled with biomass residues like coconut shell, straw and wood the electric efficiency is higher than 20 % and HD GT gives the highest plant efficiency. Plant fuelled with groundnut shell, rice husk and olive husk show electric efficiencies around 15-20 % for mGT and efficiency decreases with GT size increasing; for mGT electric efficiency is quite low while produced heat is quite high, therefore may be used in small cogenerative plant (see Figure 3). With some fuels IPRP technology does perform as available technologies do but at a lower capital cost because no bottoming steam cycle is required.

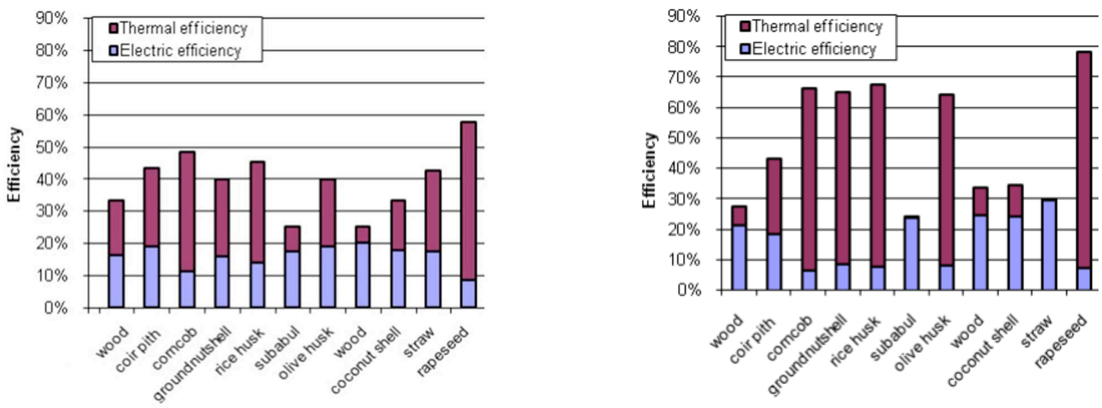


Figure 3: Electric and thermal efficiency for microGT (left) and big size heavy duty GT (right)

Performances were analyzed [10] for whole oil fruit to electrical energy conversion plant based on IPRP (Integrated Pyrolysis Regenerated Plant) which pyrolyzes oil cake obtained from milling oil fruits. Pyrolysis products are high density energy biofuels which are used to fuel a gas turbine (syngas) to sustain the process and for cogeneration (char) and to fuel an engine (tar) in emulsion with the vegetal oil extracted from the initial fruits. Three oil fruit were considered: Sunflower, Soy and Palm. For small plant, where it is difficult to use a recuperator, efficiency ranges from 19 % (Soy) to 22 % (Sunflower); for big power plant efficiency ranges from 26 % (Soy) to 40 % (Sunflower). For the three whole oil fruit considered the efficiency of small plants is quite low, more or less 20 %, but the plant may provide a solution for the energy conversion where there are no mature technologies. For bigger plants, the efficiency is around 40 %, therefore this technology does perform as IGCCs but at a lower capital cost because no steam cycle is required. Figure 4 shows the thermal (black) and electrical (cyan+purple+green) efficiency for the three oil fruit and for the three plant size considered.

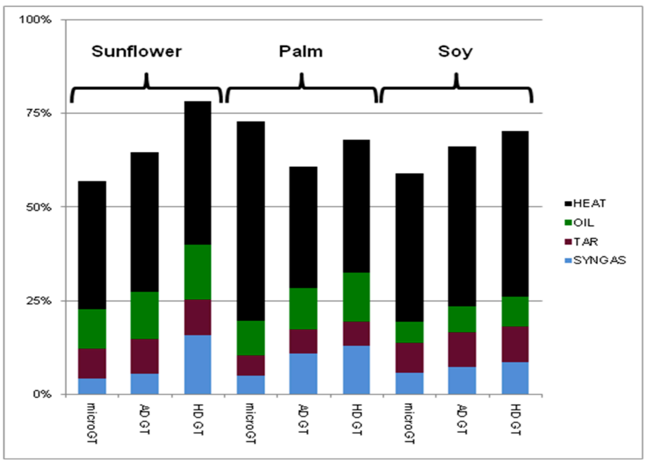


Figure 4: Electric and thermal efficiency for different oil fruit and different GT size

IPRP technology was evaluated even for wastes to energy conversion [9]. Wastes considered were waste tyres, plastic (PE) and Municipal Solid Wastes (MSW). Results (see Figure 5) showed that for plants fuelled with PE and MSW electric efficiency do not change changing plant size; efficiency is 27 % for PE and 20 % for MSW. Efficiency of plant fuelled with waste tyres increases from 23 % for small plants up to 33 % for big size plant.

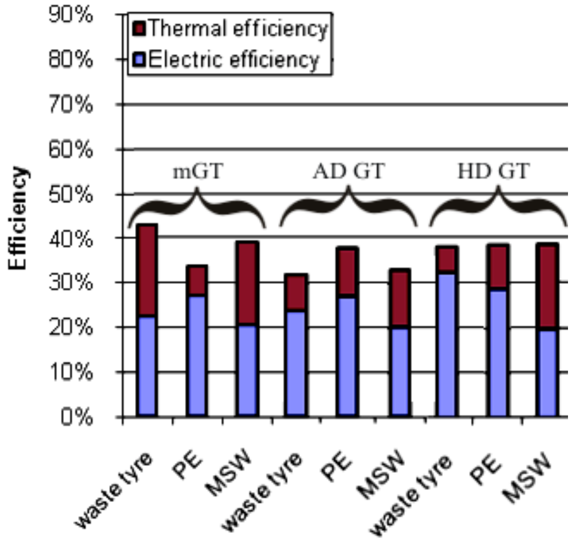


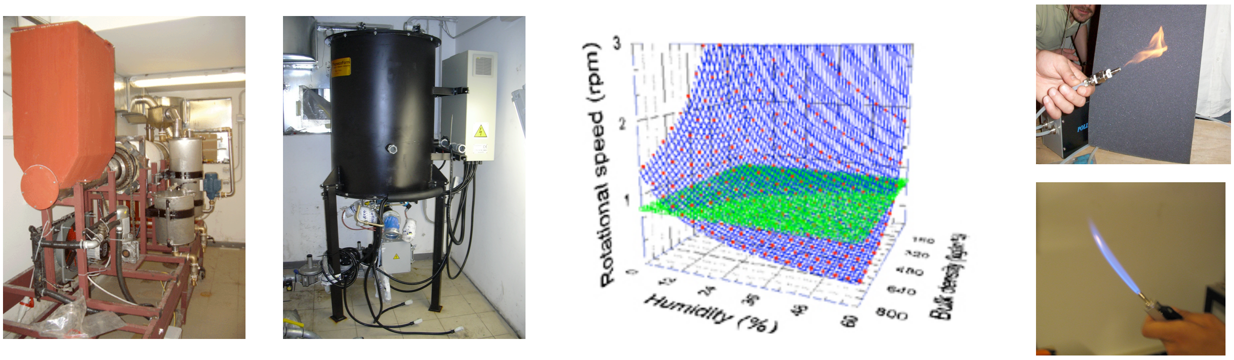
Figure 5: Electric and thermal efficiency for different wastes and different GT size

Solid waste, and bio-residuals in general, are usually disposed of or alternatively converted into energy by means of medium to big scale power plants. For isolated communities, usually in protected natural areas, this turns into high energy and waste management costs because of their intrinsic distance from landfills and power plants. When evaluating wastes conversion effect on global warming it is also important to take in account CO_2 and CH_4 avoided emission from landfilling and transportation.
Results obtained in previous work [11] show an acceptable cost positioning for the plant that makes it an interesting solution for distributed waste to energy systems.

The laboratory scale pyrolyzer

To verify mass and energy balance on different biomasses and wastes and with different operating condition an electrically heated laboratory scale rotary kiln was designed and built (Figure 6). In the laboratory scale plant, biomass is loaded into a hopper and fed continuously into the rotary kiln through a screw conveyor driven by an electric motor.
The rotary kiln is made of an AISI 304 steel pipe provided with external ceramic heaters to maintain the reactor to the required temperature for pyrolysis. The heaters are realized with two semi-cylindrical shells in ceramic fiber crossed by an internal resistance spanning reactor.
The Pyrolysis process products move through natural motion to the discharge section, at the end of pyrolyzer, the gaseous phase (tar and gas) is expelled from the top while the solid phase (char) is discharged by gravity.
Char is collected in a tank while the gaseous phase passes through a cleaning section: namely a calm chamber, for dust removal and char dust deposit, and a humid quencher-scrubber, made of a cylinder full of water through which the gas gurgles, condensing water and tar vapors [12]. The cooled gas pass thorough a filter system and is sucked by a side channel blower.
Cleaned and cooled gas is burned in a combustion chamber whose pilot flame is powered by natural gas grid.

The burner installed on the gas line, is medium speed, type “nozzle mix”, whose constructive characteristics allows to work in a stable flame with air excess of 800 %.
The burner has an “always on” pilot flame, to ensure the ignition of gas-air mixture where the composition is within the flammability limits; the pilot flame is an independent burner (2.3 kW) complete of the programmer and ignition electrode and flame detection system.
For flue gas combustion monitoring is used the Lancome III portable analyzer, placing the sampling probe at the exit section of the exhaust gases.



a b c d

Figure 6: Laboratory scale pyrolyzer (a) and adiabatic burner (b) for pyrogas combustion. The working envelope of the reactor (c); pyrogas flame (d) before the cleaning section (top) and after the cleaning section (bottom)

Experimental activity was also carried out to tune a pyrolysis simulation code used for preliminary yield assessment and to determine the working envelope of the laboratory scale reactor, given the fixed amount of thermal energy provided by the electric heaters [13-14].
The computational code utilises Literature data for equilibrium constant which as well are not fully available therefore recent research is being carried out at the Biomass Research Centre laboratory to infer equilibrium constants from TGA analysis on selected fuels [15].

The IPRP demonstrative unit

To demonstrate the feasibility of the IPRP concept an 80 kW electric pilot unit was designed and built at the Terni facility of the University of Perugia.
Figure 7 shows the IPRP plant layout. Biomass is fed through a hopper to the rotary kiln pyrolyzer.
The inside cylinder is the reaction chamber where the thermal degradation to pyrogas, char and tars of the biomass is achieved, in the absence of oxygen. To allow rotational motion the cylinder rolls on four steel disks placed in parallel couples on two iron skids, one at the beginning of the pyrolyzer, the other at the end.
At the beginning section of the cylinder an external gear is welded to transmit rotational motion to the cylinder through a chain and an electric motor. The air-tight sealing between rotary kiln and oven is realized through rings of high temperature resisting graphite while air-tight sealing between rotary kiln and charge and discharge sections are realized through iron rings.
The refractory chamber that contains the pyrolyzer houses on the bottom an underfeed combustion system which is continuously fed with char conveyed with a screw conveyor from the outlet section of the pyrolyzer. Char combustion provides the heat required for pyrolysis while combustion oxygen is provided either by a dedicated air blower or from gas turbine exhaust gases, depending on operational requirements. Ashes are normally eliminated from an opening on the lower part of the casing.

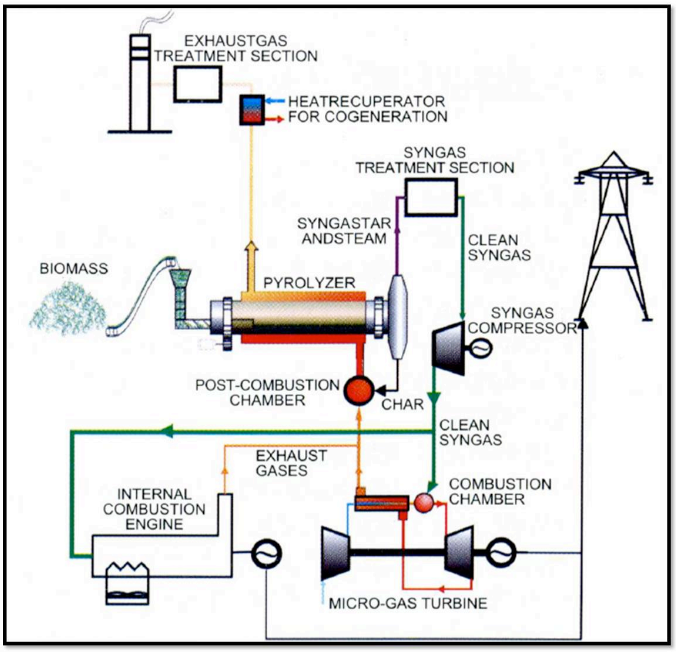


Figure 7: IPRP plant layout

A dual fuel gas burner (natural gas and pyrogas) exhausts directly in the refractory chamber above the char combustor to provide eventual additional heat, for temperature control, and for start ups. At the end of the cylinder raw gas is conveyed to the cleaning section sucked by the pyrogas compressor. Figure 8 shows the pilot plant as built. Pyrogas from the pyrolyzer is cleaned from particulate in a cyclone and eventually cooled, to condense tars and water, and cleaned in the wet scrubbing section, to eliminate aggressive compounds that may damage the gas compressor and the turbine. The fuel gas is then compressed and injected in the ICE or in the GT combustion chamber. A flanged pipe connects the outlet of the reactor to the gas cleaning section composed of a cyclone, for dust elimination and of a humid quench-scrubbing section for pyrogas cooling and tars separation. The pyrogas humid cleaning system is composed of: a two stage quencher for temperature abatement, a variable throat Venturi, a two stage scrubber with final demister.

Figure 8: The IPRP demonstrative unit

The cleaning section condensates water and tar vapours that fall into the bottoming pool and mix with the cleaning water. Heavy and light tars are extracted from the bottom and the top of

the pool and may be returned through a hot pipeline to a dedicated burner inside the refractory chamber of the pyrolyzer, although this solution is still under study.
Syngas is sucked from pyrolyzer through cleaning section by a side channel blower; whose rotational speed is regulated to maintain rotary kiln in slight depression providing the required pressure for the syngas compressor of the microturbine.

The microturbine is a radial geometry turbocompressor with an anular combustion chamber adapted for pyrogas use. The compressor is a rugged stainless steel radial flow design; the approximate compression ratio is 4. The radial super-alloy turbine provides energy to drive both the compressor and alternator. The electric power is generated through a 4 pole, permanent magnet alternator rotating within an oil cooled stator assembly. The stator assembly is energized as a motor during initial start-up reducing the need for auxiliary starting hardware. The microturbine is equipped with a regenerating heat exchanger for air preheating through exhaust gas cooling that lower exhaust gas temperature to approximately 270 °C. Main operational data of the microturbine, as provided by the manufacturer, are shown in Table 1.

Parameter	**Value**
W_E (kW)	80
η_E (%)	27
Turbine inlet temperature (°C)	1010
Manometric compression ratio	4
Exhaust gases flow (kg/s)	0.77
RPM	68000
Exhaust gases temperature (°C)	270

Table 1: Parameters of the micro gas turbine (manufacturer data)

The exhaust gas treatment section is provided with a cyclone, a blower and the stack. Such a simple circuit may not be sufficient for particulate elimination therefore a bag house or electrostatic filtering system may be required. In order to decrease flue gas temperature and to recuperate thermal energy, a heat exchanger for hot water production is provided. Heat recovered from the plant is around 140 kW and is currently utilized for cogeneration purposes.

With respect to an Internal Combustion Engine (ICE) the microtrubine shows an overall better performance in terms of emission (gaseous and acoustic) and maintenance requirements, while efficiency performance are comparable. The economics of the ICE however are far better both in terms of capital costs and running costs, also because it is not required specialized man labor. With focus on small scale application it was then interesting to verify the perfomance of the IPRP when an ICE is substituted to the GT. To this aim a four-stroke, spark ignition, inline six cylinders CATERPILLAR 3306 was modified from the a landfill gas configuration and installed at the facility. The engine is connected to an alternator with two pole pairs keyed to the crankshaft and is connected to electrical resistance for variable load experiments. Main operational data of the engine are shown in Table 2.

Parameter	**Value**
Engine speed (rpm)	1500
Generator set power (kW)	110
η_E (%)	29
Exhaust stack temperature (°C)	512

Table 2: Parameters of the engine

In order to use syngas to fuel the ICE, considering its variability, an electronic ignition system was installed. Now ignition timing can be changed, up to 30° before TDC, thorough a rotational potentiometer, in the future it will be changed by the PLC that control the plant. The low calorific value of the syngas required the diameter increasing of the holes of the Venturi tube where syngas is mixed to air, in order to increase the syngas flow.
Maximum tar content in syngas is one of the main issues to deal with when fuelling both the GT and ICE and this was also one of the main concerns during experiments. For satisfactory Internal Combustion engine function, the particulates content must be below 50 mg/Nm^3 and the tar content less than 100 mg/Nm^3 [16]. Hence it is necessary to verify tar content in gas, as a function of operation parameters to prevent engine failure and pipeline fouling. To this aim a sampling line to determine tar content in syngas (see Figure 9) was designed and built according to technical specification CEN/TS 15439:2006 "biomass gasification-tar and particles in product gases-sampling and analysis" [17].

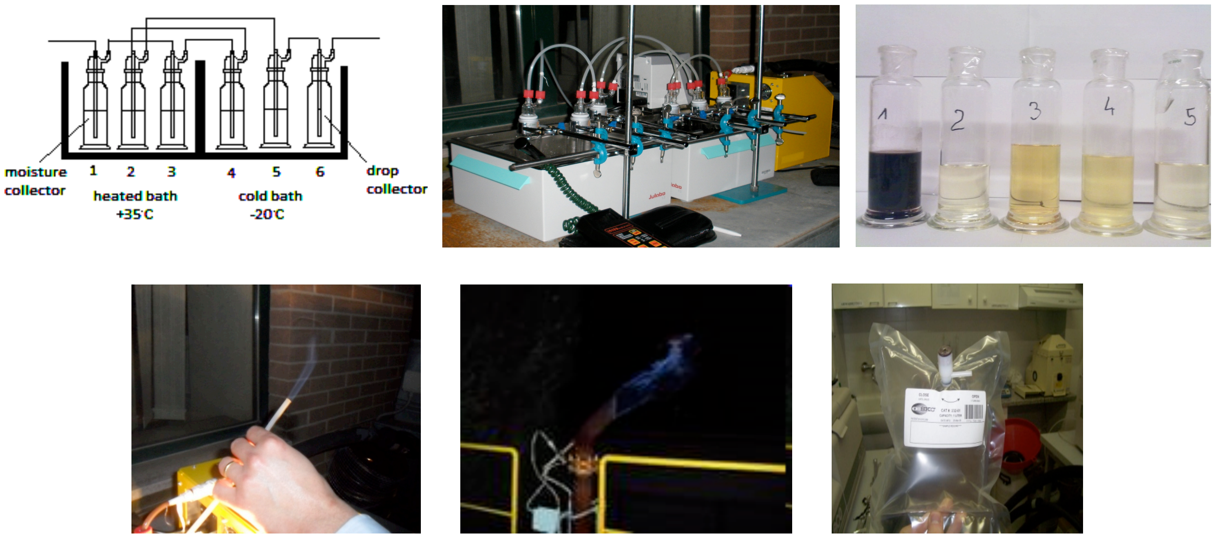


Figure 9: Tar Sampling: layout, photo and results (top) sampled gas flame, syngas flare and tedlar bag for GC analysis (bottom)

The first section is a particle collection in the form of quartz filter used to separate solid components for particles of size 0,3 μm. The following section is a heated tube which reduces system pressure and cool the inlet gas from 450 °C to 350 °C. The whole line is heated to 350 °C to prevent tar condensation before the sampling train. The section three is responsible for a partial condensation of tar, the retention of moisture and the tar trapping in an impinger bottles. The tar is collect in a series of six impinger bottles. The first impinger bottle is called "moisture collector" and it's used for water and tar condensation by absorption in 2-propanol. After the moisture collector there is a series of four impinger bottles with solvent (2-propanol) followed by a empty impinger bottle called "drop collector". The series of impinger bottles is placed in two separate baths: bottles 1, 2 and 3 are heated electrically in water bath to +35 °C while bottles 4, 5 and 6 are cooled with NaCl/ice to -20 °C. Tars accumulated in organic solvent will be immediately transferred in dark bottles and stored in freezer and later analyzed by laboratory techniques. The last section contains a pump with gas flow meter, pressure and temperature indicators. The gas at the outlet of the valve by-pass of pump will be collected in a Tedlar gas bag and then measured by GC-MS.

IPRP Performance with different heat recovery options

Different options for plant heat recovery were considered. Table 3 describes plant performances depending on different destination of waste heat and different initial humidity of the feedstock. Three cases were analyzed, as hereafter described.

CASE A – Cogeneration. This is the actual functioning of the plant in which waste heat is used to produce hot water for winter heating of the school of Engineering. Electricity is sold to the grid and green certificates on the entire production is obtainable. Such a configuration requires a quite dry biomass (~20 %).

CASE B – Feedstock drying. In this case waste heat is used to run a dryer, that may also be built as a rotary kiln, allowing humid biomass to be used directly in the plant. No waste heat is then available for cogeneration purposes while electricity is sold to the grid and the green certificates are obtainable on the entire production.

CASE C – Pellet production and feedstock drying. This solution requires more biomass available and provides a way to store waste heat in the form of solid bio-fuel namely pellet. Biomass required for pellet must be grinded to powder, dried to reach around 10 % humidity, and finally compressed to pellet. The whole electricity produced is required to grind and compress additional biomass therefore no energy is sold to the grid but green certificates are however obtainable on the entire production. No waste heat for cogeneration purposes is available because that energy is used to dry biomass. That energy may be considered "contained" in pellet thus resulting as the positive effect in global efficiency.

Results exposed in Table 3 show that for case A thermal energy available is 140 kW; for case B the highest biomass moisture content is 60 %; for case C the highest biomass moisture content is 28 %, pellet production is 372 kg/h.

	A	**B**	**C**
Biomass LHV (MJ/kg db)	15	15	15
Moisture (%)	20	60	28
Biomass flow (kg/h wb)	122	242	613
Gross electric power (kW)	80	80	80
Net electric power (kW_E)	65	60	0
Thermal power for cogeneration (kW)	140	0	0
Electric efficiency (%)	16	15	0
Global efficiency (%)	50	15	75
Pellet production (kg/h)	0	0	372
Yearly production (7000 h/year)			
Electricity sold to grid (MWh/y)	455	420	0
Heat recovered (Gcal/y)	843	0	0
Pellet production (ton/y)	0	0	2.600
CO_2 reduction (ton/y)	520	520	2.000

Table 3: Expected plant performance

Summary

Results of thermodynamic analysis of IPRP show that for some kind of biomasses, like coconut shell, straw and wood, highest efficiency (higher than 20 %) is obtained with big size plants. Plant fuelled with groundnut shell, rice husk and olive husk show a lower electric efficiency (around 15-20 %) that is obtained for mGT and efficiency decreases with GT size increasing. Results for wastes show that for plants fuelled with a high plastic content residue (PE) and Municipal Solid Wastes (MSW) electric efficiency is respectively 27 % and 20 % and do not change changing the plant size. Efficiency of plant fuelled with waste tyres increases from 23 % for small plants up to 33 % for big size plant.

Performances were analyzed also for whole oil fruit (Sunflower, Soy and Palm) to electrical

energy conversion plant based on IPRP (Integrated Pyrolysis Regenerated Plant) which pyrolyzes oil cake obtained from milling oil fruits. Pyrolysis products are used to fuel a gas turbine (syngas) to sustain the process and for cogeneration (char) and to fuel an engine (tar) in emulsion with the vegetal oil extracted from the initial fruits. For small plant efficiency ranges from 19 % (Soy) to 22 % (Sunflower); for big power plant efficiency ranges from 26 % (Soy) to 40 % (Sunflower).
IPRP technology can perform as available technologies but at a lower capital cost because no bottoming steam cycle is required. Moreover IPRP technology provides a solution for the micro-scale where there are no available technologies.
A pilot scale demonstrative unit of IPRP (Integrated Pyrolysis Regenerated Plant) biomass fed was designed and built at the Terni facility of the University of Perugia, Italy. The plant consist of a 120-150 kg/h rotary kiln pyrolyzer, a humid quenching-scrubbing section for tar removal and a modified 80 kWe microturbine for pyrolgas use. Char obtained from pyrolysis is burnt in an underfeed combustor to provide the energy required by the reactor.
The proposed plant would make it possible to avoid emissions into the atmosphere of about 290t/year of CO_2 corresponding to the amount emitted by traditional ENEL thermo-electric plants to produce 400.000 kWh of EE. Waste heat for the plant is recovered for district heating of the school of Engineering. Plant performance show around 16 % of electric efficiency and an overall thermal efficiency of around 34 % assuming initial biomass humidity of 20 %. Different option for waste heat recovery are analyzed such as pellet production and feedstock drying. They are both feasible yielding respectively 372 kg/h of pellet at an initial biomass humidity of 28 % or allowing the use of biomass at 60 % humidity. The paper describes also the sampling line realization for measuring the content and characteristics of the tar. The sampling line was realized on the basis of the CEN technical specification “biomass gasification-tar and particles in product gases-sampling and analysis” and it will be used to determine tar content in syngas from pyrolysìs process, necessary for mass and energy balance.

Nomenclature

AD: Aero-derivative
B&W: Biomass and Waste
CEN/TS: European Committee for Standardization - Technical Specifications
DCM: dichloromethane
GC: gas chromatograph
GC-FID: gas chromatography with flame ionisation detector
GC-MS: chromatography coupled with mass spectrometry
GC-PID: chromatography coupled with photo ionization detector
GT: Gas Turbine
HD: Heavy Duty
H-NMR: high-resolution proton nuclear magnetic resonance
HPLC: high performance liquid chromatography
ICE: Internal Combustion Engine
IPRP: Integrated Pyrolysis Regenerated Plant
LHV: Lower Heating Value [kJ/kg]
PAH: Polycyclic aromatic hydrocarbons
REC: Recuperator
REG: Regenerator
RR: Regeneration Ratio [%]
SPA: solid-phase absorption method
TIT: Turbine Inlet Temperature [K]

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