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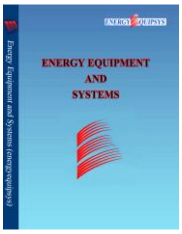

Thermoeconomic comparison between the performance of small-scale internal combustion engines and gas turbines integrated with a biomass gasifier

Pantea Hadi Jafari [a]
Farshad Kowsary [a*]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

Recently, many countries have paid substantial attention to power generation from biomass gasification, particularly through small-scale plants. A number of power plant models have been suggested and analyzed; however, certainly, desirable configurations have not been identified yet. Moreover, their performances are ordinarily difficult to compare, especially owing to the fact that working hypotheses are often inconsistent. The objective of this research is to provide an overview on small-scale technologies regarding woody biomass syngas utilization for power production, with the purpose of introducing the most promising solutions from both thermodynamic and economic viewpoints. Existing technologies or those possibly anticipated to be available on the market in the near future have been taken into consideration. Three plant scales have been investigated including 100 kW_{el}, 1 MW_{el} and 5 MW_{el}. As small-scale power plants, internal combustion engines and internal (micro) gas turbines have been taken into account, while gasification has been focused for biomass. Simulations demonstrate that internal combustion engine integrated with an ambient pressure gasifier and regenerative gas turbine integrated with a pressurized gasifier are the most favorable technologies at all the three sizes from a thermodynamic point of view. However, among these two solutions, the former configuration is the most promising one at all the scales from an economic point of view as well.

Keywords: Biomass gasification, Electrical efficiency, Gas turbine, Internal combustion engine, Thermoeconomic analysis.

1. Introduction

Global warming due to human activities is a recent crucial issue; thus, the decrease in greenhouse gas emissions becomes a vital target in many countries. As a result, some international agreements such as the Kyoto protocol and the EU 20-20-20 plan have been considered to restrain the undesirable outcomes of industrial development.

The utilization of renewable energy sources for power generation can have a great contribution towards the progress of this trend. Amongst these alternative energy sources, biomass is considered a son of the interesting types and the reason lies in the fact that besides the principal benefit of renewable energies (CO2-neutrality), it has the capability of being gathered and exploited through a combustion process, coupling its conversion with more conventional technologies, hence it allows combined heat and power (CHP) production as well. Moreover, an enormous potential of this resource can be available almost worldwide. Of course, woody biomass in particular is the most considerable type and is furthermore an appropriate fuel to produce power due to its versatility.

Although the exploitation of biomass to generate power is more common for large plants, its utilization may still be indeed more compelling on small scales. This is because of the higher potential for the application of a co-generative unused heat recovery, the difficulty in providing large amount of raw

*Corresponding author:
School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran
E-mail address: fkowsari@ut.ac.ir, (Farshad Kowsary)

material to feed plants as well as the very little effect of the installations on the environment. Additionally, small-scale plants benefit from higher economic incentives than larger ones in many countries.

Gasification as the biomass conversion process is taken into account. Biomass has specific chemical properties (compared to other materials like coal) and makes it particularly appropriate for gasification technologies. Moreover, exploitation of biomass syngas (the main product of gasification process that is a gaseous fuel) has been recently investigated widely, although the most desirable small-scale biomass gasification power plant configurations have not been established yet. Furthermore, owing to different operating conditions, a proper comparison of the performances of the configurations is often too troublesome to investigate. On the basis of these considerations, the main goal of the present work is to carry out an assessment of small-scale biomass syngas fired power generation technologies, focusing on woody biomass, allowing a comprehensive comparison and recognizing the most favorable solutions from both thermodynamic and economic points of view.

Existing power plant configurations or those which are anticipated to be possibly available on the market in the future have been taken into account. Three power plant scales have been considered: 100 kWel, 1 MWeland 5 MWel. In fact, the two first-mentioned capacities have been more focused, because the last one can practically be taken into consideration as a medium-scalefor biomass power plant. However, it has been considered in order to have a better comparison values.

Internal combustion engines (ICE) and (micro) internal gas turbines (mGT/GT) have been considered as the power plants. The commercial Thermoflex™ software has been used in order to simulate the overall thermodynamic performances. Maximization of power generation by providing potential regeneration has been taken into consideration through setting different plant configurations. Subsequently, the most efficient configuration have been subject to an economic analysis, performed on the basis of available European legislations, which provide substantial economic incentives to generate power from renewable energy sources.

2. Woody biomass gasification technologies

Gasification is a thermochemical process converting solid or dense liquid fuels such as biomass, coal, tars and so on into gaseous energy fuel, which is called syngas, by partial oxidation at high temperature (800 – 1000°C) with a specific substoichiometric quantity of an oxidizer like air, oxygen, steam or a mixture of them.

As already mentioned, biomass has special chemical properties such as carbon reactivity, high volatility and low percentage of ash and sulphur that turn it to an appropriate fuel for gasification. The process, in comparison with coal, is able to be performed at lower-level temperature, with a less amount of time and fewer difficulties concerning emissions as well as the reactor walls corrosions. Nevertheless, biomass also has significant disadvantages including its high content of moisture and low density of energy. The gasification process includes four stages: drying, devolatilisation, solid char and volatile products of incomplete oxidation, and reduction reactions among the emitted gases. The primary reactions occurring in a biomass gasifier are indicated in Table 1[1].

As mentioned before, syngas is the main product of the gasification process in gaseous phase which is composed of partial combustion products (such as CO and light hydrocarbons like CH_4) and of H_2 and CO_2. Nonetheless, several parameters are influential on determination of its actual composition, such as the types of biomass and gasifier, working conditions and so forth. Obviously, the adopted oxidizer is one of the most significant and causes a great difference as demonstrated in Table 2[2].

Table 1. The primary reactions in a biomass gasification process

Reactions
Heterogeneous reactions
Combustion
C + ½O2 → CO (partial oxidation)
C + O2 → CO2 (total oxidation)
Pyrolysis
4 CnHm → m CH4 + (4n - m) C
Gasification
C + CO2 → 2 CO (Boudouard)
C + H2O → CO + H2 (carbon reforming)
C + 2 H2 → CH4 (hydrogasification)
Homogeneous reactions
Gas-phase reactions
CO + H2O → CO2 + H2 (water gas shift)
CO + 3 H2 → CH4 + H2O (methanation)

Table 2. Molar percentage composition of syngas based on different oxidizers [db]

	Air	**Oxygen**	**Steam**
CO	15-25	30-37	32-41
CO_2	5-15	25-29	17-19
H_2	10-20	30-34	24-26
CH_4	1-3	4-6	11-12
C_2H_4	0-1	1	2-3
N_2	43-55	2-5	2-3
LHV [MJ/Nm^3]	**4-6**	**9-11**	**12-15**

As it is clear, when the air plays the role of oxidant agent, a noticeable amount of nitrogen is found in the syngas that results in the lower LHV than the other two cases. However, it must be noted that all small-scale power plants only utilize air as oxidizer, since installation of required systems for steam production or oxygen separation would not be justified. It is easy to figure out that gasification is influenced by several losses, like heat dissipations related to the LHV or the sensible heat of discharge charcoal or ash. However, the syngas exits the gasifier owns an applicable part of the thermal energy output (approximately 20%) due to its high temperature. But, this energy contribution is usually lost during the essential cleaning processes or being recovered by heat exchangers; therefore, the only useful output of the gasifier, the syngas LHV, is being considered to calculate the gasifier performance. The parameter that called cold gas efficiency, takes into account the syngas LHV against the solid fuel power input which expresses the quantity of the gasifier performance. That is,

$$\eta_g = (\dot{m}.LHV)_{SYNGAS} / (\dot{m}.LHV)_{BIOMASS} \quad . \qquad (1)$$

It is important to note that, in spite of the process losses, the gasification process (converting solid fuels into gaseous ones) has numerous benefits including easily being transported and accumulated, lower burning emissions, and beyond everything else, higher combustion efficiencies and using the gaseous fuel in high-efficiency gas-fed plants. Regarding this fact, it must be recalled that despite the several syngas applications, the only purpose of the work is to focus on producing power of biomass syngas. The typical solution to use up syngas on small-scale power plants is CHP with internal combustion engines and micro/small gas turbines. Eventually, since syngas exited the gasifier is full of contaminants which are required to be eliminated; the gasification unit system is built by syngas cooling and cleaning systems in addition to the gasifier. The reason for cooling the syngas lies in the fact that the cleaning process usually cannot be performed at high temperature, so the cooling process of the syngas is essential at earlier step.

2.1. Types of gasifiers

While gasification is not an entirely verified technology, there are several solutions available at commercial level. Gasifiers are distinguished by a fixed, fluidized or entrained bed from an operating viewpoint. Fixed-bed gasifiers, on the basis of the direction of the flow of air and biomass, are characterized in updraft (counter current), downdraft (co-current) and crossdraft type, whereas in fluidized-bed ones, different types are made in bubbling, circulating and dual gasifier based on the features of the bed. The main value parameters of these gasifiers are shown in Table 3[3, 4].

Table 3. Main operating parameters of gasifiers

		Reaction temperature [°C]	**Output gas temperature [°C]**	**Tar [mg/Nm^3]**	**Biomass size [cm]**	**Maximum moisture [%w/w]**	**Input flow capacity [t/h]**	**Power capacity [MW_{el}]**
Fixed bed	*Updraft*	1000	250	High	0.5 – 10	50	10	1 – 10
	Downdraft	1000	800	Low	0.1 – 10	20	0.5	0.1 – 1
	Crossdraft	900	900	High	1 – 10	20	1	0.1 – 2
Fluidized bed	*Bubbling*	850	800	Medium	< 2	30	10	1 – 20
	Circulating	850	850	Medium	< 1	30	20	2 – 100
	Dual	800	700	High	< 2	30	10	2 – 50
Entrained bed		1000	1000	Low	< 0.2	20	20	5 – 100

As it can be discerned, fixed-bed gasifiers are more suitable for small-scales, due to the requirement of keeping a compact and firm bed that restricts dimensions of the plants, whereas fluidized and entrained bed reactors are more used on larger sizes and they would be unreasonable for small scales as well. Moreover, plant size in thermal capacity is equal to the product of the electrical terms multiplied by 2.5 – 5.

As previously mentioned, the main aim of this work is to assess small-scale biomass syngas fired power generations, therefore the different types of fixed-bed gasifiers will only be focused and described [2, 3].

Updraft or counter-current gasifiers: In these gasifiers, biomass and air or producer gas (syngas) move in contrary directions, inasmuch as the fuel is supplied from the top of the reactor by means of a hopper and descends, being in contact with the hot syngas current rising up from the base point (Fig.1). As it shows in the Fig.1, the solid fuel faces the drying region at the beginning, releasing its moisture due to the hot ascending producer gas; in lower layers, pyrolysis reactions occur, and biomass is decomposed into charcoal, tar, pyrolysis gas and freeing its volatile matter via using the hot gases heat; there is then the reduction region and combustion zone at last, while air is injected there on the underneath grate, where H_2O and CO_2 are mainly created at high-level temperatures according to burning charcoal. In fact, the products of combustion reactions rise up through the spaces of the charcoal bed, transforming the stored thermal energy into chemical one to some degree through the endothermic reduction reactions, resulting in the syngas.

As indicated in Table 3, the exited syngas of the gasifier is rich in condensable volatile matters, i.e. tars, the reason is related to this fact that the gas flow finally passes the pyrolysis region (drying region is not relevant in chemical terms). Although due to raising the LHV by tars, this may be considered as a desirable point from an energy view point, their condensation can cause occlusions on pipes or nozzle. Therefore, owing to unacceptability of the fouling in combustion chambers or valves, the syngas produced by this type of gasifier is not directly practical in ICEs and GTs. However, since a full drying and substantial biomass pre-heating are provided by freeing part of the ascending syngas sensible heat and thus leaving the reactor at low temperature, the plant can be fed with vey moisturized solid fuel (up to 50%) achieving high cold gas efficiencies.

Downdraft or co-current gasifiers: As shown in Table 3, the last features of updraft gasifiers regarding tar amounts, moisture acceptability and syngas exit temperature are not obtained in downdraft gasifiers. Figure 2 reports two of the most accepted configurations: throated (or Imbert) and open-core (or stratified). In both configurations, solid fuel and oxidant agent generally move in the same direction through the reactor.

In throated gasifiers, air is inserted through a set of nozzles placed at almost one third of the reactor height by the reduction zone, where the combustion reactions occur and feeding by the volatile products of the pyrolysis process, thus leading to the syngas with low tar content. Upper layers involve non-reacted materials and those which supported by the throat and supplied by means of the combustion released heat.

An incandescent bed is formed under the throat by produced charcoal during the pyrolysis process which

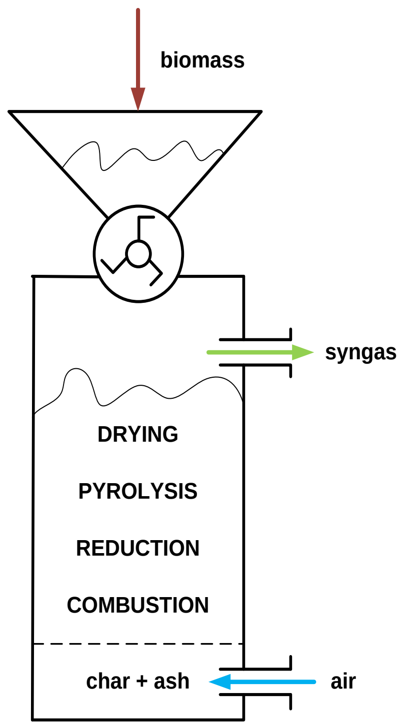

Fig. 1. Scheme of an updraft gasifier

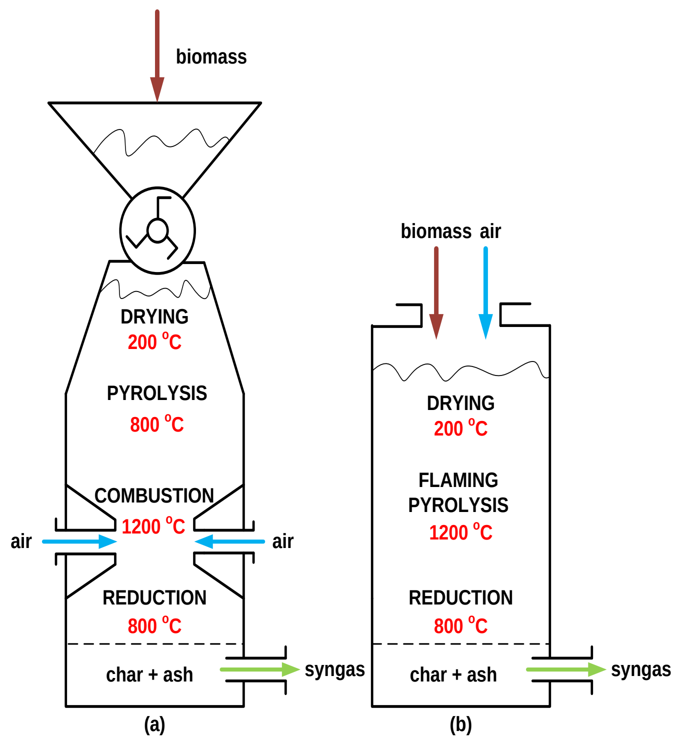

Fig. 2. Schemes of downdraft gasifiers a) throated, b) open-core

is held up by a perforated grate. In fact, the syngas is formed by the gaseous products of combustion process passing though the mentioned bed and being involved in the reduction reactions, that then crossing the grate and leaving the gasifier. The material left over in a cinerary underneath the grate includes reduced char in dust together with ash, which represents 2 – 10% of the input solid fuel. Of course, charcoal is usually separated from the leftover materials and utilized for energy objectives, due to its roughly high LHV (≈ 20 MJ/kg).

On the other hand, the syngas exit temperature is considerably higher and cold gas efficiency is lower than in the updraft type, because its sensible heat cannot be recovered in the reactor after the reduction zone. Therefore, in order to thermodynamically optimizing the process, a subsequent syngas sensible heat recovery is required. Moreover, drying capacity is not high enough similar to the updraft case and input biomass has to be previously dried, since the drying zone heat is supplied from the lower layers. However, due to the low tar content, these gasifiers are able to be integrated with ICEs and GTs directly or later than some treatments with much less difficulty than those which would be needed in the updraft type, and this is the main reason why these plants are more appropriate for feeding of power generation plants.

Another crucial point is relevant to biomass pieces size which must be large enough (more than 10 mm), due to the fact that the bed has the features of being self-supported on the throat besides the regularity. Thus biomass pieces with elongated and irregular shapes may lead to the phenomena of bridging (the circumstance of forming an obstacle during material descending flow causing temperature fluctuations) and channeling (the phenomenon of falling of non-pyrolysed biomass fuel in the reduction region leading to producing high amounts of tar and other non-reacted materials). Another drawback to the configuration is that if the plant is scaled-up, the throat is too wide for the oxidant agent to reach the center of the bed, thus causing problematic conditions and limitations in larger scales.

In order to solve the problems of onerous injection of the oxidizer though the nozzles and hence to plant scaling up, the open- core type has been developed. As shown in Fig. 2, removing the throat, solid fuel and oxidizer can easily enter the reactor from the top and go together in a downward direction, thus being mixed together uniformly from the beginning. Due to this early mixing, pyrolysis and combustion process take place together after the drying zone, which is called flaming pyrolysis, because volatile matter produced during pyrolysis process is burned by the oxidant agent at once. Nevertheless, except the last point, the entire process is similar to the throated configuration.

Crossdraft gasifiers: these types of gasifiers are considered as a halfway solution between the downdraft and updraft cases. While solid fuel is loaded from the top of the reactor, the oxidant agent is inserted through a nozzle from only one side at high velocity and the producer gas exits the gasifier from the other one. Due to the very small volume of the reaction encompassed by layers of biomass, charcoal and ash, it has the benefit of thermal dissipation and provides the opportunity of using the low-priced materials for the gasifier walls that are prone to lower thermal stress. However, the most significant feature of these gasifiers is the low inertia, resulting in favorable response to load changes and fast starting-up, because of the small amount of biomass involved in the reactions. Due to this reason, these gasifiers are usually more applicable for small scales where a number of starts and stops may take place throughout a day, although their utilization is nowadays rather limited [2, 3].

2.2. Syngas treatment

Syngas leaving the reactor can be directly utilized just in a burner for direct combustion, otherwise it has to be cleaned up due to the syngas impurities which would cause heavy damages in pipes and the user apparatus itself. The syngas cleaning system following the gasifier is an essential section of the entire gasification plant which is as significant as the reactor itself; in fact, the main issues which limit conclusive commercial rise in gasification technology primarily lie in this section.

A comprehensive review on the principal pollutants found in syngas, their relevant difficulties and the most useful technologies for their treatment is indicated in Table 4 [5].

The final usage of syngas (ICEs, GTs, heat production, co-combustion, burners and so on) determines the plant configuration, regarding both the gasifier and the treatment system, and noticeably the need to concentrate on some pollutants rather than the others, and thus each one has its own special requirements. In general, internal combustion engines are more tolerant of pollutants than gas turbines. In fact, the most detrimental effects on gas turbines are caused by alkali metals and sulphur compounds which result in corrosion of the blades. Besides, chlorine compounds which can interact with the metals are able to cause corrosive effects. Particulate materials also have damaging and eroding effects on the moving components, again more extremely on gas turbines than internal combustion engines. Indeed, although turbines are slightly vulnerable to tars, due to the high gas temperature maintaining them in vapor form, these tars become condensate on the piping apparatus, and having problematic impacts especially while passing though the compressor. Therefore, tars requirements are absolutely strict for GTs rather than for ICEs [6]. Table 5 gives reports of some limit values of the contaminants amount for ICE and GT power plants [7]. However, it is essential to recall that the data just are taken into account as a rough guide.

3. Small-scale power plants

In the present work, three specific sizes have been considered: 100 kW_{el}, 1 MW_{el} and 5 MW_{el}.

Table 4. Syngas contaminants, the difficulties and treatment methods related to them

Contaminant	Samples	Difficulties	Treatment method
Particulates	Ash, Char, Fluidized bed material	Erosion	Filtration, Scrubbing
Alkali metals	Sodium, Potassium compounds	Hot corrosion	Cooling, Adsorption, Condensation, Filtration
Fuel-bound N_2	Mainly ammonia and HCN	NO_x formation	Scrubbing, SCR
Tars	Refractive aromatics	Clog filters, difficult to burn, deposit internally	Tar cracking, Tar removal
Sulphur, Chlorine	HCl, H_2S	Corrosion, Emission	Lime or dolomite scrubbing, Absorption

As a matter of fact, although the latter size cannot appropriately be taken into consideration as a small scale power plant, in order to having a kind of upper scale reference values, it has been considered. Moreover, all the adopted power technology considerations for the two former sizes can be ordinarily utilized for the 5 MW_{el} sizeas well. In general, commercially available power plants have been taken into account, on the basis of internal combustion engines (ICEs) and gas turbines (GTs) (in case in the micro turbine (mGT)).

3.1. CHP production

Small-scale power generation is included in the extensive concept of Distributed Generation (DG), being expressed by on-site power generation (close to a house, middle-sized industrial factory and so on as the final user) and creating electric surplus with low or medium-voltage grid. This feature gives the opportunity of easily following the power load variations and prevention of losses, concerning the essential transmissions and distribution processes in case of centralized generation in large-scale power plants. On the other side, DG led to heavy penalties in case of natural gas usage in comparison with large-scale power plants in all cost determining factors including investment, fuel and O&M (Operation and Maintenance). Accordingly, natural gas-fed DG systems may be reasonable in both energy and economic terms, only if the waste heat through a CHP (combined heat and power) system is recovered.

This way, the adoption of small-scale power plants can be justified and competitive with larger ones, due to the fact that heat production compensates for the lower electrical efficiency [8].

In general, since biomass is exploited through a gasification process, which its processes often overlap the combustion ones, the above discussion can be applied for it, while the necessity of heat recovery is less essential due to the two main factors. First, the performance of small-scale biomass-fed power plants, differently from natural gas-fed (methane-fed) ones, is considerably comparable to that of large-scale ones. For instance, the electrical efficiency of 1 MW_{el} – size plant is almost equal to that of large steam cycles (≈25%).Actually, it should be considered that while large scale natural gas plants denote approximately 300 – 500 MW_{el} size, it equals to 10 – 20 MW_{el} for biomass ones. Second reason to take into account is related to the noticeable economic incentives which many countries grant for small-scale power generation from renewable energies, but are not considered for heat generation and whose incidence is then lower. It is another reason why this work has focused mainly on the power generation maximization, although effect of thermal production of waste heat has been investigated as well, due to its influential contribution on the overall plant optimization. As a result, while in case of biomass feeding, CHP production is not obligatory, it is essential on small-scale methane-fed power plants.

Table 5. Limit value of the gas quality in order to use in ICEs and GTs

	Tar [mg/m^3]			Particles [mg/m^3]			
Internal Combustion Engines	Max		Preferred	Max		Preferred	
	< 100		< 50	< 50		< 5	
Gas Turbines	**Tar**[mg/m^3]	Particles [ppm]	Na [ppm]	K [ppm]	S [ppm]	HCl [ppm]	Other metals [ppm]
	5	< 1	< 1	< 1	1	< 0.5	< 1

3.2. Internal combustion engines

Internal combustion engines are available in a broad range of sizes, i.e. 1 kW_{el} – 10 MW_{el}, hence covering the three cases mentioned here. In fact, the smallest sizes (engines with a capacity less than 30 kW_{el}) are suitable for little business activities or residential buildings and have not yet been developed for industrial applications. Therefore, the following considerations are applied for the engines with the capacity higher than 30 kW_{el} size [9].

Internal combustion engines are conventionally reciprocating with several processes taking place in the cylinders in accordance with the piston movement. They are generally able to use a broad range of fuels; nevertheless natural gas is usually adopted for CHP application, because of being environmentally compatible and constantly accessible as well as having comparatively low costs. There are commonly two primary engine types: spark ignited (SI) based upon Otto cycle and compression ignited (CI) on the basis of Diesel cycle. Due to characterizing by an appropriate anti-knock behavior, methane is proper for utilization in SI engines which is the mainly used solution and is just discussed in this work.

SI engines performance is realized by four movements of the piston. During intake stage, the injected fuel is mixed with air flow and adiabatically compressed, then a plug produces a spark to ignite the mixture, and in final stage it adiabatically expands to create useful work. After discharging hot gases, the cycle is being performed again [10]. It is supposed that the high temperature in compression phase could lead to mixture self-ignition (knocking), thus limiting the compression ratio ranging between 10 and 14. As already mentioned, the entire work is accomplished via four strokes of the piston, two upwards and two downwards, while two-stroke engines may be considered as well, nevertheless the latter one is not ordinarily adopted for CHP applications and has poor environmental performance.

In SI machines, the mixture can be either stoichiometric or more frequently lean burn (the condition which the stoichiometric air to fuel ratio is less than the real one, due to limiting NO_x production). Internal combustion engines have some advantages including high reliability, low specific cost, high electrical efficiency, suitable service life as well as high flexibility in load changes under different operating conditions. On the other hand, they are influenced by some imperfections: high O&M costs, high vibrations and noise, and necessity to install catalysts in order to control high emissions of contaminants such as NO_x and CO [8].

Nevertheless, except for these disadvantages, due to their high efficiency and reliability they are considered as the most adoptable solution for CHP applications on small scales. In this case, heat recovery can be done both by using hot flue gases leaving the engine at 350 – 550°C, and by cooling water (cylinders jackets, lube oil) usually available at 90°C. Moreover, it is quite important to consider that the electrical efficiency of SI internal combustion engines is approximately30%, 35 – 40 % and 45% for 100 kW_{el}, 1 MW_{el} and 5 MW_{el} – capacity, respectively (obtained results based upon [11]).

3.3. Gas turbines

Gas turbines stem from the Joule-Brayton cycle, including an adiabatic compression, an isobaric heating up, an adiabatic expansion and an isobaric cooling. In most cases, air through an open cycle is being compressed, and then sent to a chamber where the fuel is mixed with air and combustion occurs, afterwards, hot gases expansion takes place through turbine in order to produce useful work, and they eventually are released in the open air.

The design of gas turbines is particularly complicated involving numerous related issues regarding aero and fluid dynamics, heat transfer, metallurgy sciences and so forth. Basically, these plants include a broad variety of power capacity that is between 500 kW_{el} and 350 MW_{el}, nevertheless real competitiveness is ordinarily attained beginning from 5 – 10 MW_{el} sizes only. In fact, in order to achieve good efficiencies on small scales, high technological contents of these plants are inapplicable or unjustified. For example, as it is known, an increase in turbine inlet temperature (TIT) can improve the performance which needs to adopt complex materials and metallurgical methods in addition to use progressive techniques to install a first stage cooling system for turbine. As a result, accompanied by the increase of TIT, maximum pressure gets higher, which implies the necessity of the installation of first stages cooling to the machine, leading to additional costs, which would be unreasonable for small-scale plants. Moreover, the efficiencies of small turbines and compressors are penalized by size effects, which lead to negatives impacts on the overall plant performance.

Actually, the reason lies in the fact that small turbines are simply built by scaling-down the larger ones while their basic architectures remain the same. Indeed, gas turbines are particularly axial configurations, whereas the adoption of radial configuration is more suitable for the smallest scales (500 kW_{el} – 1 MW_{el}), due to their low mass flow rates. At last, it must be noted that small-scale turbines need a higher rotational speed with a transmission system which becoming more troublesome with reducing size, while larger ones (with the capacity of higher than 40 – 50 MW_{el}) can be directly integrated with an alternator. Besides, again according to the results of [11], the electrical efficiency of the small scale alters from 20 – 25% up to 40 – 45 %. Therefore, as the efficiencies of small gas turbines are extremely low, it is obvious that smaller sizes (< 500 kW_{el}), in this condition, would have unsatisfactory performance. Consequently, reconsidering machine architecture and operating characteristics, numerous configurations have been suggested and investigated among which the regenerative open cycle is considered as the mainly prevalent and recently developed solution.

In fact, this specific solution is ordinarily adopted for all the various plant types on these scales, so-called micro gas turbines.

Micro gas turbines differ from the classic ones in almost all their primary components except for the combustion chamber. The device is made-up of a single-stage centrifugal compressor and a single-stage centripetal turbine which are mounted on a shaft running at a high rotational speed (50,000 – 120,000 rpm) which is essential to obtain a good performance with such low mass flow rates. Due to absorbing heat from hot gases exited the turbine by air, a recuperator before the combustor is always installed through which the air exited the compressor passes. Therefore, hot gases which expanded through the turbine cross the recuperator.

Eventually, since hot gases usually have appropriate heat content, passing through a cogenerative exchanger to produce useful heat in the form of low-pressure steam or hot water. Most of the time, a fixed magnet generator is installed on the shaft, avoiding the mount of a mechanical reduction gear, to produce high efficiency electricity and finally invert to 50 Hz (or 60 Hz) AC. It is quite necessary to adopt the recuperator in order to attain suitable efficiencies even with the pressure ratio of 4 – 4.5 which enabled by single-stage radial machines. As a matter of fact, at such a low pressure ratio, concerning simple cycle, temperature would become too high at turbine outlet and too low at combustor inlet resulting in an acceptable efficiency. Besides, in order to increase the pressure ratio, the adoption of multi-stage machines would be required leading to an increase in investment costs.

Therefore, since the installation of a recuperator can exploit the energy of the flue gases to heat up the entering air to the combustion chamber, it is considered as the best solution for these problems [8]. Under the mentioned condition (pressure ratio of 4 – 4.5), turbine inlet is usually 900 – 950 °C, and since there is no turbine cooling, electrical efficiency will be achieved around 30 % which is as high as the one obtained by simple-cycle gas turbines with the capacity of 5 MW_{el}. Obviously, higher turbine inlet temperatures result in higher efficiencies.

At this time, there are a few models of micro turbines available on the market with a power capacity of 30 – 250 kW_{el} and corresponding efficiencies ranging between 25 – 33%. Therefore, it seems that micro-turbines performance is able to be compared with the internal combustion engines one. However, its investment costs are slightly higher and its reliability cannot be comparable with the engines one. On the other hand, it is also interesting to be considered that micro gas turbines have the great advantage of consisting very low content of contaminant emissions which is considerably lower than those of internal combustion engines. However, apart from this point, internal combustion engines are more often adopted, except from particular cases which strict environmental requirements are needed.

4. Working hypotheses

In this section, issues and hypotheses are introduced to simulate thermodynamic performance obtained by the considered power plants. As previously mentioned, Thermoflex™ has been selected to simulate considered power plants. The 19th version of the software has been used that is the second one having a section particularly dedicated to gasification.

4.1. Thermoflex™

Thermoflex™ is considered as one of the preferred thermal engineering software products provided by Thermoflow Inc. and designed in order to simulate power and cogeneration industries. Differently from other Thermoflow products, i.e. GT PRO™, GT MASTER™, STEAM PRO™, STEAM MASTER™ and RE-MASTER™ each of which is dedicated to a specific single type of power plant, Thermoflex™, instead, is a fully-flexible software which not only enable to be coupled with aforementioned power plants, but it can also be developed subsequently to model various thermal systems. In fact, it can be taken into account as a modular program which has a graphical interface that lets the user build a plant model by choosing different icons representing various components with an immediate meaning, i.e. boiler, turbine, compressor and so forth. Moreover, depending on the treated fluid, a specific color is dedicated to the different components. For instance, red color is designated to gas or combustion products, while the color of blue and orange are considered for water flows in any phase and fuels respectively (with the help of [11]). Moreover, defining all design parameters such as operating conditions, efficiencies, head or heat losses, etc., an option menu is related to each component. Subsequent to drawing and checking phases, the simulation can be performed and results are eventually depicted. Therefore, the information regarding the simulated plant including overall plant data, i.e. power output, electrical efficiency and so forth, typical characteristics of the different components, i.e. size, produced or absorbed power and so on, as well as quantities of thermodynamic parameters, i.e. temperature, pressure, enthalpy, mass flow rate, etc, are then provided.

Moreover, it should be noted that results are absolutely relevant to full-load steady conditions, and transient phase is not considered in the present work. Besides, Thermoflex™ has another great advantage of consisting pre-built commercial power plants, i.e. gas turbines and internal combustion engines that are extremely significant for the aims of this work. The reason is that models of ICEs cannot be assembled from simpler elements, although gas turbines can be constructed assembling its smaller components involving compressor, combustion chamber and turbine.

4.2.Gasification device

There are three specified models of gasifiers that can be applied in addition to a user-defined general purpose one. However, all the three types are especially usable for oxygen-blown commercial gasifiers designated to large coal gasification power plants. Therefore, it is clear that the user-defined case is the only solution to be fed with any fuel and has been considered here as well. However, a necessary component of fuel preparation is present in the gasifier figure placed after the input fuel component before entering the gasifier, which is applied for large pressurized coal power plants, where coal must be mixed with a stream of water and nitrogen before feeding the device.

While the mentioned component is normally not present on small-scale gasifiers, since they are operated at ambient pressure with mechanically fed fuel, Thermoflex™ compels to consider a water/nitrogen source anyhow. Consequently, due to the aforementioned reasons, its mass flow rate has simply been considered equal to zero in all simulating models.

In addition to the described component, there are two input flows including solid biomass and oxidant agent, and two output flows, the raw syngas as well as the slag. Indeed, in order to define the gasifier, type of oxidant agent, air flow ratio, gasifier temperature and pressure have to be given to the software. Also, while biomass type has already been recognized, the model can be completed by considering auxiliaries power consumption, slag exit temperature and other subsidiary parameters. After running the simulation, syngas composition, lower heating value (LHV), mass flow rates and cold gas efficiency are provided as the results.

4.2.1. Considered reference plant

Gasifiers manufactured by Ankur Scientific which is the name of an Indian company, are taken into consideration as the reference plants here (their products are also distributed in some of the European countries), [12].They are air-blown ambient pressure downdraft gasifier, with average combustion temperature ranging between 1000 – 1100°C and reduction temperature of 600 – 800°C.The produced syngas is composed of 16 – 18% CO, 16 – 18% H_2 and 2 – 3% CH_4 (molar fraction (db)) with the LHV of nearly 5 MJ/kg and exits the reactor at 500°C. The cold gas efficiency is reached to 80%.

It must be noted that, in fixed-bed gasifiers, differently from fluidized-bed ones, there are different reaction regions with their own temperatures, thus referring to a unique gasification temperature is not accurate. However, Thermoflex™ needs to indicate a singular value for this parameter, hence considering an intermediate equivalent temperature is essential to appropriately simulate a fixed-bed gasifier. In the present work, an average temperature of 800°C is considered, since it is the most proper choice in order to achieve the LHV of 5 MJ/kg and cold efficiency of 80% (according to the results obtained by [11]).

4.3. Syngas considerations

In order to distinguish the exploitation of biomass syngas in power plants from classic natural gas feeding one, there are main issues required to be carefully investigated including combustion processes, syngas treatment and low LHV of syngas. For the first issue, it must be considered that syngas has the features of high flame speed and temperature, broad flammability limit and most importantly, the presence of hydrogen. Concerning the mentioned issues, there is a broad range of literature available; nevertheless, it is adequate to hypothesize that the device is suitably designed and regularly operated. However, the two other aspects must be discussed more meticulously.

4.3.1. Syngas treatment

As already discussed, pollutants contained in syngas can cause potential difficulties, hence utilization of cleaning systems is essential. In this section, the procedure of modeling the syngas treatment phase in Thermoflex™ as well as the considered assumption will be described. In fact, a real complete gasification plant includes a cleaning section usually made-up of a dry multi-cyclone in addition to a cyclone for separating water, a syngas-air heat exchanger, a wet scrubber, a compressor, a condenser as well as biomass filters and a fabric one. Fortunately, in the recent versions of Thermoflex™, models for all these components are considered, thus a cleaning section following the gasifier can be assembled. However, as before stated, syngas exiting the gasifier is previously clean, since it is just composed of CO, CO_2, CH_4, H_2, H_2O and N_2, apart from hydrogen sulphide (H_2S) and carbonyl sulphide (COS); hence, we can conclude that it has no effect in the subsequent power plant section. Therefore, all the syngas cleaning section components will be useless, and thus they are only applied for completion the plant to introduce their head losses, and concerning scrubber or wet compression, a moisture variation is determined. It is obvious that taking these components into account often cause computational difficulties, hence the final model just involves two simple components, i.e. a moisture separator as well as a heat exchanger in order to simulate the temperature drop (down to 20°C) and head losses. Of course, the real components power consumption has been loaded to the gasifier. Figure 3 indicates the last considered model in Thermoflex™.

As it is visible in the Fig.3, there is a hypothetic cooler after the reactor in order to reduce temperature from 800°C to 500°C at the output (the desired syngas exit temperature is usually equal to 500°C). Moreover, largest part of the syngas sensible heat is vanished at the heat exchanger reaching to about 60 – 100°C, while the other remaining part is dissipated during the subsequent treatment operations, thus the sensible heat contained in the raw syngas is mostly recovered in the reference plant. Therefore, in the present work, syngas sensible is sent to a heat exchanger to absorb its heat by an air stream which blown by a fan whose mass flow rate is set in order that the effectiveness of heat

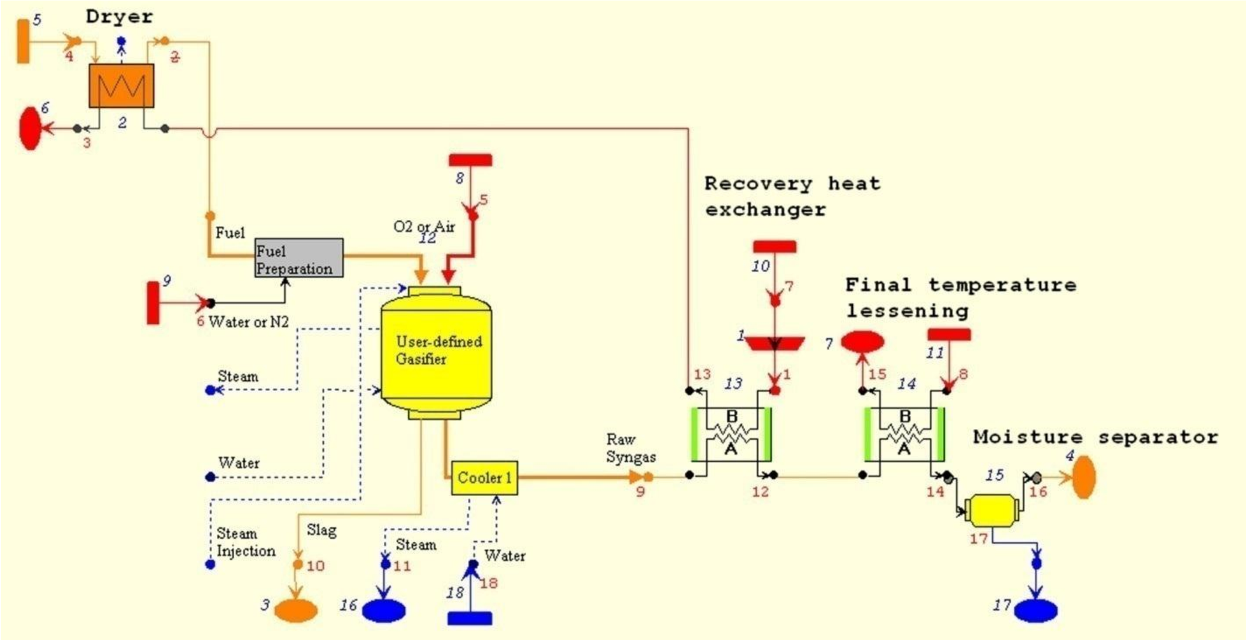

Fig.3. Final gasification model

exchanger reaches to 90%. Subsequently, the absorbed heat utilized for biomass input drying. The last decrease of temperature occurs through another heat exchanger by which temperature of 60 – 100°C reaches to 25°C, and then exited syngas passes through a moisture separator.

4.3.2. Low LHV of syngas

As already stated, the produced syngas with air as the oxidant agent results in a lower heating value of 5 MJ/kg or 5 MJ/Nm^3 (its density equals to about 1 kg/Nm^3), while those of methane equals to roughly 50 MJ/kg and 35 MJ/Nm^3, which implies that if syngas is utilized to feed the plant instead of methane, in order to get the same power input or the equivalent maximum temperature a considerably higher amount of biomass fuel would be required that includes surplus significant changes on the plants. Due to the important differences concerning these issues between ICEs and GTs, these plants will be individually discussed.

4.3.2.1. Internal combustion engines

As previously stated, Thermoflex™ has pre-built components of internal combustion engines, assumed to be fed by natural gas (methane) regarding SI devices. Each model is featured by default values of power output, electrical efficiency as well as mass flow rate of flue gas. Feeding the engine with a fuel with lower LHV than that of methane, a higher mass flow rate of the fluid is needed, thus the software in order to compensate the mentioned increase reduces the amount of entering air, so that flue gas mass flow rate remains constant, that resulting in the equivalent power output with the same electrical efficiency. In order to verify the correctness of this assumption, some calculation will be performed. The reaction of methane combustion in air is written as (the air molecule is considered as the (O_2 + 3.76 N_2))

$$CH_4 + 2\,(O_2 + 3.76\,N_2) \rightarrow CO_2 + 2\,H_2O + 7.52\,N_2 \quad . \qquad (2)$$

This indicates that the needed air to burn one cubic meter volume of methane equals to 9.52 m^{3}of air. Thus, the stoichiometric mass air to fuel ratio, α_{st}, can be considered as (MW refers to molecular weights of chemical elements):

$$\alpha_{st,\,CH4} = 2MW_{air} / MW_{CH4} = 17.16\ kg_a / kg_f \quad . \qquad (3)$$

On the other hand, real air to fuel ratio for commercial models, on the basis of several technical catalogues, is reported averagely around 25 – 30, [11]. Therefore, the parameter λ, introduced as α/α_{st}, is roughly 1.45 – 1.75. As a result, lower heating value of the mixture of air and methane (its mass flow rate equals to the flue gas one) entering the ICE which is calculated by dividing LHV_{CH4} into (α+1), will be about 1.6 – 1.9 MJ/kg$_g$. In order to carry out a similarcalculation for biomass syngas, its composition should be first defined.

Table 6 reports the syngas composition in terms of mass (X) and molar (Y), inaddition to the molecular weights of compounds.

Among the reported substances, CO, H_2 and CH_4 are only involved in the combustion reactions, while the two others, i.e. N_2 and CO_2 are neutral. The oxidation reactions of CO and H_2 can be written as was (CH_4 previously mentioned)

$$2\,CO + (O2 + 3.76\,N2) \rightarrow 2\,CO2 + 7.52\,N2 \qquad (4)$$

$$2\,H_2 + (O_2 + 3.76\,N_2) \rightarrow 2\,H_2O + 7.52\,N_2\,. \qquad (5)$$

Stoichiometric air/fuel ratio in both cases is 2.38 m^3

of air, which means this amount of air is needed to burn one cubic meter of the fuel. Also, corresponding to the methane stoichiometric ratio in mass terms, those of CO and H_2 are equal to 2.45 and 34.32 kg_a/kg_f respectively. Eventually, the overall air amount essential for burning 1 kg of syngas can be calculated as follows:

$$\alpha_{st,syngas} = \sum_i \alpha_{st,i} . X_i = \alpha_{st,CO} . X_{CO} + \alpha_{st,H2} . X_{H2} + \alpha_{st,CH4} . X_{CH4} = \\ = 1.24\, kg_a / kg_f . \quad (6)$$

Table 6. Syngas percentage composition

Compound	Y [%, mol]	X [%, mass]	MW [kg/kmol]
CO	20	23.1	28
CO2	10	18.1	44
H2	20	1.6	2
CH4	1	0.7	16
N2	49	56.5	28
Total	100	100	24.28

In this case, the requirement of applying a lean burn configuration seems less crucial, since syngas is previously diluted with a large amount of nitrogen which came from gasification air. Thus, in general, these engines are able to operate under stoichiometric conditions [13]. Besides, a large quantity of air can be properly exploited, thus λ can be assumed ranging between 1 and 1.5, suggesting a real air/fuel ratio of around 1.2 – 1.85 kg_a/kg_f.

On the other hand, syngas LHV can be calculated according to weighting single LHV values of the three fuel gases (i.e. CO, H_2 and CH_4 with LHV of 10.1, 120 and 50 MJ/kg, respectively). On the basis of mass fractions this is given as [11]

$$LHV_{syngas} = \sum_i LHV_i . X_i = LHV_{CO} . X_{CO} + LHV_{H2} . X_{H2} + LHV_{CH4} . X_{CH4} = \quad (7) \\ = 4.6\, MJ / kg_f .$$

Then, the lower heating value of the mixture of air and syngas can be obtained by analogous calculations to that of methane's one, and thus roughly ranging between 1.6 and 2.1 MJ/kg_g, that means the LHV of air/syngas mixture is very analogous to that of air/methane mixture, resulting in a similar fuel powerinput, and thus a similar gas mass flow rate. Hence, it can be concluded that, in case of syngas feeding, keeping the same electrical efficiency of methane one is a reasonable hypothesis. As a result, since fuel power input and electrical efficiency are the same, electric power output will be the same as well. After all, it has been indicated that assumptions of Thermoflex™ are satisfactory and its methane-fed internal combustion engine models can properly be applied for the purpose of this work.

It must be noted that this analysis has been carried out based on mass terms, due to the fact that energy balances are governed by mass flow rates and are the actual aim of the simulations.

4.3.2.2. Gas turbines

The air/fuel ratio, in methane-fed gas turbines, is ordinarily equal to around 50, i.e. fuel mass flow rate is roughly 2% of the air one, while if syngas is assumed to be applied and the compressor operates with the same air mass flow rate, thus the air to fuel ratio would become 20%, and a tenfold syngas mass flow rate would be needed. Therefore, the mass flow rate of the gas entering the turbine would rise up correspondingly. However, this couldn't be possible, because an increase in the gas mass flow rate passing through the turbine causes an increase in the pressure input, thus it is necessary to supply a higher pressure ratio for the compressor, which means that the operation point get farther from the design one, and particularly becomes close to the surge line. Therefore, it is required to take some specific actions on the power plant. The most desirable solutions would be perfectly to create an increase in the area of turbine nozzles or adding high pressure stage to the compressor device. Nevertheless, these changes lead to laborious interventions on the existing power plants from a technical point of view, and, besides, all these can be possible if shaft and turbine can stand the higher power output. Hence, most of the time, as a normal solution, input air mass flow rate of the compressor is being decreased, resulting in regulating Inlet Guide Vanes (IGVs); moreover, part of the power output increase is being lost [14]. Besides, concerning pressurized gasifiers, output air of the compressor can be used to some degree in order to feed the gasifier, so that the increase in fuel mass flow rate would be compensated (and gas as well). On the other side, obviously, if the gas turbine were particularly built up to be fed by syngas, these difficulties would not take place.

In this work, a number of plant solutions on the basis of gas turbines which are commercially available for methane feeding have been investigated. First of all, they have been particularly built up based upon disassembling the reference plant, and then the various components have been reassembled. The turbines were replaced by ones having similar characteristics, but matched with the new conditions (however, the air mass rate maintained constant). In fact, this would be in agreement with previously mentioned increase in the turbine nozzle area or adopting a particularly designed device.

4.4. Design parameters

In each one of the simulated models, ISO ambient conditions have been determined, i.e. pressure and temperature are equal to 1 atm and 15 °C, respectively; and relative humidity has been fixed to 60%.

Waste heat recovery, as mentioned before, has been carried out in all cases, resulting in low-temperature hot water for heating applications. First of all, one particular plant has been considered as the reference plant for each one of the mentioned sizes, i.e. the mGT for 100 kW_{el}, and the ICEs for 1 MW and 5 MW_{el} sizes. Therefore, in all these plants, the mass flow rate of the process water has been considered constant, in order that it is being heated up from 50 °C to 70 °C in the hot gas recuperator. However, in all the other power plants in each size, the water mass flow rate is also maintained fixed, and the return temperature has been determined at 50 °C, while the delivery one varies in the range between 65 and 100 °C, in accordance with the heat availability. Process water mass flow rates of each size are equal to 1.994 kg/s, 13 kg/s and 55 kg/s, respectively.

Actually, ICE reference plant of each size is taken from [11], and concerning gas turbines, reference plants for 1 MW_{el} and 5 MW_{el} have also been made according to [11], while for 100 kW_{el} size, a commercial plant, whose technical database has been obtained from the web, has been selected [15, 16]. Table 7 reports all the considered models of internal combustion engines and gas turbines. As it is shown, three reference plants are considered for the 5 MW_{el} size, i.e. simple, regenerative and STIG cycles (VAP refers to vapor). In general, all of these three plants are obtainable on the market just on the reported size.

However, in 1 MW_{el} case, a regenerative case has also been taken into consideration, since it is feasible due to the working temperatures and pressures and can be accomplished simply by adding a recuperator, while its STIG solution is not regarded to be justified.

In Table 8, the most relevant design data of the ICE power plants are listed. It must be noted that data related to the engine operation and performance including gas mass flow rate, exhaust gas temperature as well as net electric power, electrical and CHP efficiencies are all default parameters of Thermoflex™ software. However, data regarding heat recovery is selected by the user. For flue gases and engine cooling water, classic design parameters have been considered, except for 1 MW_{el}-size for which inlet and outlet temperature of engine cooling water have been taken at 92/82 [17].

Thus, mass flow rate of cooling water is determined by the system, according to aforementioned two temperatures. Moreover, the effectiveness of the two heat exchangers has been considered, so that the given temperatures and mass flow rates can be observed.

On the other hand, in both exchangers, since the specific thermal process does not participate in the

Table 7. ICEs and mGTs/GTs reference power plants

Size	Model	
	ICEs	mGTs/GTs
100 kW_{el}	Cat 3306	Turbec T100
1 MW_{el}	Deutz TBG 620 V12k	Solar Saturn 20-T1600
5 MW_{el}	Rolls Royce B35:40-V12 AG	Solar Centaur 50 (SIM)
		Solar Mercury 50 (REG) Rolls Royce 501-KH5 (VAP)

Table 8. Design data of reference internal combustion engines

Parameter		Unit	100 kW_{el}	1 MW_{el}	5 MW_{el}
Engine operating data	Gas mass flow rate	kg/s	0.153	1.53	8.25
	Exhaust gas temperature	°C	515	515	395
Cooling water circuit	Cooling water inlet temperature	°C	80	82	80
	Cooling water outlet temperature	°C	90	92	90
	Cooling water mass flow rate	kg/s	3.387	11.16	45.49
	Pump isentropic efficiency	%	85	85	85
	Pump mechanical efficiency	%	97	97	97
Cooling water heat exchanger	Effectiveness	%	42.1	23.9	25.1
	Heat loss	%	1	1	1
	Head loss (process water side)	%	0	0	0
	Head loss (engine water side)	%	2	2	2
Exhaust gas heat exchanger	Stack gas temperature	°C	120	120	120
	Effectiveness	%	88.7	87.1	82.2
	Heat loss	%	1	1	1
	Head loss (water side)	%	0	0	0
	Head loss (gas side)	%	0	0	0
Nominal performance	Net electric power	kW_{el}	108.7	1008	5046
	Electrical efficiency	%	30.1	39.6	45.3
	CHP efficiency	%	88.6	84.5	84.5

power plant calculation directly, its losses are not essential to be charged, and have been fixed equal to zero. Besides, pressure drop on the gas side of the exhaust heat exchanger, in order to lessen the computations, has been neglected. Eventually, efficiencies are according to the aforementioned values, and CHP efficiency is a little higher in smallest scale.

Concerning gas turbines, obviously, not all data regarding the models were known. Global cycle parameters like air mass flow rate, pressure ratio, power output, electrical efficiency, TIT and turbine outlet temperature (TOT) are known, nevertheless, other specific data like gas turbines polytropic efficiencies, head and heat losses and so on, are yet to be known. Thus, assembling the plants with those features was the first step of this work in order to clarify the unavailable data complying with the design ones.

Table 9 indicates all technical data concerning the gas turbines. It is obvious that data in relation with the recuperator at 1 $MW_{el}$is just used for the regenerative solution, and as it is clear in the table, its characteristics are also applied for the 100 kW_{el} and 5 MW_{el} regenerative case. As already mentioned, electrical efficiency of the micro gas turbine is close to 30%, while the 1 MW_{el} model is featured by low electrical efficiency except the case with recuperator in which electrical efficiency exceed 30%. Moreover, the simple 5 MW_{el} model has a lower efficiency than the regenerative power plants of smaller size, whereas this parameter in regenerative and STIG cases gets higher than 35%. On the contrary, simple cycle power plants has the best thermal efficiencies, thus their CHP efficiencies are better, whereas this parameter is a little lower in the regenerative configuration and much in the STIG case. In the STIG case, the HRSG has been displayed by a simple heat exchanger which has an effectiveness of 96% and yields a pinch temperature difference ranging between 50 and 60°C.

Table 9. Design data of gas turbines

Parameter		Unit	100 kW_{el}	1 MW_{el}	5 MW_{el} (SIM)	5 MW_{el} (REG)	5 MW_{el} (VAP)
Compressor	Air mass flow rate	kg/s	0.793	6.46	18.86	17.40	15.34
	Pressure ratio	-	4.5	6.5	10.6	9.8	13.4
	Polytropic efficiency	%	81.6	85	79	85	86
	Mechanical efficiency	%	98	98.5	98.5	98.5	99
	Inlet head loss	%	1	1	1	1	1
Recuperator	Effectiveness	%	89.3	89.3	-	89.3	-
	Heat loss	%	1	1	-	1	-
	Head loss (cold side)	%	1.5	1.5	-	1.5	-
	Head loss (hot side)	%	2.5	2.5	-	2.5	-
Combustor	COT	°C	950	899	1054	1093	1054
	Heat loss	%	1	0.5	0.5	0.5	0.5
	Head loss	%	3	4	4	4	4
	Δp/p fuel/water injection	%	40	40	40	40	40
Fuel compressor	Polytropic efficiency	%	75	75	80	80	80
	Mechanical efficiency	%	98	98	98	98	98
	Inlet head loss	%	2	2	2	2	2
	Outlet head loss	%	2	2	2	2	2
Turbine	Polytropic efficiency	%	82.2	88	92	88	83.5
	Mechanical efficiency	%	98	98.5	98.5	98.5	99
	Outlet head loss	%	1	1	1	1	1
HRSG	Effectiveness	%	-	-	-	-	96
	Heat loss	%	-	-	-	-	1
	Head loss (water side)	%	-	-	-	-	2
	Head loss (gas side)	%	-	-	-	-	2.5
	Pump isentropic efficiency	%	-	-	-	-	85
	Pump mechanical efficiency	%	-	-	-	-	97
Recovery heat exchanger	Effectiveness	%	91.8	91.8	91.8	91.8	91.8
	Heat loss	%	1	1	1	1	1
	Head loss (water side)	%	0	0	0	0	0
	Head loss (gas side)	%	2	2	2	2	2
Shaft	Rotational speed	rpm	70,000	22,516	14,950	14,180	14,600
Generator/motors	Generator efficiency	%	92	93	95	94.5	95.5
	Auxiliaries motor efficiency	%	92	92	92	92	92
Nominal Performance	Net electric power	kW_{el}	101.3	1068 (1012)*	4109	4211	5547
	Electrical efficiency	%	29.7	22.0 (32.1)*	26.7	36.1	35.5
	CHP efficiency	%	78.7	84.6 (81.3)*	85.1	83.8	61.1

* performance data put into brackets refer to 1 MW_{el} regenerative case

Then, production of steam correspondingly varies in terms of temperature and mass flow rates. Besides, in all configurations, a cogenerative heat exchanger model has been applied same as the one for internal combustion engines and its head loss on water side has been also determined as zero.

Finally, biomass devices including gasifiers, dryers and syngas heat recovery systems are presented in Table 10. As previously expected, data regarding gasifier specific consumption does not just take the gasifier power requirement into consideration, but also those associated to the whole syngas treatment systems that are disregarded here. Naturally, small-scale gasifiers operate at ambient pressure; however, in the case of pressurized solutions for gas turbine feeding, an air compressor is needed and its value varies from case to case depending upon the conditions in the combustor.

As shown in the table, concerning dryer, the percentage of evaporated biomass fuel moisture is considered as 100%, which means that a full drying, if available, is performed. As indicated, drying operation is carried out by using the air stream already considered for cooling purposes.

5. Thermodynamic analysis

After presenting the working hypotheses, thermodynamic results are indicated and analyzed now, so that the most favorable solutions among them are determined from a thermodynamic view point which will be then subject to an economic investigation to find the best solution for each size.

5.1. Investigated solutions

First and foremost, the considered configurations are listed and explained, and then results in terms of electrical efficiency (η_{el}) and CHP efficiency (η_{CHP}) are demonstrated.

Table 10. Design data of biomass devices

Parameter		Unit	Value
Gasifier	Carbon conversion	%	98
	Heat loss	%	1
	Specific consumption	kWh/t	70
	Slag exit temperature	°C	200
	Air compressor isentropic efficiency	%	75 (80 at 5 MW_{el})
	Air compressor mechanical efficiency	%	98
	Air compressor motor efficiency	%	92
Dryer	Evaporated fuel moisture	%	100
	Dried fuel outlet temperature	°C	80
	Head loss (gas side)	%	2.5
	Specific consumption	kWh/t	5.5
	Moisture evacuator isentropic efficiency	%	87
	Moisture evacuator electromechanical efficiency	%	90
Syngas heat recovery	Heat exchanger effectiveness	%	90
	Heat exchanger heat loss	%	1
	Heat exchanger head loss (air side)	%	2
	Heat exchanger head loss (syngas side)	%	0
	Air fan isentropic efficiency	%	75
	Air fan mechanical efficiency	%	98
	Air fan motor efficiency	%	92

Certainly, the prior parameter is more prominent than the latter one, since the primary goal of the present work is to investigate power generation; however, CHP efficiency is also important to provide information regarding the whole plant energy efficiency. Eventually, a feasible gasification configuration is being described, so that the best solution to reach the best performance is identified.

On the other hand, wood pellets with a lower heating value equal to 16,784 kJ/kg, have been applied as biomass fuel, which is composed of 45.8%C, 5.5% H, 39.4% O, 0.08% N, 0.01% S and 0.01% Cl [11]. It is obvious that wood pellets should not be taken as the fuel for plants feeding, since it would be unjustified in both technical and economical terms, nevertheless, it was chosen here due to its good energy features and low moisture level to achieve the most appropriate results.

One plant configuration based on internal combustion engines and six ones on the basis of gas turbines have been analyzed and discussed in this work. The considered solution for internal combustion engine integrated with a biomass gasifier which will be shown by the acronym of ICE GAS since then is demonstrated in Fig. 4. Solid biomass is fed to a gasifier which operates at ambient pressure, and afterwards syngas is produced to use for an internal combustion engine feeding. Gas turbine integrated with a biomass gasifiercon figuration (GT GAS) is analogous to the earlier one as well; however, there are a number of feasible plant versions now, in relation to the gas turbine thermodynamic cycles, i.e. simple, regenerative and STIG, and to the gasifier operating pressure including ambient pressure and pressurized. Therefore, six possible solutions based upon the combination of These various conditions are considered involving:

- GT GAS with simple cycle and ambient pressure gasifier (GT GAS SIM AMB)
- GT GAS with regenerative cycle and ambient pressure gasifier (GT GAS REG AMB)

- GT GAS with STIG cycle and ambient pressure gasifier (GT GAS VAP AMB)
- GT GAS with simple cycle and pressurized gasifier
- (GT GAS SIM PRES)
- GT GAS with regenerative cycle and pressurized gasifier (GT GAS REG PRES)
- GT GAS with STIG cycle and pressurized gasifier (GT GAS VAP PRES)

The first three plant schemes are demonstrated in Figs. 5-7, respectively. Besides, the latter three solutions are very analogous to the earlier three ones, except two details differing in which the syngas compressor is replaced by a control valve, since the fuel is previously pressurized, but on the other side an aircompressor is considered to feed the gasifier. Therefore, for brevity reasons, the last three plant schemes are not graphically presented.

Of course, not all the reported solutions concerning gas turbines have been taken into account for each scale. As already mentioned, at 100 kWel just the regenerative solution, at 1 MWel size both simple and regenerative ones, whereas at 5 MWel all three models including simple, regenerative and STIG have been considered.

Moreover, the drying system in gasification plants are indicated a little more complicated than that appeared in Fig. 3 which is solely associated to computational aspects and does not affect simulation hypotheses.

5.2.Results

In this part, results of thermodynamic models are demonstrated in form of charts, and columns of the two groups of power plants, i.e. internal combustion engines and gas turbines are shown with different textures.

As previously mentioned, results are reported in terms of electrical (η_{el}) and CHP efficiencies (η_{CHP}).

100 kW$_{el}$ size – At this scale, three types of solution have been taken into account including ICE GAS, GT GAS REG AMB and GT GAS REG PRES, which graphically depicted in Figs.8 and 9. In Fig.8, as previously mentioned, it is visible that the electrical efficiencies of the different solutions are comparable.

The electrical efficiency of ICE GAS is roughly 24% which is a predictable value, since it could be obtained by the product of electrical efficiency of natural gas-fed gas turbine (30%) and cold gas efficiency value of the gasifier (80%).

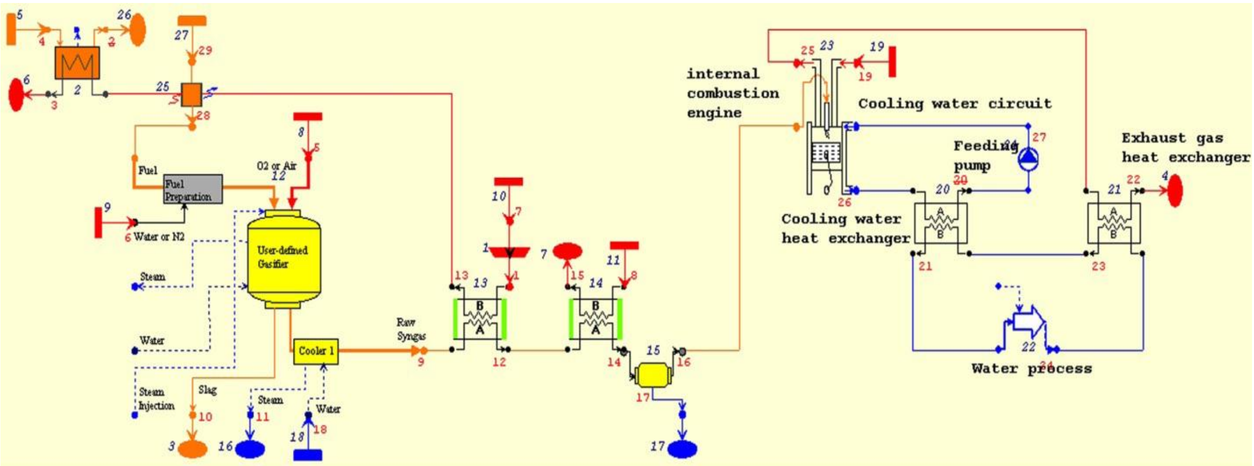

Fig. 4. ICE GAS: internal combustion engine integrated with a biomass gasifier

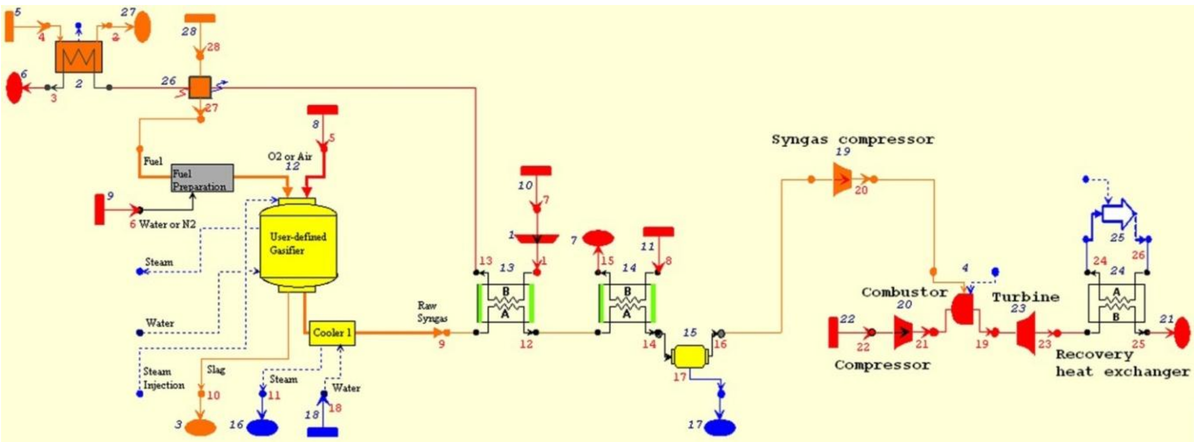

Fig. 5. GT GAS SIM AMB: simple-cycle gas turbine integrated with a biomass gasifier

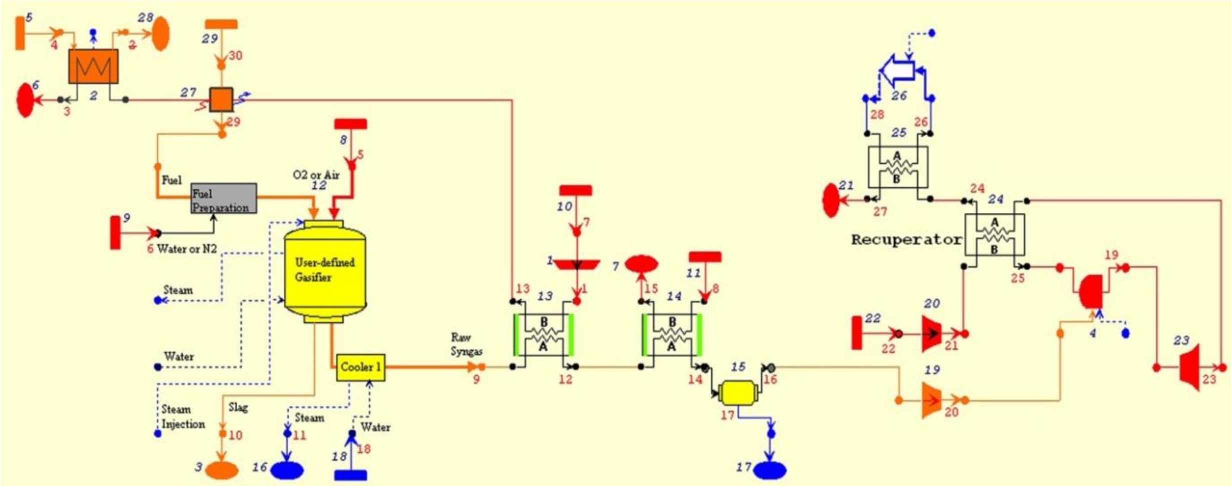

Fig. 6. GT GAS REG AMB: regenerative-cycle gas turbine integrated with a biomass gasifier

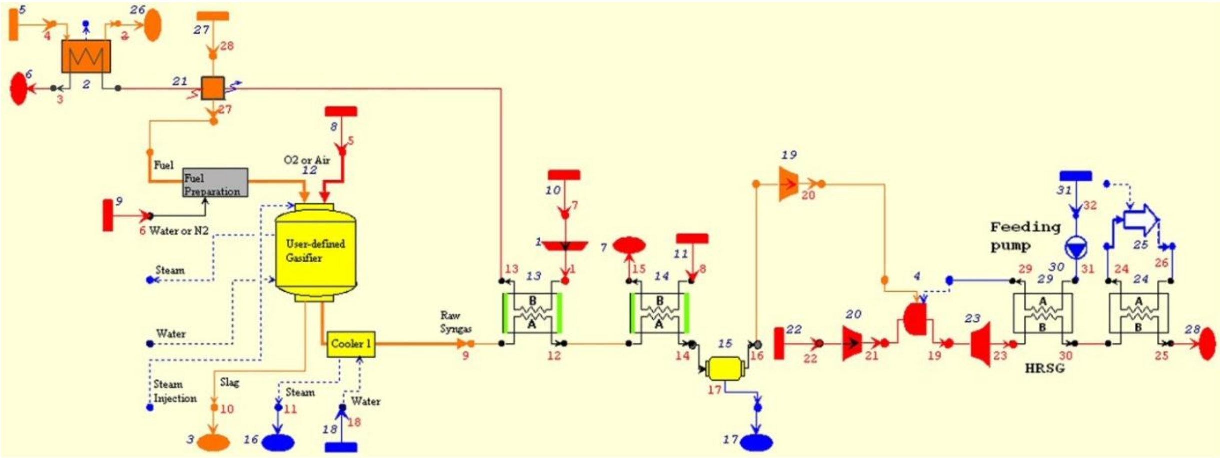

Fig. 7. GT GAS VAP AMB: STIG-cycle gas turbine integrated with a biomass gasifier

The same result is approximately achieved by GT GAS REG PRES, while the ambient pressure one is excessively reduced by electricity consumption of the compressor ranging between about 3 kW_{el} and about 28 kW_{el}, which is applied in order to supply the larger syngas mass flow rate in comparison with natural gas one, so it annuls the advantages regarding the higher power output of the turbine, which raises gross power output around 18kW_{el}. However, concerning pressurized gasifier, there is no fuel compressor anymore and the power consumption of the air compressor in order to feed the gasifier is lower (around 13 kW_{el}). Besides, it is important to note that the gasification process brings about more efficient results under pressurized conditions, which is equal to 6.5 in this case.

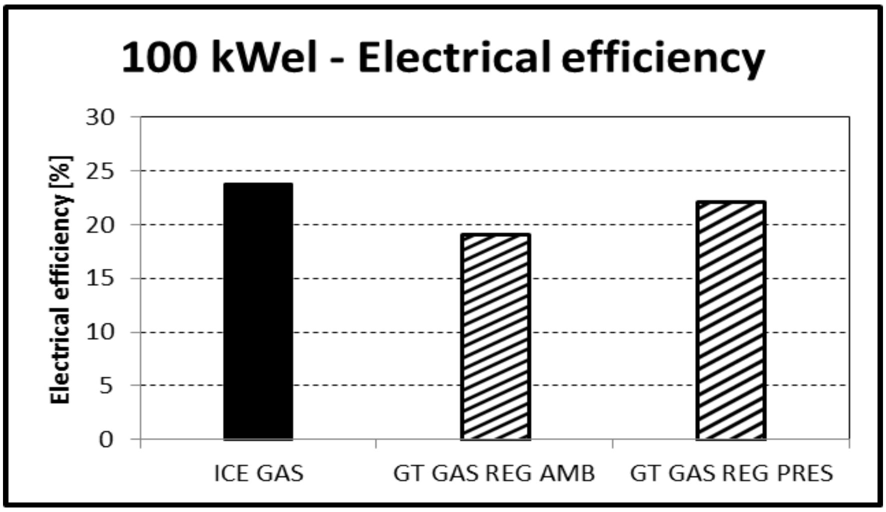

Fig. 8. Electrical efficiency at 100 kW_{el} size

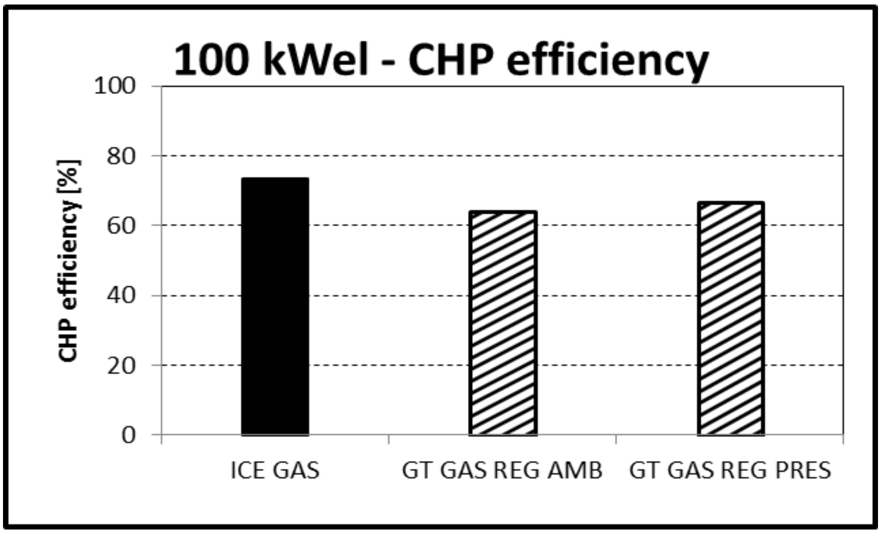

Fig. 9. CH P efficiency at 100 kW_{el}size

The first reason lies in the effective contribution ofpressure itself to increase the cold gas efficiency, while the second one to take into account is the positive effect of air compression to raise its temperature resulting in higher performance. Regarding CHP efficiencies (Fig.9), all of the solutions are penalized by the losses of syngas sensible heat leading to a reduction of around 12 – 15% in comparison with the natural gas feeding case. The results of three solutions are analogous again, same as the former ones. Therefore, it is obvious that ICE GAS and GT GAS REG PRES are the most favorable solutions at this size.

1 MW_{el} size – Five solutions have been taken into consideration for this size. In fact, in addition to the three ones already analyzed, the two GT GAS simple cycle solutions, i.e. AMB and PRES cases are now investigated. Overall results for this size are demonstrated in Figs. 10 and 11. Concerning electrical efficiency, differently from the 100 kW_{el} solution, where a balance has been observed, the ICE GAS case has the best result compared to the gas turbine plants.

Same as the 100 kW_{el} case, the result could be obtained by the product of the engine efficiency (40%) and the gasifier cold gas efficiency (80%) which is equal to about 32%. In absolute terms, an increase of around 7% compared to the former size is observed.

On the other hand, in case of GT GAS SIM plants, electrical efficiencies are the lowest ones among the gas turbine solutions, since they suffer the weak performance of simple cycle GTs, while a better result (about 25%) is obtained just with the REG PRES case.

On the other side, the analysis of CHP efficiencies does not provide any specific indications, and in all the configurations, this parameter reaches to about 65 – 70%. Similar to the previous size, the CHP efficiencies of pressurized gasifiers are 4% higher than the ambient pressure cases; this means that their cogenerative configurations are more preferable again. Therefore, as a result, the most desirable solutions are similar to those reported concerning the 100 kW_{el} case.

5 MW_{el} size – Apart from the five configurations previously investigated concerning 1 MW_{el} size, STIG cycle gas turbine plants have been analyzed, andtheir results are indicated in Figs.12 and 13. Regarding electrical efficiencies, results are similar to those concerning the 1 MW_{el} size, from a qualitative point of view. As usual, ICE GAS results exceed those of gas turbine solutions due to the engine's very high electrical efficiency. Concerning STIG cycle configurations, it is visible that they are nearly equal to the regenerative cycle cases among all of the GT GAS plants. On the other hand, relating to CHP efficiencies, the same remarks made in the 1 MW_{el} can be suggested again. It must be regarded that STIG cycle solutions lead to a strong decrease in the process heat gain, since heat is absorbed to generate steam in order to increase electrical efficiency. Finally, the most desirable solutions are the configurations already proposed.

5.3. Improving the solutions

As already described, in gasification plants, it is possible to recover the syngas sensible heat by an air stream for biomass drying applications. If the biomass moisture is high, the air stream thermal energy is completely used to dry the fuel and thus cannot be exploited for other applications, while if a fuel with low water content is utilized, such as wood pellets with about 9% moisture, the air stream after biomass drying can still be applicable for other purposes (an interesting temperature of roughly 200°C). Therefore, as a first step, the thermal energy can be exploited to feed the gasifier, that as already stated, leading to higher plant performance. On the other hand, it can be proved that input air mass flow rate is roughly twofold the syngas one, while only two thirds of syngas mass flow rate stems from gasification air leading to the fact that available hot air is approximately threefold the required one by the gasifier.

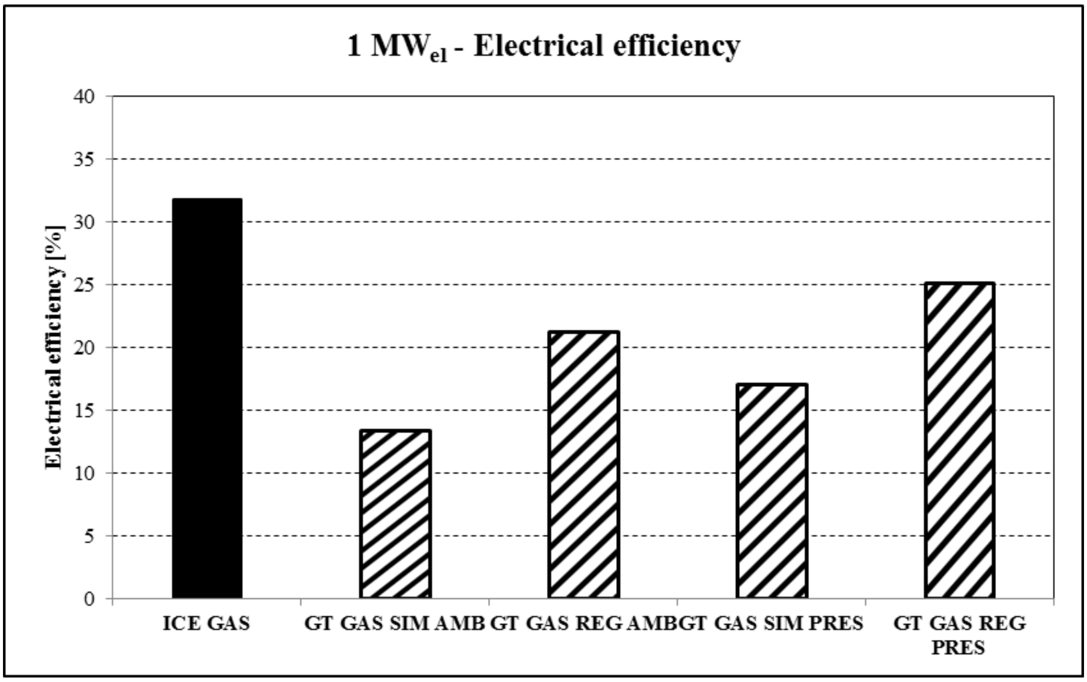

Fig. 10. Electrical efficiency at 1 MW_{el} size

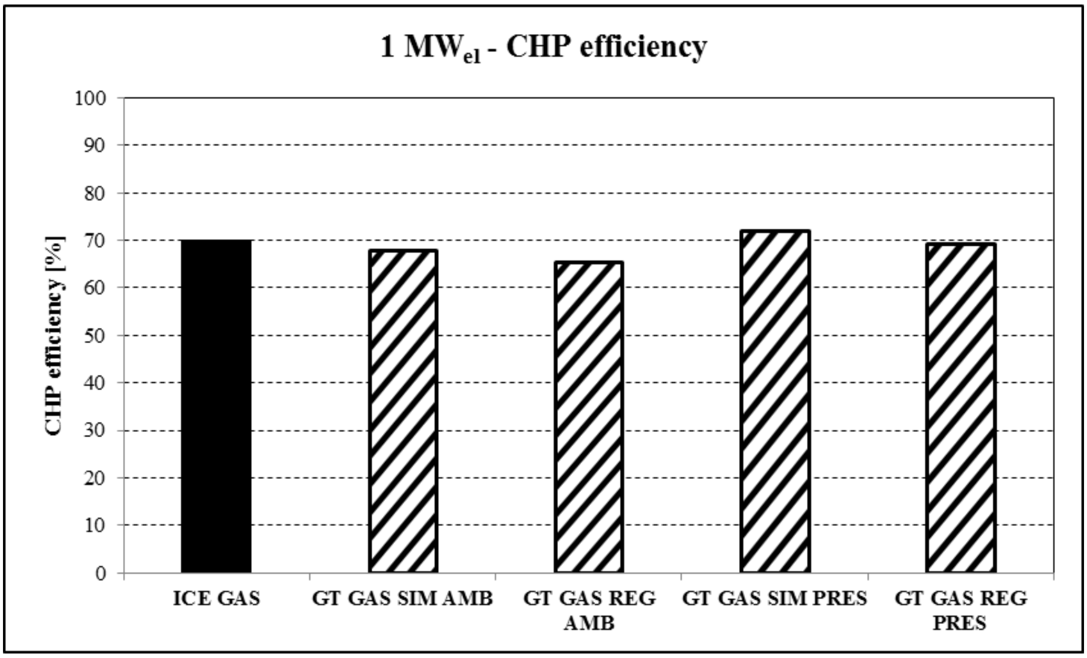

Fig. 11. CHP efficiency at 1 MW_{el} size

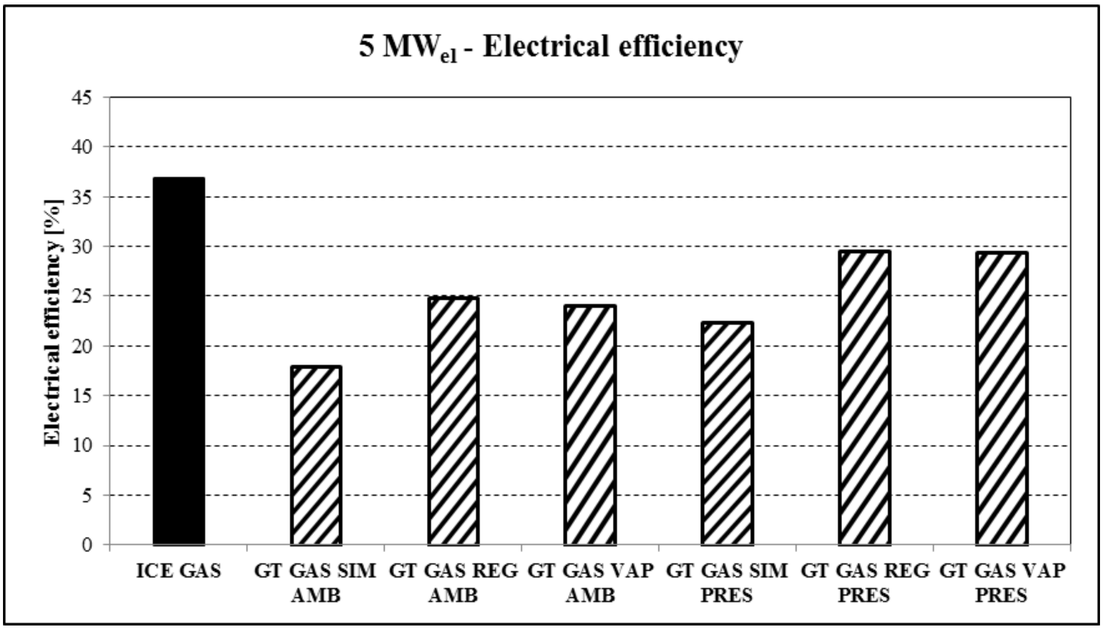

Fig. 12. Electrical efficiency at 5 MW_{el} size

As a result, the excess air mass flow rate can be utilized to provide surplus process heat. These two versions of gasification plant, i.e. exploitation of the hot air leaving the fuel dryer to feed the reactor (pre-heat) in addition to the heat recovery process of the excess air mass flow rate (heat recovery), have been investigated.

Three plant samples have been analyzed including ICE GAS as well as the most promising GT GAS solutions, i.e. GT GAS REG AMB and GT GAS REG PRES, and the size of 100 kW_{el} is considered as the reference scale. It is obvious that other configurations and scales can easily be adopted this type of devices.

Then, results are indicated in Figs.14 and 15, in terms of electrical and CHP efficiencies. Obviously, the base case is pertained to the already described solutions. Doubtlessly, air pre-heating process is beneficial for ICEs and GT GASs with ambient pressure, the reason is due to the fact that power and applicable heat become equal, and then resulting in a higher cold gas efficiency which specifies a lower fuel power input, suggesting a rise of around 1% in the

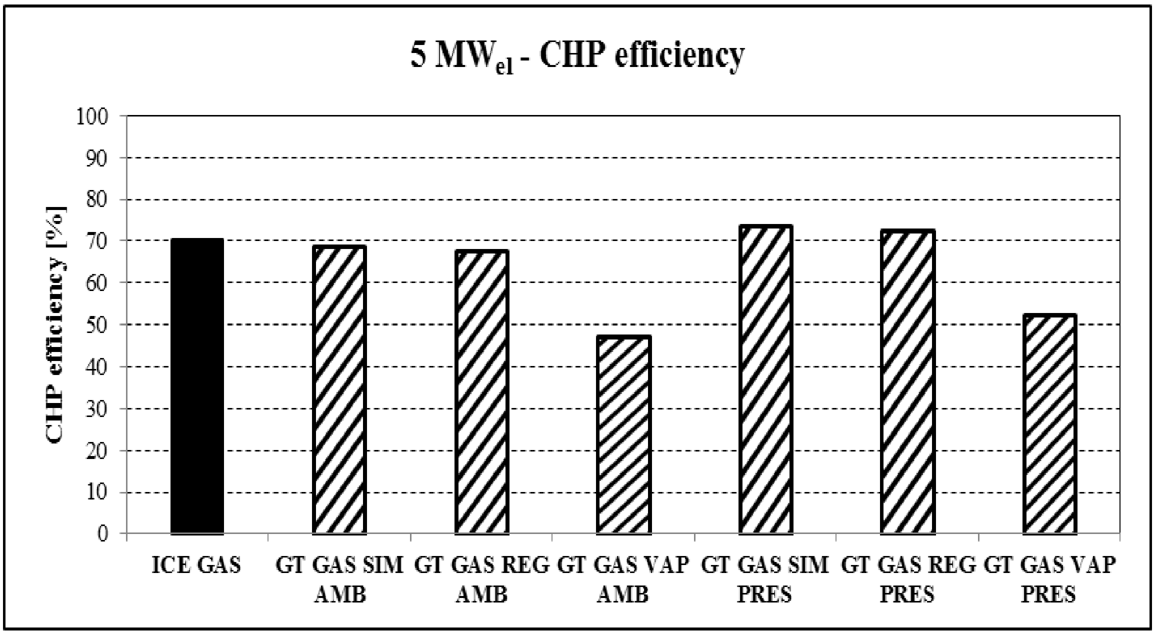

Fig. 13. CHP efficiency at 5 MW_{el}

electrical efficiency and about 2% in the CHP one. With respect to the pressurized gasifier model, indeed, pre-heating air does not lead to a sustainable result in the electrical efficiency, and the reason lies in the fact that the share of gasification air mass flow rate to be fed the gasifier, after leaving the dryer, has to be passed through the compressor. Although, this compression enhances the air temperature (around 200°C), compression work under this condition is higher than the one from ambient pressure air. Therefore, the advantages regarding the increase of air temperature are counteracted by the greater electricity consumption of the compressor itself. On the other hand, CHP efficiency increases about 2% like the other two models, since in all of the configurations, cold gas efficiency correspondingly gets higher, and so fuel power input reduces.

On the other hand, exploitation of the excess air mass flow rate for additional heat recovery leads to an increase in the thermal efficiency, and thus CHP one (averagely 3%). Concerning electrical efficiency, there is no variations in all the three solutions, except a little reduction in the power output due to head losses pertaining to the recovery heat exchangers.

Therefore, it has been indicated how an improved gasifier model, involving a recovery of syngas sensible heat in order to feeding the gasifier with high temperature air as well as utilizing surplus heat recovery, in general, results in greater electrical and CHP efficiencies.

In conclusion, thermodynamic analysis of the model performances has indicated that, the most favorable solutions for the utilization of biomass syngas for electricity generation include internal combustion engines integrated with a gasifier (ICE GAS) and regenerative-cycle gas turbine integrated with a pressurized gasifier (GT GAS REG PRES). These configurations will be taken into account for the economic analysis. Of course, the improved solutions have been considered for the two configurations, thus results become a little more pleasant than those already showed.

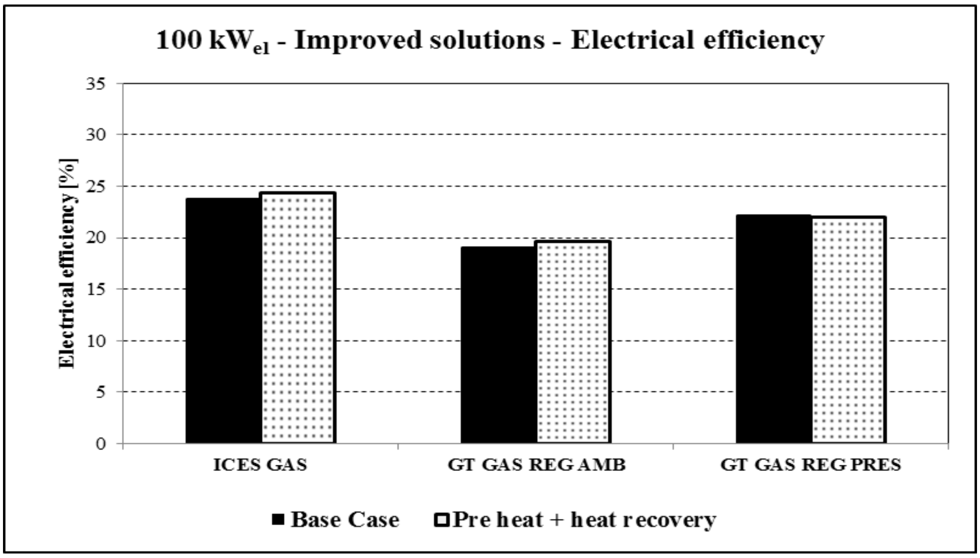

Fig. 14. Electrical efficiencies of the improved solutions

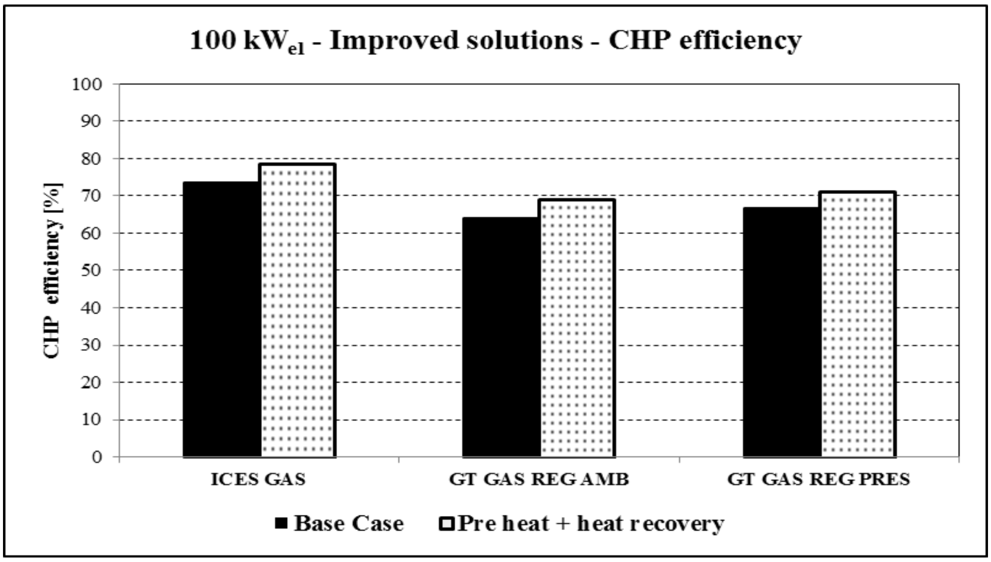

Fig. 15. CHP efficiencies of the improved solutions

6. Economic analysis

Certainly, besides the technical performance of an engineering project, the project cannot be progressed, unless it is accompanied by a sustainable financial support. Therefore, in this section, the best configuration between the two solutions selected in the thermodynamic analysis, has been identified in economic terms for all of the three mentioned sizes. The analysis particularly is carried out referring to the European contexts concerning legislation, costs and so on.

First of all, working hypotheses upon which the investigation is based are considered; subsequently, obtained results are demonstrated and discussed. In the thermodynamic analysis, electrical and CHP efficiencies have been focused, whereas the real power output of the plants has been ignored, the reason is due to the fact that efficiencies can be representative of the entire plant performance, while power output depends on the particular plant configuration considered as reference. Thus, only efficiencies have been also taken into consideration in this section again, whereas net electrical power output has been determined exactly the same, i.e. 100 kW_{el}, 1 MW_{el}, 5 MW_{el}. Consequently, the results can be clearly compared with the other plant solutions, apart from the real plant power output.

6.1. Working hypotheses

Investment costs – It is important to note that precise evaluation regarding investment costs of the investigated power plants are very laborious to be performed, especially concerning small-scale biomass gasification power plants, which are among the state of art ones, and not all of them are available on the market; moreover, an appropriate estimate of commercially available ones is not a piece of cake as well, because their market has not been stabilized yet. Hence, data present in the literature are commonly contradictory.

Numerous sources have been conferred to introduce the investment costs of the considered plants, and some of them are referred throughout the discussion. Considered values for the three sizes in €/kW_{el} are reported in Table 11. For internal combustion engines integrated with a gasifier, the total costs have been obtained by adding the engine device and the gasification systemones, while regarding regenerative gas turbines integrated with a pressurized gasifier, it must be noted that small-scale pressurized gasifiers are not present on the market, hence their costs have been estimated; indeed, it has been presumed to enhance costs of mentioned ambient pressure gasification systems by 30%. Eventually, the overall investment costs in k€ are also demonstrated in Table 11 which have been obtained by multiplying the specific costs by 100, 1000 and 5000 respectively [8, 11, 18].

Sale price of electric energy – Some of the European countries have legislated substantial economic incentives to fortify power production from renewable energies [19]. Their regulation is really complicated, but for the objectives of this work, it is adequate to determine a general possible option. In some countries, there is usually an inclusive tariff lasting 15 years for plants with a power output less than 1 MW_{el} which grants an overall payment about 25 – 30 c€/kWh_{el} for the produced electricity from biomass. This incentive has been applied for 100 kW_{el} and 1 MW_{el}. Moreover, another general option is available for plants of any size with a contribution which is added to the normal sale price of the electricity. The annual average sale price of the electricity energy varies between 8 and10 c€/kWh_{el}, as maximum value is considered for plants with a size less than 1 MW_{el}, hence there is a potential benefit just regarding 100 kW_{el} size.

While the contribution of the latter economic incentive is equal to ranging 13 – 18 c€/kWh_{el}, the overall income for 1 and 5 MW_{el} scale is therefore 21 – 26 c€/kW_{el}, and for 100 kW_{el} 22 – 28 c€/kWh_{el}. However, in the present research, the minimum values

Table 11. Specific and overall investment costs

Solution	ICE GAS				GT GAS REG PRES			
	ICE	AMB Gasifier	Total Investment Costs (€/kW_{el})	Overall Investment Costs (k€)	GT	PRES Gasifier	Total Investment Costs (€/kW_{el})	Overall Investment Costs (k€)
100 kW_{el}	1200	3300	4500	450	1250	4290	5540	550
1 MW_{el}	900	1800	2700	2700	1000	2340	3340	3340
5 MW_{el}	700	1300	2000	10,000	750	1690	2440	12,200

have been considered in any case. In conclusion, it is significant to consider how high incentives are actually necessary togain progress in these projects and also to emphasize power generation with renewable energy sources.

Other hypotheses – There are other essential hypotheses in order to completely simulate a powerplant: first of all, sale price of thermal energy has been determined equal to 5 c€/kWh$_{th}$ which isanalogous to burning methane with a cost of 40 c€/Sm^{3}with a thermal efficiency of 85%. On the other hand, the cost of biomass raw material in addition to its transportation is considered about 75 €/t in all. As already proposed, economic incentives have to continue for 15 years considering a yearly 7000 hours working period, i.e. 80% accessibility, while the period of the investment is determined equal to 10 years, i.e. the overall life would be taken 70,000 hours into account. As regards the thermal energy sale duration, three scenarios have been considered including 0 hour, i.e. no heat sale, 2500 hours for heating purposes throughout the cold season as well as 7000 hours for industrial applications during the entire year. Concerning considered loan, it is assumed to acquire one covering fifty percent of the whole investment with repayment time of 8 years. System maintenance is relevant to the investment costs, i.e. a rate of 3% for internal combustion engine plants and 2% for gas turbine plants, while a rate of 2% is added to both cases each year. Moreover, insurance and other charges bear on the investment costs at a rate of 1%. On the other hand , for 100 kW$_{el}$ and 1 MW$_{el}$ plants, one equivalent operator is needed for running the plant, while two ones are required for the 5 MW$_{el}$, with the unit salary of 30,000 € during 13 months. At last, tax is considered equal to around 30 – 35% of the earnings and job costs.

6.3. Results

Results of analyzing the investment are shown in terms of PayBack Time (PBT), Net Present Value (NPV), during 10 years, and Internal Rate of Return (IRR) of the investments. *100 kW$_{el}$*size –Analyzed results are demonstrated in Figs.16-18. Looking at PayBack Times values (Fig.16), in spite of high specific investments, it is visible that all solutions lead to positive results. Moreover, it is clear that PayBack Time is influenced by the heat sale, as its value at 7000 h is about half of 0 h, despite the fact that earnings obtained from heat sale are absolutely much less than those from electricity.

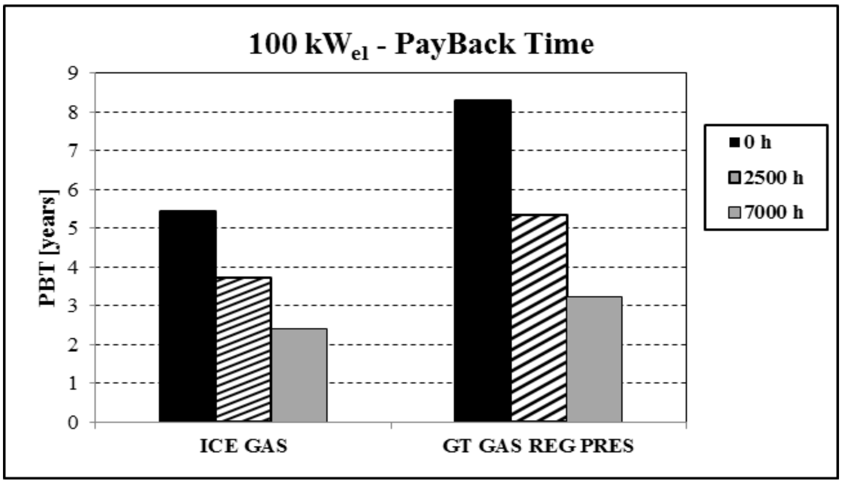

Fig. 16. PayBack Time at100 kW$_{el}$ size

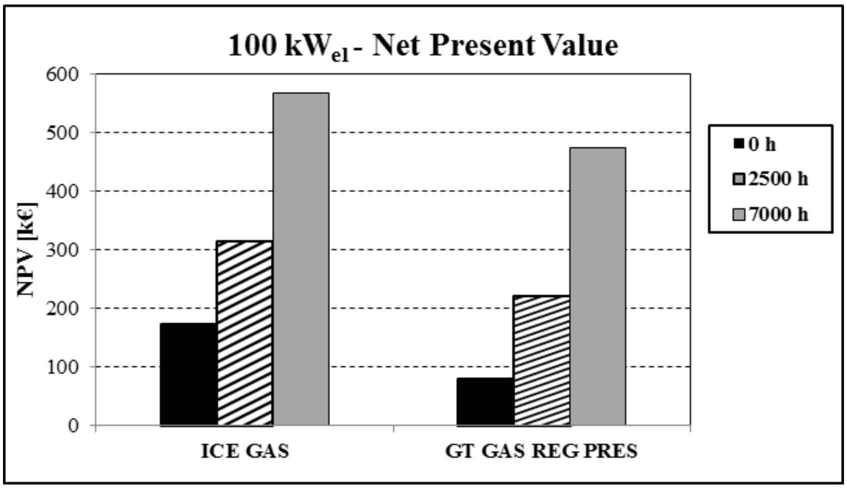

Fig. 17. Net Present Value at 100 kW$_{el}$ size

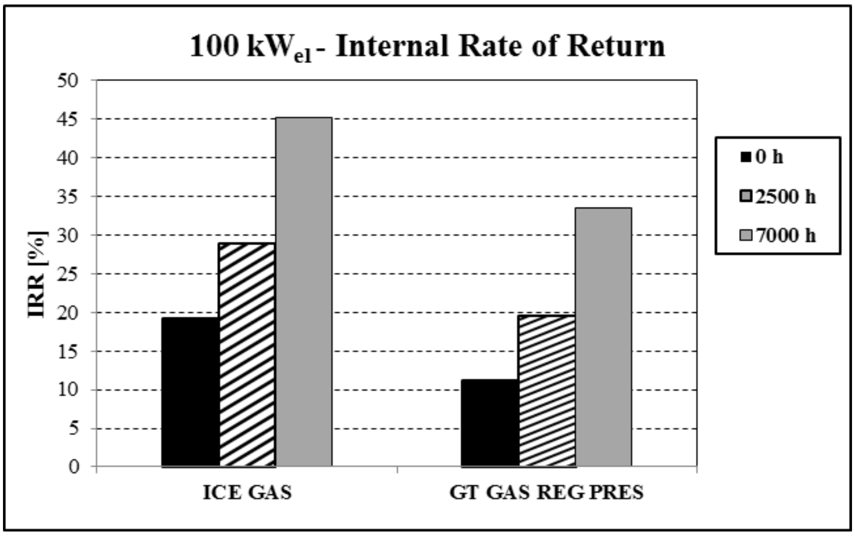

Fig. 18. Internal Rate of Return at 100 kW$_{el}$ size

Observing Fig. 17, it is roughly perceived that electricity sale allows to partly prevailing over the break-even point, whereas added value is then provided by heat sale. However, the best solution appears to be ICE GAS from all viewpoints, i.e. PBT, NPV and IRR as well as in all heat sale models. Moreover, its electrical and CHP efficiencies are higher than the other case too, while it benefits the lower investment costs. On the other hand, GT GAS REG PRES naturally suffers the installation costs, especially regarding pressurized gasifier.

1 MW$_{el}$ size –The investigation results at 1 MW$_{el}$ are indicated in Figs.19–21. As shown in Fig. 19, due to less installation costs, PayBack Times become much lower, as this value ranges 1–1.5 years concerning the best solutions.

Moreover, it is visible that the difference between solutions in the three scenarios gets lower that in the former case. The reason lies in the fact that although CHP efficiencies are approximately analogous to the 100 kW$_{el}$ results, electrical ones get roughly 5% higher, which implies that thermal energy production is relatively less important, so its prevalence is lower in the scenarios.

5 MW$_{el}$ size – The analyzed results for 5 MW$_{el}$ are shown in Figs. 22 – 24. As already mentioned, the incentives considered for the two previous cases are not applied for this scale, while another incentive is used now, which discussed further previously. It is noticeable that, in general, results are very similar to those achieved in the 1 MW$_{el}$ size particularly regarding PayBack Times which still range 1 – 1.5 years.

The reason is due to this fact that the higher electrical efficiencies obtained on this size, i.e. 30 – 40% versus 25 – 30% of 1 MW$_{el}$ scale, are in balance with the less economic incentives related to the one considered for larger sizes. Therefore, ICE GAS, once more verifies to be the best solution, in accord with the all the economic terms, i.e. PBT, NPV and IRR.

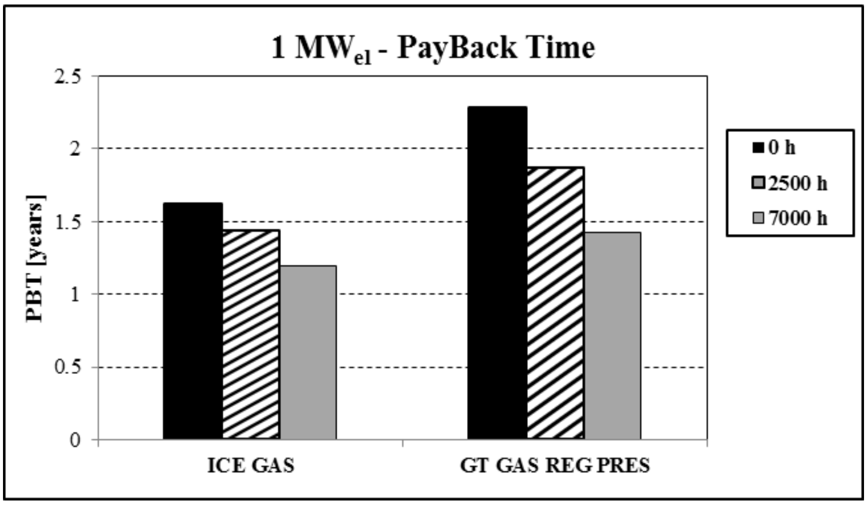

Fig. 19. PayBack Time at 1 MW$_{el}$ size

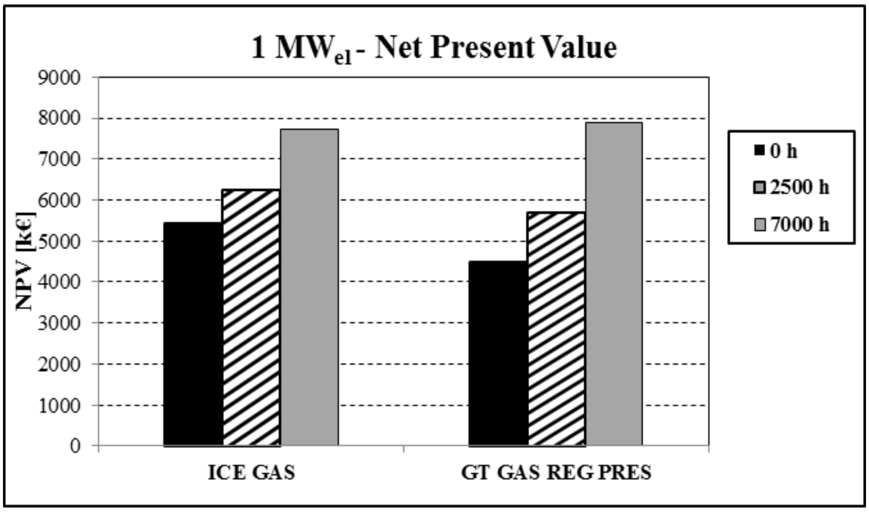

Fig. 20. Net Present Value at 1 MW_{el} size

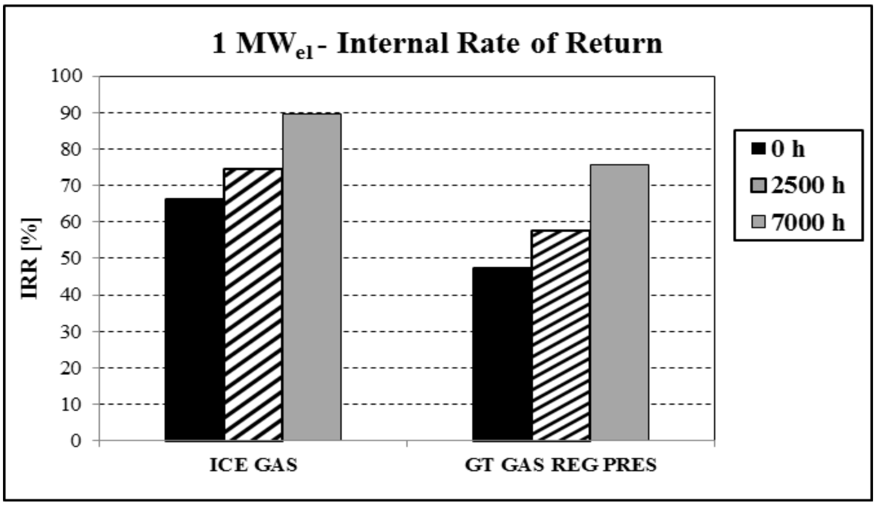

Fig. 21. Internal Rate of Return at 1 MW_{el} size

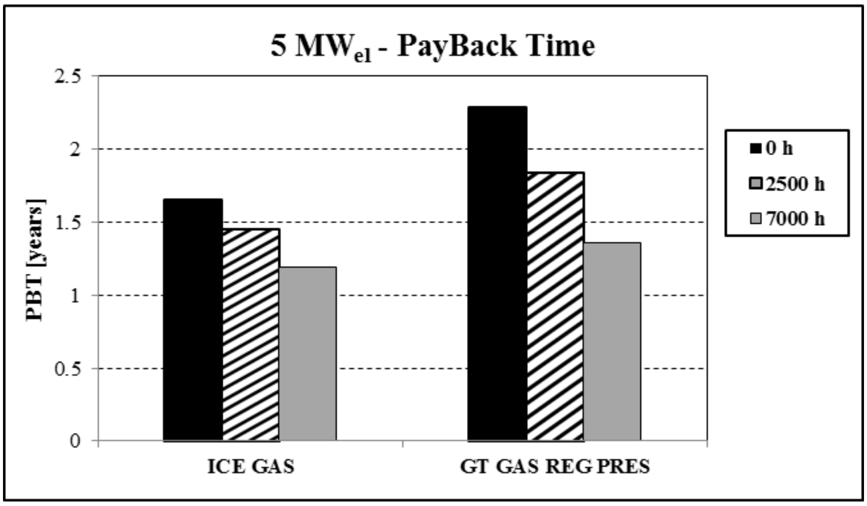

Fig. 22. PayBack Time at 5MW_{el} size

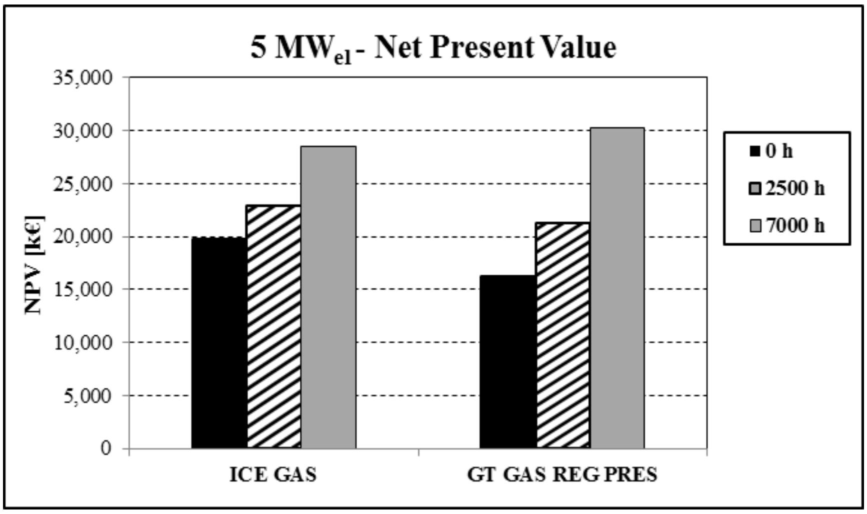

Fig. 23. Net Present Value at 5 MW_{el} size

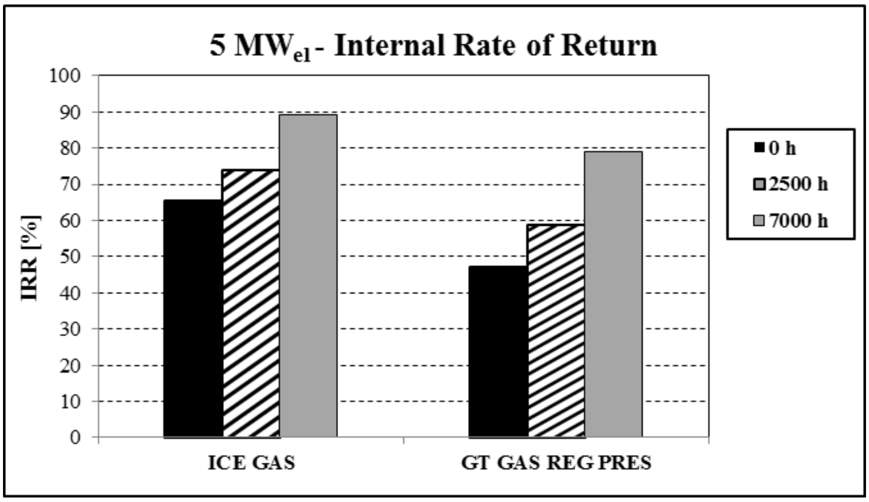

Fig. 24. Internal Rate of Return at 5 M W_{el} size

7. Conclusion

The goal of the present research was to provide an analysis on the performance of small-scale power plants integrated with a wood-fed gasifier, in order to recognize the most promising configurations both thermodynamically and economically.

Thermodynamic results of the performance simulation indicate that the most efficient solutions include internal combustion engine integrated with an ambient pressure gasifier and regenerative gas turbine integrated with a pressurized gasifier. Obtainable electrical efficiencies for both configurations are roughly 24% at 100 kW_{el}, 30% at 1 MW_{el} and 35 – 40% at 5 MW_{el}. A more thorough evaluation has demonstrated that an appropriate heat recovery from the cooling process of syngas in gasification systems leads to a substantial enhance, both in electrical and thermal terms. Subsequently, the two most thermodynamically desirable solutions have been considered for economical analysis. This study has indicated that the internal combustion engine integrated with a gasifier is more preferable at all the three sizes than the other configuration. If considerable incentives, like European ones, are provided, economic performance will be really reasonable, as PayBack Time of the mentioned best solution, i.e. ICE GAS, is about 2 – 5 years at 100 kW_{el} and around 1 – 1.5 years at both 1 MW_{el} and 5 MW_{el}, depending on the duration of the year to sell the recovered heat, although, in general, thermal energy recovery and the heat sale are not obligatory, while its positive impacts are obvious.

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