A small-scale agricultural biomass Combined Heat and Power (CHP) system: The SMARt-CHP project

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***Abstract*—A small mobile agricultural residue gasification unit for decentralized Combined Heat and Power (CHP) production is designed and constructed within the framework of SMARt-CHP LIFE+ project. This unit applies the technology of biomass gasification coupled to an Internal Combustion Engine (ICE) for electricity generation. The CHP unit has a maximum thermal output of 12 kW while the maximum electrical output is approximately 5 kW.**

Four different locations close to biomass feedstock origin in rural areas of Western Macedonia in Greece, two in Ptolemaida and two in Amyntaion, are chosen for the demonstrative operation of the unit. Peach, olive and grape kernels are utilized as biomass feedstocks while the unit is operated constantly on a 24/7 basis overcoming possible technical problems.

The present paper describes the unit performance in terms of constant operation, application of different agricultural residues, energy performance and process efficiency. The results show the effect of different types of biomass feedstock, gasification parameters and engine intake mixture to long-term operation and electrical output efficiency while the obtained data will aid in the direction of CHP systems scale-up and optimization towards possible commercialization.

I. INTRODUCTION

Biomass is considered to be one of the renewable energy sources with high potential to contribute to the world's energy need. The use of biomass can provide a more positive solution-a renewable source of energy services, including heat, electrical energy, and transportation fuels, which can reduce CO_2 emissions, sulphur and heavy metals in the atmosphere, while potentially improving rural income and energy security through the substitution of coal, oil and natural gas [1].

The majority of bioenergy is produced from woody wastes followed by Municipal Solid Wastes (MSW), landfill gases as well as agricultural residues such as cotton stalks, wheat straw, rice straw, coconut shells, rice husks, etc. [2], [3]. Therefore, the agricultural sector has the potential to provide substantial amounts of raw material for energy production. Especially, small scale mobile power generation units for the energy utilization of agricultural residues from rural areas, where large amounts of biomass agro-residues are available, are of great importance towards a sustainable energy world.

The SMARt-CHP project concerns the manufacturing, demonstration and dissemination of a an innovative 12 kW_{th} and 5 kW_{el} small scale mobile gasification unit coupled with an ICE for energetic exploitation of agricultural residues in rural areas of Greece, where large amounts of biomass wastes are available. It aims at offering a practical solution to the problem of biomass logistics, such as biomass residue transportation over long distances, protection from weather variations, storage and general handling. Demonstration attempts promote the concept of bioenergy use via decentralized electrical energy generation units, an integrated system of great potential towards sustainable development of rural regions.

II. COMBINED HEAT AND POWER GENERATION

Combined heat and power generation (CHP) or cogeneration has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation [4].

The term *small-scale CHP* refers to combined heat and power generation systems with electrical power less than 100 kW while the term *micro-scale CHP* is also often used to denote small-scale CHP systems with an electric capacity smaller than 15 kW_{el}. Small-scale CHP systems can help to meet a number of energy and social policy aims, including the reduction in greenhouse gas emissions, improved energy security, investment saving resulted from the omission of the electricity transmission and distribution network as well as the potentially reduced energy cost to consumers [5].

Currently, micro-scale and small-scale CHP systems are undergoing rapid development while emerging on the market with promising prospects for the near future [5], [6].

Various technologies have been developed regarding energy conversion in biomass-fuelled CHP systems including a primary conversion technology that converts biomass into hot water, steam, gaseous or liquid products by means of pyrolysis, combustion or gasification and a secondary conversion technology that transforms these products to heat and power by applying steam engine, steam turbines, stirling engines, internal combustion engines, gas turbines or fuel cells. One of the most widely used combination technology is *gasification* and *ICE*, which is particularly utilized for large-scale and medium-scale biomass-fuelled CHP systems.

A. *Gasification process*

Gasification is a thermo-chemical process that converts carbonaceous materials (coal, petroleum coke, biomass, etc.) into a combustible gas called producer gas. Biomass energy is economic to produce and provides more energy than using other renewable energy sources [7]. The producer gas can be further utilized either for power generation in combined heat and power (CHP) plants or in secondary processes (e.g. Fischer Tropsch synthesis, methanation), which convert syngas into synthetic biofuels. Furthermore, it can be used to produce hydrogen, methanol as well as basic chemicals like dimethyl ether [8].

Biomass gasification is expected to play a key role in expanding the use of biomass as a major renewable energy source. The process is carried out at high temperatures, where solid biomass undergoes thermal decomposition to form gas-phase products, which react eachother as well as with the biomass left, resulting in a mixture that typically includes H_2, CO, CO_2, CH_4, H_2O, larger gaseous hydrocarbonds, tars, char, and ash [9].

Gasification usually takes place in the temperature range of $750-1000$ ºC using either air, steam, oxygen or a combination of these as gasification medium. Composition and quality of the producer gas depends on several factors such as the physicochemical properties of biomass, bed material (inert or catalytic), and gasification medium (air, steam, special mixtures), as well as operating conditions (temperature, pressure, equivalence ratio, steam to biomass ratio, etc.).

B. *CHP technologies based on biomass gasification*

CHP technologies based on biomass gasification are currently under development and demonstration but have not reached market maturity yet. So far, many efforts have been made to commercialize biomass gasification-based CHP system applying either the technology of internal combustion engines, Stirling engines, gas turbines or Organic Rankine Cycle (ORC) systems [10], [11], [12]. Commercialization has not been achieved due to the large variation in the key parameters determining the quality of biomass gasification producer gases, which can cause extreme engine wear due to tar contamination and unstable operation.

Small-scale biomass CHP systems can reduce transportation cost of biomass and provide heat and power where they are needed. Regarding the continuous rise in gas and electricity prices and the advances in the development of biomass technologies and biomass fuel supply infrastructure, biomass-fuelled CHP systems will become more economically competitive.

A gasification-based CHP system can potentially have higher electricity efficiency than a direct combustion-based CHP system. The gas obtained by gasification can be combusted in a diesel, gas or dual fuel engine, or in a gas turbine [10]. The output of a gasifier is usually stated in terms of the peak electric power (kW_{el}) that it can produce when connected to an engine generator set [13].

Spark-ignition (Otto engines) as well as compression ignition (Diesel engines) can be operated on producer gas, therefore are widely utilized for CHP production. Spark-ignition engines can be operated on producer gas only while diesel engines must be operated on mixtures of diesel fuel and producer gas. Highest power output of a producer-gas engine is realized at lowest gas temperature. Thus, in power applications, it is advantageous to cool the gas as far as possible while it is necessary to filter and clean the gas of soot, ash, and tars [13].

ICE based power plants have a relatively low investment cost while the plant construction time is short. Other advantages are flexible operation parameters such as fast start-up and shutdown times, high efficiency on partial loads, relatively easy maintenance as well as multi-fuel capability. ICE's can use a wide variety of fuels including gaseous and liquid bio- and fossil fules. Possible biofuels include biogas from waste treatment plants and landfills or from gasification of biomass and wastes [14].

III. SMARt-CHP UNIT DESCRIPTION

The SMARt-CHP unit utilizes solid biomass (agricultural residues) for combined heat and power production. The unit combines the technologies of Bubbling Fluidized Bed Gasification (BFBG) and Internal Combustion Engine (ICE). BFBG is used to convert solid biomass into a gaseous fuel which is in turn fed to an ICE coupled to an electricity generator. As a result, producer gas utilization leads to electricity production. Additionally, water is used in heat exchangers in order to keep the ICE and generator operation temperatures at specified levels. The heated water can then be utilized by a consumer, thus making SMARt-CHP a cogeneration unit. The total layout of the unit is presented in figure 1.

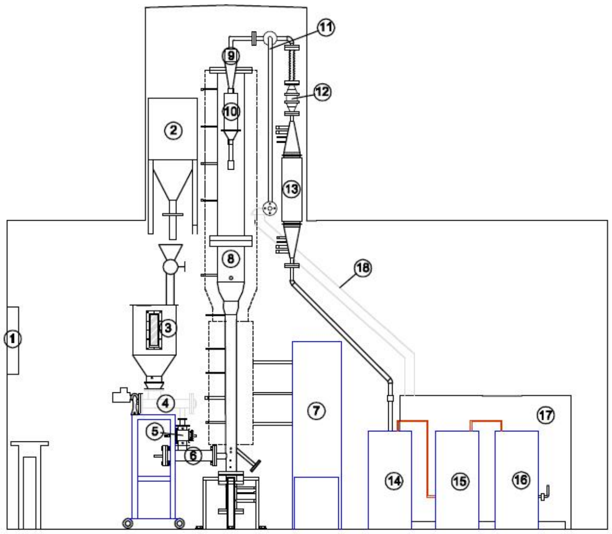

Fig. 1. SMARt-CHP unit layout.

It consists of the following parts: data acquisition unit (1), secondary biomass silo (2), primary biomass silo (3), screw feeder 1 (4), rotary valve (5), screw feeder 2 (6), electric oven (7), bubbling fluidized bed reactor (8), cyclone (9), particle collector (10), gas by-pass to flaring (11), valve (12), particle trap (13), tar removal vessels (14-16), ICE-generator (17), ICE exhaust (18).

Biomass is originally stored in the two silos above the first screw feeder, which is the feeder used to modulate the fuel flow into the reactor. The fuel passes through the rotary valve and the second screw feeder before entering the gasification reactor at the bottom of the fluidized bed. Olivine is used as bed material. Compressed air flows through a perforated plate at the bottom of the reactor to ensure fluidization. An electric oven assists the operation start-up.

The produced gas exits the reactor from the top. It passes through a cyclone filter for particles removal, which are collected in a vessel. At this point, the producer gas contains gas phase tars and fine particles. Depending on operation mode, there are two available routes for the gas. The first route is called *the by-pass route*. It is used during operation start-up and system maintenance. There is no power production during this time period. The gas flows to a flaring system outside of the unit where the gas is burned in order to minimize environmental pollution.

The second route is the *electricity production route*. The gas flows through a heated ceramic blockage filter. Almost 99% of the gas particle load is removed at this stage. After the filter, the gas flows through a water scrubbing unit consisting of three condensation stages where the tar content is minimized. The first stage (14) is a water tank where the gas comes in direct contact with the water in the vessel. After the gas is washed, it exits the vessel from the top. The second stage (15) is a water scrubbing tower. Gas enters the tower from the bottom. The tower is packed with metal parts which are sprayed with water from a nozzle at the top of the tower. The gas follows an upward route and exits the tower from the top as well. The third stage (16) is a heat exchanger. It consists of copper tubing that is immersed in a water tank. Gas flows through the tubing. The water in the tank absorbs the excess heat (above ambient temperature) from the gas to ensure low gas temperature before the ICE.

After gas cleaning, there are also two different routes for the cleaned gas. The first one leads to the flaring set-up outside the unit and it is used for the excess gas that is produced and is not introduced into the ICE. The second gas line drives to the ICE. Two additional high efficiency filters are used at this point to ensure that clean gas flows into the engine cylinder.

The engine originally runs on propane but it has been redesigned and converted to run either on propane or on propane-producer gas mixtures. The gas is introduced to the engine system at the air intake before the propane-air mixing valve. The new *fuel-air* mixture contains propane (*fuel*) and premixed air-gas (*air*). The engine is coupled to a DC generator. The produced current is converted to 3-phase AC current by an inverter. Part of the produced electricity is consumed for the unit's needs. The remaining power is supplied to the consumer's grid. Apart from electric power, hot water is also a product of the unit. The heat from the unit is received by the consumer through a plate heat exchanger. This heat is transferred from the coolant that flows through the engine jacket, the generator jacket and an exhaust gas heat exchanger.

The whole setup of the mobile SMARt-CHP unit in the container is illustrated in figure.

Fig. 2. Mobile SMARt-CHP unit.

IV. Results and discussion

The unit is demonstrated in four different locations in rural areas of Western Macedonia, two in Ptolemaida and two in Amyntaion, for a time period of two weeks in each location. Peach, olive and grape kernels are the biomass feedstocks which are utilized during experiments in the unit, which is tested regarding its long term operation.

The proximate and ultimate analysis of the three aforementioned biomass feedstocks are presented in table I.

TABLE I
CHEMICAL COMPOSITION OF THE THREE BIOMASS FUELS.

	Olive	Peach	Grape
Proximate analysis, %wt (db)			
moisture	12,3	8,53	9,13
ash	3,63	0,65	10,31
volatiles	79,9	81,25	65,67
fixed carbon	16,47	18,1	24,02
Heating value			
HHV (MJ/kg)	20,46	21,55	21,21
Ultimate analysis, %wt (db)			
C	48,59	51,95	52,88
H	5,73	5,76	5,42
N	1,57	0,796	4,46
S	n.d.	0,01	n.d.
Cl	n.d.	0,14	0,02
O	40,48	40,694	26,93

The demonstration's goal is to operate on a twenty-four hour basis for ten days total at each demonstration location. Unfortunately, this is not totally achieved due to technical issues, however great effort in testing and improving of the unit is applied in order to reach the desired operational stability.

The fact that operation hours increase in every demonstration shows that despite the original difficulties such as biomass quality and feeding system operation, improvement of the unit by targeted part modification and adaptive process control is succeeded while it should be also highlighted that all the faced difficulties are surpassed.

Regarding biomass feedstock, the unit is tested almost equally on every used fuel. Grape seeds application is increased compared to the other two fuels because due to technical reasons, the unit seems to be more stable and operates longer (see figure 3).

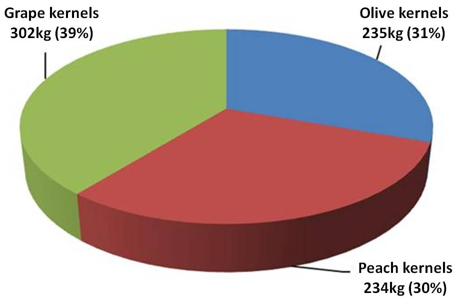

Fig. 3. Biomass feedstocks consumption (in kg and percentage) during the demonstrations.

During the four demonstration periods, the unit is improved to meet the operation target hours. The achieved improvement is remarkable as the unit operated for 50 hours in the first demonstration, 64h in the second, 140h in the third and 207 hours in the fourth one. It is clear that depending on the applied circumstances (personnel availability, fuel quality, proper location), the goal of 24-hour operation on a minimum basis of 10 days is an achievable target.

The duration of each demonstrative operation as well as the percentage of the unit operation on gasification and on electricity generation mode are depicted in figure 4 and figure 5, respectively.

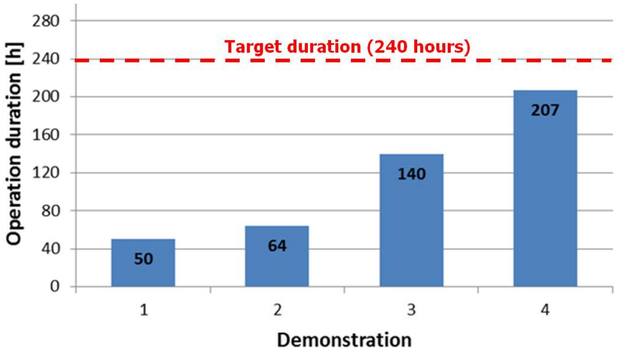

Fig. 4. Operative duration of each demonstration.

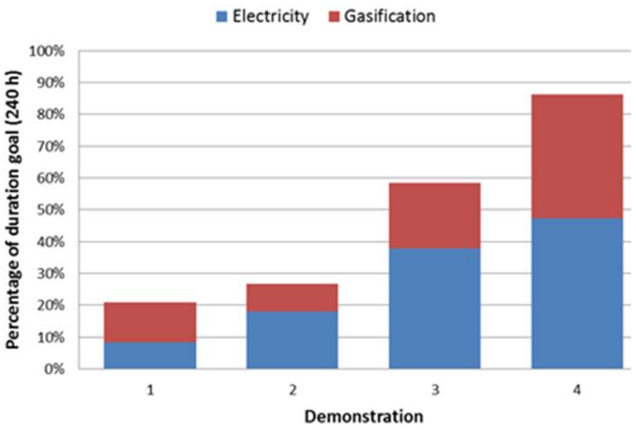

Fig. 5. Real/Proposed duration on electricity and gasification mode.

Regarding unit operation on CHP production mode, best results in terms of electricity generation are observed during peach kernel gasification, followed by olive kernel and grape seed. Producer gas composition concerning peach kernel gasification is presented in figure 6, where higher hydrogen gas concentrations can be observed in the temperature range of 770 – 780 ºC.

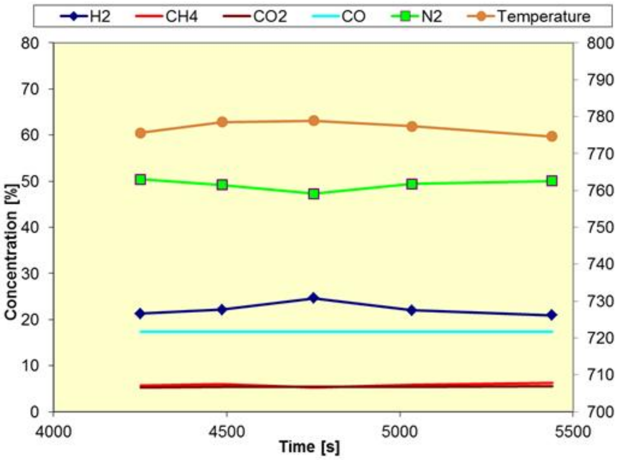

Fig. 6. Producer gas composition during peach kernel gasification.

Electricity generation for each biomass feedstock is depicted in figure 7 and 8. Figure 7 presents the electrical output of the CHP unit for different engine speed values at the same mass fraction of the engine fuel (mixture of gasification producer gas and propane) while 8 depicts the electricity production for each biomass feedstock at 3000 rpm regarding different mass fraction of the engine fuel.

Both figures show that the electical output of the CHP unit is in most of the cases higher when peach kernels are utilized as biomass feedstock during gasification process. It can be also noticed that the energy output of the unit is practically independent of the biomass species as they result in the same range of electricity generation. Minor fluctuations exist but at this scale, it is obvious that the same unit can successfully operate on any of the selected biomass feedstocks without any major process parameter modification.

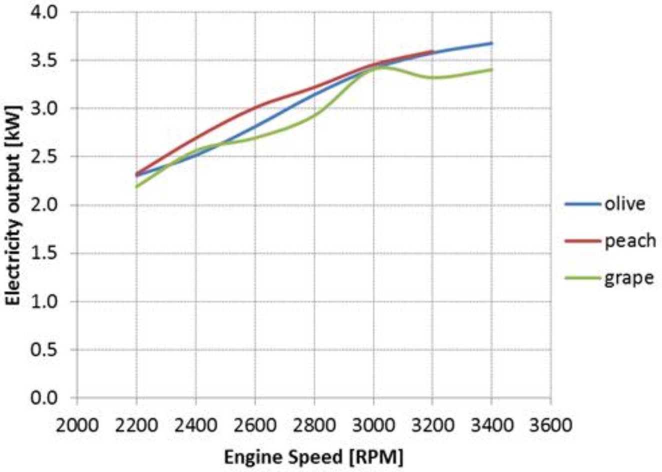

Fig. 7. Electricity generation for each biomass feedstock (gasification gas mass fraction 70% ± 2,5%).

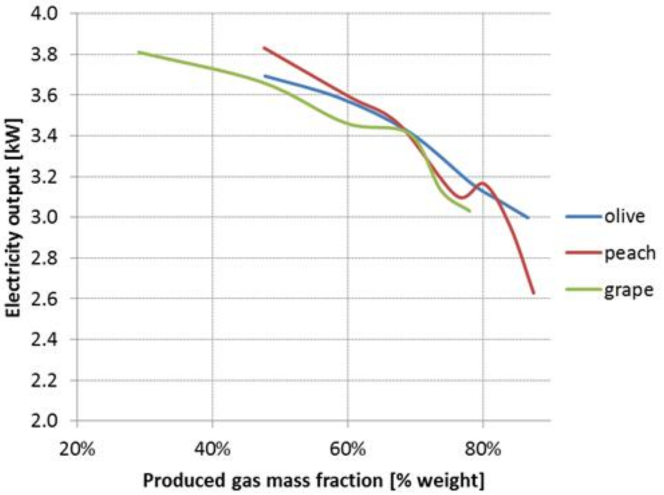

Fig. 8. Electricity production at 3000 rpm for each biomass feedstock.

V. CONCLUSION

Biomass gasification coupled with an ICE engine has the potential to promote bioenergy in rural areas. Although it is a promising technology of producing renewable power in a sustainable way, there are still some important technological issues that should be further examined. High solid conversion and sufficient produced gas cleaning are necessities towards the development of efficient units while fuel feeding versatility and agricultural residue logistic management are crucial aspects that are still under development.

The future of biomass energy supply lies in the optimization of old techniques such as gasification and their combination with modular versatile units for energy production and exploitation. The SMARt-CHP unit has the potential to create significant business opportunities in rural areas of Europe, and especially in the Mediterranean region where various agricultural residues can be gasified and lead to electricity production as long as the produced heat is commercially forwarded.

Scientific research and international cooperation, under the assumption of law establishment and political enforcement through economic incentives in the field of biomass energy exploitation, are going to strengthen the interest in agricultural waste management, enforcing also the possibility of their expanded exploitation in energy production.

SMARt-CHP focuses on the application of thermochemical technologies for alternative methods of agricultural waste exploitation. The project envisages the production of cost-effective renewable energies for rural areas and villages, for regional or national energy supply and infrastructure, for SMEs and production plants. SMARt-CHP project enforces the creation of mobile energy production units that will utilize byproduct of agricultural and forestry activities, which are otherwise treated as waste and are by no means involved in the food chain.

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