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Performance analysis of a small-scale combined heat and power system using agricultural biomass residues: The SMARt-CHP demonstration project

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ABSTRACT

A small mobile agricultural residue gasification unit for decentralized CHP (combined heat and power) production is designed and constructed within the framework of the SMARt-CHP LIFE+ project. This unit applies the technology of biomass gasification coupled with an ICE (internal combustion engine) based generator-set for CHP production. The unit is sized for a maximum thermal output of 12 kW in addition to approximately 5 kW electrical output.

Four different locations close to biomass feedstock origin in rural areas of Western Macedonia in Greece, two in Ptolemaida and two in Amyntaion, were selected for the demonstrative operation of the unit. Peach, olive and grape residues were utilized as biomass feedstocks while the unit operated continuously on a 24/7 basis.

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

1. Introduction

Climate change, security of energy supply and fossil fuels depletion have become increasingly well-known issues, and their combination has caused worldwide attention on finding pathways of sustainable energy production [1]. Biomass is considered to be one of the renewable energy sources with high potential to contribute to the world's energy need. It is considered as a renewable and carbon neutral energy resource, as long as replanting takes place, because it releases the same amount of CO_2 during combustion as captured during growth. Electricity supply from bioenergy has been rising steadily since 2000; in 2010 bioenergy provided some 280 TWh of electricity globally, equivalent to 1.5% of world electricity production [2].

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 metal release in the atmosphere, while potentially improving rural income and energy security through the substitution of coal, oil and natural gas [3].

The majority of bioenergy is produced from woody wastes followed by MSW (municipal solid wastes), landfill gases as well as agricultural residues such as cotton stalks, wheat straw, rice straw, coconut shells, corn stover, rice husks, etc. [4,5]. 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 by promoting decentralized energy production.

Towards this direction, the SMARt-CHP project was implemented. It concerns the design, manufacturing and demonstration of a mobile small scale mobile gasification unit coupled with an ICE (internal combustion engine) for the energetic exploitation of agricultural residues in rural areas of Greece. The technology of the unit is based on experimental results of a bench scale unit

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described in previous work [6,7]. 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 that constitute integrated systems of great potential towards sustainable development of rural regions.

2. Combined heat and power generation from biomass

Cogeneration (also known as combined heat and power, CHP) is the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream such as oil, coal, natural or liquefied gas, biomass or solar [8]. CHP production has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation [9]. CHP production is a good example where the thermodynamic integration of processes leads inherently to higher effectiveness (up to 20%), fuel saving and therefore decrease of CO_2 emissions [10].

The maturity of the conversion technologies differs. Combustion is a well established and fully commercial biomass conversion technology, while gasification can still not be considered as fully commercial for biomass since it is more complex than combustion, and biomass is a difficult fuel to handle compared to conventional fossil fuels. Steam turbines, steam engines, gas turbines, micro gas turbines, hot air turbines, gas engines, ORC, Stirling engines and fuel cells are potential biomass CHP technology options [11].

Small scale units (up to 100 kW_{el}) usually apply the technologies of combustion with Stirling engine and gasification with ICE. From 200 up to 2000 kW_{el}, more suitable technologies are steam engines, steam turbines and especially the ORC process (organic Rankine cycle). Finally, at large scale (>2 MW_{el}), the steam turbine is the most relevant technology for CHP production from biomass [12].

One disadvantage of using large scale central facilities is the biomass transportation, because the biomass feedstocks and production are distributed. In this aspect, decentralized and smaller combined heat and power (CHP) plants are more beneficial. 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 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 [13].

Currently, micro-scale and small-scale CHP systems are undergoing rapid development while emerging on the market with promising prospects for the near future [13,14]. Gas engines, microturbines and fuel cells are suitable systems for small scale power production because of their high efficiency at low power ranges [15]. These technologies though, operate solely on gaseous fuels, thus the coupling with a gasification technology is necessary for system integration.

2.1. 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 [16]. 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 the gas into synthetic biofuels. Furthermore, it can be used to produce hydrogen, methanol as well as basic chemicals like dimethyl ether [17].

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, a mixture that typically includes H_2, CO, CO_2, CH_4, H_2O, N_2 (in the case of air gasification) larger gaseous hydrocarbons, tars, char, and ash [18].

Biomass gasification usually takes place in the temperature range of 750–900 °C using air, steam, oxygen or a combination of the aforementioned compounds as oxidation medium [19]. The gasifier technology, that is the principle of fuel–oxidizer contact and mixing during the process, seriously affects the amount of tars and particles in the producer gas, thus also its gas composition and its heating value. The main gasification reactor categories are the fixed bed reactor and the fluidized bed reactor. Fluidized bed reactors are characterized by high rates of heat and mass transfer and good mixing of the solid phase, which means that reaction rates are high and the process temperature is relatively constant. In this technology, which is applied in the SMARt-CHP unit, the composition and quality of the producer gas depend on several factors such as the physicochemical properties of biomass, the fluidized bed material (inert or catalytic), the gasification medium (air, steam, special mixtures), as well as the operating conditions (temperature, pressure, biomass to oxidant ratio etc.).

2.2. CHP technologies based on biomass gasification

The gas obtained by gasification can be combusted in a diesel, gas or dual fuel engine, or in a gas turbine or be used as an input in fuel cells. CHP technologies based on biomass gasification are currently under development and demonstration but have not reached market maturity yet [20]. So far, many efforts have been made to commercialize biomass gasification-based CHP systems applying either the technology of internal combustion engines, Stirling engines, gas turbines or organic Rankine cycle (ORC) systems [21–23]. The integration of biomass gasification systems in decentralized CHP plants with microturbines is a very promising scenario since it results in highly effective systems [15]. However, gas turbines are highly sensitive to the concentration of condensable tars and particles in the producer gas thus creating the need for very efficient gas cleaning which increases operation and maintenance costs. Combinations of thermal gasification and fuel cells have previously been studied by several researchers [24,25] however mostly through computer simulations [15] and short duration experimental testing.

Internal combustion engines have the advantages of robustness, high efficiency at small sizes, higher tolerance to contaminants than turbines, easier maintenance, and wide acceptability. Spark-ignition (Otto engines) as well as compression ignition (diesel engines) can be operated on producer gas, therefore are widely utilized for CHP production. Highest power output of a producer-gas engine is realized at low gas temperature in order to achieve higher cylinder volumetric ratios (lower limit around 25 °C to avoid thermal stresses at cylinder walls). 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 [26].

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. ICEs can use a wide variety of fuels including gaseous and liquid bio- and fossil-fuels. Possible biofuels include biogas from waste treatment plants and landfills or from