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Original Research Article

Indicator-based economic, environmental, and social sustainability assessment of a small gasification bioenergy system fuelled with food processing residues from the Mediterranean agro-industrial sector

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ABSTRACT

Small-scale gasification systems coupled with internal combustion engines could be innovative alternatives for combined heat and power production when fuelled with agricultural residues, providing benefits related to both food processing waste management and sustainable agriculture. In the present study, an indicator-based estimation of sustainability was performed for a gasification-based bioenergy system considering not only economic but also environmental and social issues. The analysed scenario consisted of an installed capacity of 40 kWel, with an investment cost estimated to be approximately 1520 €/kWhel and a net profit up to 20,000 €/year. However, commercial success depends on instruments of reducing capital investment, such as subsidies, electricity feed-in tariffs, and biomass prices. Additional benefits such as low- or zero-cost feedstock and zero-cost biomass logistics suggest that small-scale gasification systems based on agricultural residues are likely to play an important role in future energy supplies for Mediterranean countries.

Introduction

Through the implementation of Action Plans, Protocols and Common Decisions, the European Union (EU) aims to increase biomass-derived primary energy use, which can help to meet objectives such as renewable energy utilization and greenhouse gas emissions reduction (GHGs). Decentralized electricity production is likely to play an important role in future energy-supply scenarios, as it can decrease the logistical costs of using agricultural biomass. Facilities utilizing indigenous renewable sources, designed to supply energy local communities through micro- and small-scale units, are at the forefront of EU energy and environmental policies [1,2]. Combined heat and power (CHP) from agricultural waste could be a sustainable means of improving rural biomass utilization towards developing a source of renewable, reliable, and affordable electricity, while also improving waste management and sustainable agriculture.

Agro-industrial residues and wastes in Mediterranean countries, such as olive kernels from olive oil production units, grape waste from wineries, or fruit stones from fruit processing industries, are inefficiently utilized or even in some cases totally wasted. A considerable amount of residues are left in the fields (leaves and tops). There have already been some efforts to find economical ways to recover part of the biomass residues that are either burned or left on the ground, and there have been several debates to decide the best use for these residues, with a focus on surplus power generation and increasing soil-based organic carbon [3]. The waste-to-energy technology route can lead to the displacement of fossil energy sources and therefore contribute significantly to the mitigation of GHG emissions. The current research and discussion on bioenergy systems is based mainly on economic viability and technological feasibility; major focuses are on determining the energy efficiency parameters of biomass energy systems and the specific investment costs of the conversion technologies.

Although technological solutions based on thermal routes for bioenergy production at small scales are in the process of being implemented, the sustainability of such solutions still needs to be proven. Their sustainability should be assessed within the broader context of resource-efficient societies and sustainable bio-economies, taking into consideration environmental, social, and economic issues [2,4].

In the technological forum, apart from thermal methods, cutting-edge scientific studies also address microbial processes, proposing solutions for distributed energy generation by using microbial fuel cells (MFCs) [5–7]. MFCs have the potential to serve as distributed power systems for local uses, especially in underdeveloped regions, by using locally supplied biomass. However,

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Nomenclature

SMARt-CHP	small mobile agricultural residue gasification unit for decentralized combined heat and power production	NPV	net present value
CHP	combined heat and power	IRR	internal rate of return
ICE	internal combustion engine	PBP	payback period
SME	small medium enterprise	RES	renewable energy sources
EU	European Union	GHG	greenhouse gases
		FBG	fluidized bed gasifier

although an extremely high Coulombic efficiency (97%) has been reported [8], MFC power production is still very low [9,10] due to the very low rate of electron abstraction. The low power density level, of several thousand mW/m^2, limits real-world applications of MFCs, while areas of focus include improving the performance and reducing the construction and operating costs of MFCs. Ieropoulos et al. studied [11] one feasible way to solve this problem by storing electricity in rechargeable devices and then distributing the electricity to end users. Specifically, capacitors were used in a biologically inspired robot named EcoBot I to accumulate the energy generated by the MFCs, while the robot EcoBot-II solely powered itself by MFCs [12–14]. For these systems, the issue of sustainable long-term power applications is also a challenge. In addition to the requirements for sustainability that a gasification-based system addresses, MFCs require additional health and safety considerations related to the microorganisms used.

In the cases facing sustainability issues (i.e., thermal and microbial systems), feedstock supply, conversion technology and energy allocation are the main factors in implementation. These factors interact among the social, environmental, and economic outcomes of a bioenergy system. Thus, before putting a bioenergy production system on the market, a sustainability analysis has to be undertaken to strategically support local and national bioenergy planning and policy formulation. In a bioenergy sustainability assessment, defining the indicators upon which the system can be assessed from economic, environmental, and social points of view, as related to the needs of the stakeholders, is a crucial step. Currently, consistent definitions of those indicators are lacking, and bridging this gap seems very challenging because some of the fundamental requirements of a standard are measurements. Metrics are needed, along with research on emerging technologies by collecting data; understanding how bioenergy fits into energy markets, technological competition, and market competition; and better understanding of co-existence and symbiosis, costs, policies and end-use markets. Furthermore, sustainability and especially social indicators are affected by cultural aspects, the local and regional framework under which bioenergy is produced in each case. Recent studies extensively discuss the impacts of bioenergy production considering the educational level, cultural issues, histories, and economies of the bioenergy-producing countries [15].

The present study is based on data obtained from a demonstration performance of a gasification unit coupled with an internal combustion engine (ICE), the SMARt CHP unit (www.smartchp.eng.auth.gr), designed and constructed in Greece, funded by the EU-LIFE+ program and already reported in the international literature [16–19]. The study is based on the performance analysis results of a small-scale demonstration system fuelled with food-processing waste [19]. Key factors for its successful implementation, and indicators related to economics, markets, social factors, and job creation, were estimated. The ultimate goal was to support best practices for promoting small-scale bioenergy systems at not only the Mediterranean level but also the European level, contributing to regional development, reinforcement of agricultural activities, environmental preservation and energy self-dependency (LIFE08 ENV GR 576 SMARt-CHP Life+ EU project) [20].

Micro and small scale biomass-fuelled CHP systems

End users of bioenergy can vary in scale, from household, school, public buildings, and touristic complexes to district heating, and from heat and steam generation for agro-industrial plants to grid electricity. So far, biomass CHP systems have proven to be viable only at larger scales (>3 MWe) [21–23]. They are supported by feed-in tariffs or green certificates. Expensive investments with long pay-back times have impediments to implementation.

There is a relationship between the scale of demand and the GHG profiles of biological feedstocks. Scaling up demand will have consequences for the climate impacts of the bioenergy sector. In terms of maximizing reductions in GHG emissions and mitigating climate change, residual wastes and residues, including food waste and agricultural waste, could serve as bioenergy feedstocks. Installations using agricultural residues are restricted in scale due to feedstock supply limitations [4].

Along with the feedstock supply limitations, syngas cleaning and the operational stability of small scale gasification systems also present challenges. Small-scale gasification-based technologies integrated with engines have proven to be expensive, and several difficult-to-resolve technical issues are related to fuel quality (standardized, and therefore more expensive, fuels such as pellets are preferred), the requirement for careful operation, the high costs for effective gas cleaning, and system integration and operation stability [19,24,25].

Viable small-scale biomass installations, producing electrical and thermal power, appear to be among the most promising technologies for decentralized energy generation if they can be operated sustainably [26]. Small-scale units represent a flexible integrated technology, with the potential of successful penetration in the electricity production market, promoting regional development and reinforcing the agricultural sector. A "small-scale CHP" refers to a combined heat and power production system with electrical power less than 100 kW [27].

Within this framework, "micro-scale CHP" usually denotes small-scale CHP systems with an electrical capacity lower than 15 kWel. Currently, micro-scale and small-scale CHP systems are being rapidly developed and are being forecasted to emerge into the market with promising prospects for the near future [27,28].

The proposed bioenergy system

A bubbling fluidized-bed gasifier (FBG) was designed and manufactured for biomass gasification at the Aristotle University of Thessaloniki (www.smartchp.eng.auth.gr). The system has an atmospheric air-blown FBG unit that consists of four sections:

(a) biomass feeding section,
(b) air supply, control, and preheating section,
(c) gasification section and
(d) gas sampling and off-line analysis section.

For gas cleaning the following technology is used: