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Environmental and energy system analysis of bio-methane production pathways: A comparison between feedstocks and process optimizations

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HIGHLIGHTS

- Using local waste feedstock and optimization improves environmental sustainability.
- Optimization favors waste feedstocks.
- Transport distances should not exceed 150 km.
- The produced energy should be used for powering the green gas process first.
- The AD process should be used primarily for local waste treatment.

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ABSTRACT

The energy efficiency and sustainability of an anaerobic green gas production pathway was evaluated, taking into account five biomass feedstocks, optimization of the green gas production pathway, replacement of current waste management pathways by mitigation, and transport of the feedstocks. Sustainability is expressed by three main factors: efficiency in (Process) Energy Returned On Invested (P)EROI, carbon footprint in Global Warming Potential GWP(100), and environmental impact in EcoPoints. The green gas production pathway operates on a mass fraction of 50% feedstock with 50% manure. The sustainability of the analyzed feedstocks differs substantially, favoring biomass waste flows over, the specially cultivated energy crop, maize. The use of optimization, in the shape of internal energy production, green gas powered trucks, and mitigation can significantly improve the sustainability for all feedstocks, but favors waste materials. Results indicate a possible improvement from an average (P) EROI for all feedstocks of 2.3 up to an average of 7.0 GJ/GJ. The carbon footprint can potentially be reduced from an average of 40 down to 18 kgCO_2eq/GJ. The environmental impact can potentially be reduced from an average of 5.6 down to 1.8 Pt/GJ. Internal energy production proved to be the most effective optimization. However, the use of optimization aforementioned will result in les green gas injected into the gas grid as it is partially consumed internally. Overall, the feedstock straw was the most energy efficient, where the feedstock harvest remains proved to be the most environmentally sustainable. Furthermore, transport distances of all feedstocks should not exceed 150 km or emissions and environmental impacts will surpass those of natural gas, used as a reference. Using green gas as a fuel can increase the acceptable transportation range to over 300 km. Within the context aforementioned and from an energy efficiency and sustainable point of view, the anaerobic digestion process should be utilized for processing locally available waste feedstocks with the added advantage of producing energy, which should first be used internally for powering the green gas production process.

1. Introduction

Concerns over climate change, resource depletion, and a worsening environmental health indicate the need for a full transition to non-polluting renewable energies. Therefore, the European Union has enforced strict targets for renewable integration and the reduction of emissions [1,2]. One potential renewable energy

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Nomenclature

AD	anaerobic digestion
CHP	combined heat and power
oDM	organic dry matter
FM	fresh matter
GJ	giga joule
MJ	mega joule
Mg	mega gram (equivalent to metric tonne)
PED	primary energy demand
N m^3	normal cubic meter
(P)EROI	process energy returned on invested
GWP(100)	global warming potential 100 year scale
Pt	environmental impact in EcoPoint
LCI	life cycle inventory
LCA	life cycle analysis
aLCA	attributed life cycle analysis
MFA	material flow analysis
MEFA	material and energy flow analysis
$kgCO_2eq$	kilograms of carbon dioxide equivalent

resource is green gas production through anaerobic digestion (AD). Benefits associated with green gas production include the reduction of greenhouse gas emissions, environmental impact and the use of fossil resources. Anaerobic digestion is a promising method for producing a renewable and flexible energy carrier, which is storable and can be transformed into electricity and/or heat or can be upgraded to green gas [3]. However, renewable energy production processes like AD are often seen as (fully) sustainable, which is not always the case. Per definition, renewable is referring to the energy resource (e.g. biomass) and not the process of extracting and refining the energy from this resource. Often, the overall process of extracting energy from a renewable resource may still require fossil input, which will have an impact on the environment and therefore on the sustainability of the process [3,4]. Within this context, understanding the efficiency, carbon footprint, and environmental impacts of AD is required in the decision making and planning process in order to ensure a more sustainable production process.

Mono-digestion and co-digestion processes have been thoroughly researched based on feedstock type, energy balance and environmental impact. Depending on the study, the focus can be on specific feedstocks, mixtures of feedstocks, different biogas production pathways, variable transport distances, the biogas production process itself, and different end uses for biogas. Energy analysis studies identify and quantify all the energy and material inputs (e.g. cultivation, transport, processing) and outputs (e.g. biogas, green gas, electricity, heat) in a product's life cycle [3,5]. Studies indicate that the energy input needed within anaerobic digestion processes varies between 10% to 65% of the energy output [3,4,6]. A large share of this energy input is often provided by fossil energy (e.g. cultivation, transport, pumping, mixing, heating, filtering, and cleaning) [4,7]. The focus of the LCA approach lies in the analysis of environmental impacts of a product, a process or a system [4,5]. LCA results are often given in a wide range of impact categories (e.g. climate change, ozone depletion, agricultural land occupation, etc.) [5], which can add up to over twenty indicators [8,9]. Overall, studies indicate that the choice of feedstocks, technologies and the operational values of AD pathways (e.g. feedstock, transport, process) have a large influence on the environmental impact [4,7,9–16]. Within this context, it is important that the design of a production pathways and the location of the facilities is chosen wisely [10]. When, for instance, a green gas production pathway is not properly designed and managed; more primary energy could be invested into the production process than is finally obtained [3]; emissions and environmental impacts might become similar to or even surpass current fossil resources for similar uses [11].

Both energy analysis and LCA give a focused view into the sustainability of the biogas production process. However, the wide variability in both scope and approach makes the interpretation of the various results difficult [5,12]. Also, a reference with current fossil energy use is often missing in the studies, making comparison difficult. Additionally, within many LCA studies the energy returned on invested is not included. Furthermore, many of the studies aforementioned do not focus on possible improvement in the AD process regarding sustainability. The next logical step should be to focus on integrating several feedstocks and process optimization within an LCA analysis, expressed in clear indicators of sustainability, and compared to a fossil reference scenario. Therefore, within this article an anaerobic digestion process producing green gas operating on either energy maize, roadside grass, catch crops, harvest remains, or straw is analyzed on environmental sustainability. Optimization of the green gas production pathway is included in the shape of internal electricity and heat production through the use of a small Combined Heat and Power Unit (CHP) and green gas powered transport of the feedstocks. Also, the effects of variable transport ranges of the feedstocks are included. Sustainability is expressed in three main factors: efficiency in (Process) Energy Returned On Invested, carbon footprint in Global Warming Potential GWP(100), and environmental impact in EcoPoints. The reference scenario will be based on natural gas production and consumption in the Netherlands. Overall, this study can provide a comprehensive overview regarding the sustainability of several feedstocks and green gas production pathways including potential optimization. Furthermore, this study can also shed light on the optimum use of the anaerobic digestion process as a green gas production system from a sustainably vantage point, which can help increase the efficiency and sustainability of the national energy system by utilizing green gas from anaerobic digestion as an integral renewable energy resource.

2. Methods

In the following section the methods used during the formation of the results are described.

2.1. The biogas simulator

Within this research the BioGas simulator is used to model the green gas production pathway. This model operates on a new approach [17], based on the industrial metabolism concept, which combines Material and Energy Flow Analysis [18], Energy and Environmental System Analysis [3], temporal dynamics, a modular design and Attributed Life Cycle Analysis, in order to gain more insight into the efficiency and sustainability of green gas production pathways. Within this model the green gas production pathway is defined as a collective of physical processes working together to achieve a common goal (e.g. biogas, green gas or heat and power production). This modular approach allows the simplification of the green gas production pathway while also allowing for easy modification in order to determine the impacts of green gas production for specific conditions and scenarios.