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Sustainable synthesis of biogas processes using a novel concept of eco-profit

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ABSTRACT

The objective of this contribution is to perform the sustainable mixed-integer linear programming (MILP) synthesis of biogas processes based on life cycle assessment (LCA). An aggregated model previously developed by authors for the efficient optimisation of biogas processes has been upgraded with LCA, using the novel concept of eco-profit. Eco-profit is defined as the difference between burdening (eco-cost) and unburdening (eco-benefit) the environment, where eco-cost and eco-benefit calculations are based on LCA. The advantage of eco-profit is that it is expressed as a monetary value. Therefore, eco-profit and economic profit can be merged together and the preferred solutions are those with maximal total profit. The single-and multi-objective optimisations were performed on a model of the biogas production processes. Within the former, economic, eco- and total profit were maximised separately and, within the latter, maximisation of economic profit vs. eco-profit was introduced. All the results obtained from single- and multi-criteria optimisation show that biogas production is a sustainable alternative that provides an important eco-profit.

1. Introduction

Over the last few years, renewable energy sources have begun to play an increasingly important role in energy production due to their potential for reducing greenhouse-gas (GHG) emissions, rising energy costs, reducing dependency on energy imports, and increasing the security of supply. Another question for many countries around the world is what to do with the production wastes from agriculture, the meat-processing industries, households, and waste treatment plants. More and more companies are now recognizing and adopting a sustainable development framework within their business operations, in order to gain a major competitive advantage in the global market. Through improved quality control of final products, resource use optimisation, the adoption of cleaner technologies, waste minimisation, and pollution prevention techniques, companies have been able to demonstrate that improving their environmental performances leads to increased profitability (Dovì, Friedler, Huisingh, & Klemeš, 2009; OECD, 1999; Ore, 2001).

Nowadays, the food-processing industries produce large amounts of residues, slaughterhouse waste, animal manure, and other waste, which represent a constant pollution risk when they are discharged into the environment. In addition, most of the food-processing industries are large consumers of energy in order to operate their processes and plants. Therefore, an efficient economic and sustainable solution is needed for the utilization of animal and other organic wastes. Anaerobic digestion can be considered as one of the alternative solutions for lowering the quantity of hazardous waste whilst, in addition, generating extra heat and electricity (Drobež, Novak Pintarič, Pahor, & Kravanja, 2009). This process technology is an excellent example of reducing environmental damage with considerable economic and social benefits (El-Mashad & Zhang, 2010). However, the main weakness of biogas plants is the return on investment, mainly due to the relatively low biodegradability of waste, especially manures (El-Mashad & Zhang, 2010). On the other hand, biogas has several benefits, such as the production of renewable energy, the transformation of organic wastes into high-quality fertiliser with reduced pathogens, odour, weeds, and a reduction inorganic fertiliser consumption thus, in this way, helping to protect the soil, water and air (Dworkin et al., 2007; Monnet, 2003).

Some studies have been performed, including environmental assessment of integrated biogas processes. Prapaspongsa, Christensen, Schmidt, and Thrane (2010) identified the more significant environmental impacts from pig manure management, such as global warming potential (GWP), eutrophication potential (EP) and others. Ciotola, Lansing, and Martin (2011) performed an emergy analysis in order to assess the relative sustainability and environmental impact of small-scale biogas production. Bernstad and la Cour Jansen (2011) compared the environmental impacts from incineration, composting and anaerobic digestion from household waste in Sweden. Bailey, Amyotte, and Khan (2010) evaluated

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Nomenclature

Superscripts
D disposal
G raw materials
PC products
T transport
U consumer

Sets
P_B set of those products that only burden the environment related to processing, disposal and transportation
P_{UNB} set of those products that mainly unburden the environment if they substitute harmful products
R_B set of those raw materials that only burden the environment if they are processed
R_{UNB} set of those raw materials that mainly unburden the environment when they are used
S set of those conventional, mainly non-renewable products, that are substituted with produced products from biogas and rendering plant

Indexes
o index for those raw materials that only burden the environment
r index for those raw materials that mainly unburden the environment
w index for those products that only burden the environment
y index for those products that mainly unburden the environment

Parameters
$c_o^{R_B,G}$ eco-cost coefficient for those raw materials that only burden the environment, t/y
$c_r^{R_{UNB},G}$ eco-benefit coefficient for those raw materials that mainly unburden the environment, €/t
$c_w^{P_B,PC}$ eco-cost coefficient for those products that only burden the environment, €/t or €/GJ
$c_y^{P_{UNB},PC}$ eco-cost coefficient for those products that mainly unburden the environment, €/t or €/GJ
$c_y^{S,T}$ eco-benefit coefficient for those products that mainly unburden the environment, €/t or €/GJ
c_o^{T,R_B} eco-cost coefficient for the transportation of those raw materials that only burden the environment, €/(t km), €/(m^3 km), etc.
$c_y^{T,P_{UNB}}$ eco-cost coefficient for the transportation of those products that mainly unburden the environment, €/(t km), €/(m^3 km), etc.
c_w^{T,P_B} eco-cost coefficient for the transportation of those products that only burden the environment, €/(t km), €/(m^3 km), etc.
$c_r^{T,R_{UNB}}$ eco-cost coefficient for the transportation of those products that mainly unburden the environment, €/(t km), €/(m^3 km), etc.
$D^{P_B,D}$ distances between the locations of those products that only burden the environment, and between the location of disposal, km
$D^{P_{UNB},U}$ distances between the locations of those products that mainly unburden the environment, and between the location of the consumer, km
$D^{R_B,G}$ distances between the locations of those raw materials that only burden the environment, and between the location of the plant, km
$D^{R_{UNB},G}$ distances between the locations of those raw materials that mainly unburden the environment, and between the location of the plant, km
$f_y^{S/P_{UNB}}$ the substitution factor, defined as the ratio between the quantity of conventional product S, and the quantity of produced biomass product P_{UNB}, –.

Variables
D annual depreciation expense, €/y
E expenditures, €/y
EB eco-benefit, €/y
EC eco-cost, €/y
EP eco-profit, €/y
P economic profit, €/y
$q_{m_o}^{R_B}$ mass flow-rate of those raw materials that only burden the environment, t/y
$q_{m_r}^{R_{UNB}}$ mass flow-rate of those raw materials that mainly unburden the environment, t//y
$q_{m_w}^{P_B}$ mass flow-rate of those products that only burden the environment, t/y
$q_{m_y}^{P_{UNB}}$ mass flow-rate of those products that mainly unburden the environment, t/y
R revenues or income, €/y
TP total profit, €/y

Abbreviations
CHP combined heat and power
DMC dry matter content
EP eutrophication potential
GAMS General Algebraic Modelling System
GHG greenhouse gas
GWP global warming potential
LCA life cycle assessment
MINLP mixed-integer non-linear programming
MILP mixed-integer linear programming
NPV net present value
VSS volatile suspended solids

the sustainability of the biogas process by considering the economic, environmental, and social dimensions, using the Life Cycle Index (LInX). However this is a subjective method, where the environmental, cost, technical, and socio-political factors are grouped at 3 different levels of indices in order to yield a single index value. There are 11 environmental parameters, 3 cost parameters and 7 technical/social parameters that make up an overall index value. No studies on biogas processes have been performed so far that have included environmental and economic assessment without subjective steps within the assessment. However, in this contribution a novel concept is presented which enables the inclusion of environmental and economic dimensions within one measure – an eco-profit method.

The goal of this research was the development of sustainable life cycle assessment (LCA)-based mixed-integer linear programming (MILP) synthesis of biogas production and its supply chain, by simultaneously considering two dimensions of sustainable development – economic and environmental. This supply chain includes a variety of anaerobic conditions for the production of biogas, the production, and usages of different raw materials, an alternative supply of process water and wastewater treatment, energy production, a rendering plant, transport routes and alternatives for heat integration. For optimisation, the previously developed mathematical model (Drobež et al., 2009; Drobež, Novak Pintarič, Pahor, & Kravanja, 2010, 2011) is used but has now been upgraded for