Bulgarian Chemical Communications, Volume 54, Issue 3 (pp. 205-210) 2022 *DOI: 10.34049/bcc.54.3.5483*

Optimal synthesis and management of supply chains for production and utilization of biogas

E. Ganev*, V. Beschkov

Process Systems Engineering Laboratory, Institute of Chemical Engineering, Bulgarian Academy of Sciences, Sofia 1113, Bulgaria

Received: March 03, 2022; Revised: July 20, 2022

The continuous increase in greenhouse gas emissions due to the rapid development of world economy, as well as the growing demand for electricity require serious attention to the so-called "green energy" to meet permanently the needs of modern human society in conditions of sustainability. The present research focuses on studying biogas production technologies, evaluating raw materials and products, carefully studying and evaluating all possible flows of raw materials and products, and assessing the environmental impact of this activity. Based on the above study, an optimization model is created through mixed integer linear programming (MILP) to determine potential locations and optimal parameters, as well as transport flows of existing and potential activities.

Keywords: integrated biogas supply chain; optimal design; life cycle analysis; greenhouse gases emissions; solid waste use; economic, environmental and social criteria

INTRODUCTION

Owing to the natural processes in the Earth flora and fauna, even without human intervention, significant amounts of gases (e.g. methane) are generated with the most serious greenhouse effect. On the other hand, as a result of human activity, biodegradable waste is generated both from everyday life and from industry, i.e. from agriculture, forestry, animal husbandry, municipal wastewater treatment plants, etc. These activities reinforce the generation of putrefactive gases on an extremely large scale and promote the need to create technologies and optimally design the flows in order to achieve sustainable development in modern conditions. On the other hand, the fossil energy resources of the Earth are limited and therefore there is a growing need for putting into operation of renewable resources. This is why the social, economic and environmental impacts of biofuels have become an important research topic in the last decade. The exhaustion of the crude oil reserves and the significant levels of environmental pollution encourage researchers and industrials to seek and find solutions in this direction [1]**.**

The massive industrial production of biogas began at the turn of the last century, while in China and India this technology was applied much earlier on a domestic scale. More than 78 biogas plants were built in Japan until 2012 and more than 40 million households of anaerobic digesters were built in China from 2003 to 2013. The US market of biogas is undergoing a rapid expansion and about 2000 biogas plants were operating in the US until soon. The EU is the world leader in biogas electricity production, with more than 10 GW installed and 17,400 biogas plants, in comparison to the global biogas capacity of 15 GW in 2015. European policy on the use of biomethane as a fuel for vehicles or for injection into the natural gas network makes Europe the world's leading producer, with 459 plants producing 1.2 billion cubic meters in 2015 and 340 plants fed on the gas network, with a capacity of 1.5 million cubic meters [2].

Globally, some countries have adopted policies to enhance the bioenergy integration into their economies. For example, the Indian government in 2009 adopted a policy for the production of about 14,105 t/y of biofuels, which is the use of non-edible raw materials extracted from non-agricultural land in order to prevent food and fuel market conflicts [3].

The planning and operation of such an initiative requires special attention to be paid to regional regulation of resource management and spatial energy planning in order to avoid possible tensions and to maintain strict sustainability limits for the use of biomass [4].

The problem with the location of biodigesters is essential for the feasibility of bioenergy projects, as the location can reduce the cost of transporting biomass in combination with environmental standards in compliance with environmental legal requirements. In addition, the many scientific developments on this topic provide grounds for aspects that need to be well studied in order to

---

* To whom all correspondence should be sent:
E-mail: evgeniy_ganev@iche.bas.bg

expand the knowledge about the location of the biodigestor [5]. The social aspect in location models can be considered as an example of this, as this is rarely considered [6]. The mixed-integer mathematical model offers opportunities for optimally locate the hubs (to collect feedstock) and the plants, to minimize the total cost of operating this supply chain system for renewable energy [7]. When developing the model, it is good to pay attention to: represent capital and operational expenditures at the biogas plant; the chain from the farmer to the end market; changes of mass and energy content along the chain by modeling the losses and gains for all processes in the chain [8].

The purpose of this research is to select the optimal technology for biogas production, to evaluate raw materials and products of this technology, to research and evaluate all possible flows of raw materials and products, as well as to make environmental impact assessment resulting of this activity. Based on the above research, an optimization model will be created through mixed integer linear programming (MILP) to determine potential locations and optimal parameters of potential biogas production within the Republic of Bulgaria.

PROBLEM DISCRIPTION

The main elements of supply chain (SC) for biofuels are: farms, storage facilities, commercial sites and transport [9]. Based on this framework, a common framework for the biogas supply chain has been developed **(**see Figure 1) which includes biomass production sites, biogas production and processing plants, electricity and heat cogeneration sites, compressed gas and transport facilities between the individual nodes. In general, biomass raw materials are transported by trucks from neighboring farms to the biogas plant organized by the farmers' cooperatives. Cooperatives act as a link between producers and buyers. To this end, storage facilities between farms and biogas plants are required. It is also necessary to take into account pre-treatment prior to storage in order to improve the quality of storage and adaptability for further processing.

We introduce the superstructure of the integrated biogas supply chain (IBGSC). It is based on the overall framework of the biogas supply chain (Figure 1) and it is shown in Figure 2. It includes the following elements:

1. a set of biomass production areas where different types of biomass are used as raw material for biogas plants;
2. a set of candidate sites for the implementation of biogas plants of several capacity options;
3. a set of cogeneration zones and sale of compressed biogas, where the final products are sold with certain maximum requirements;
4. a set of existing biogas plants.

The objective is to determine the number, location, and size of the biogas plants and bioresources to be transported between the various nodes of the designed network so that the overall net present value is minimized while respecting the constraints associated with product demands. This means that biogas plants built on a stage will operate in the next time interval, while allowing renovations to increase capacity to production.

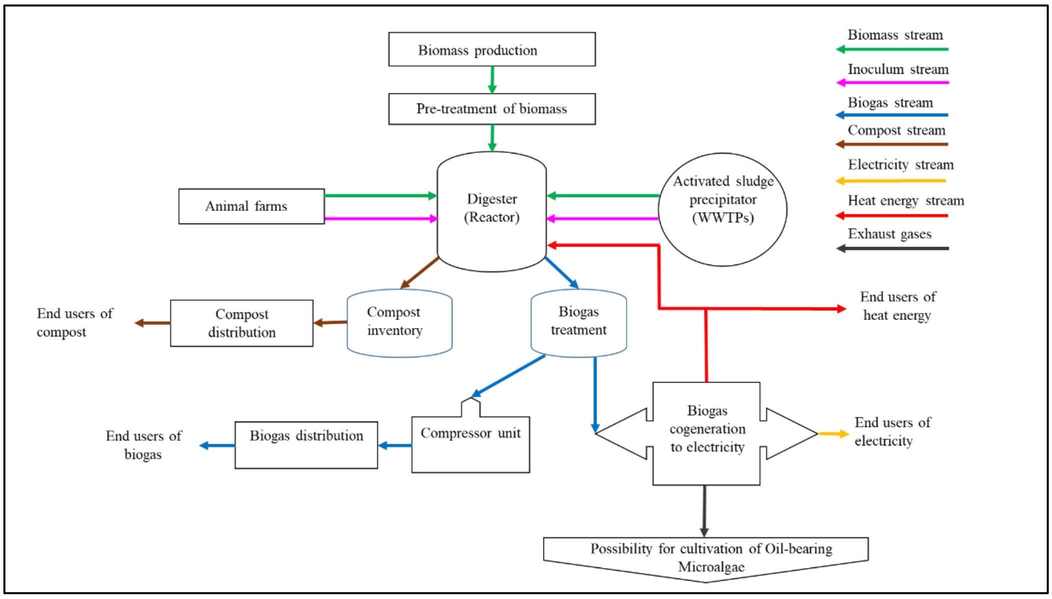

Figure 1. General framework of the biogas supply chain.

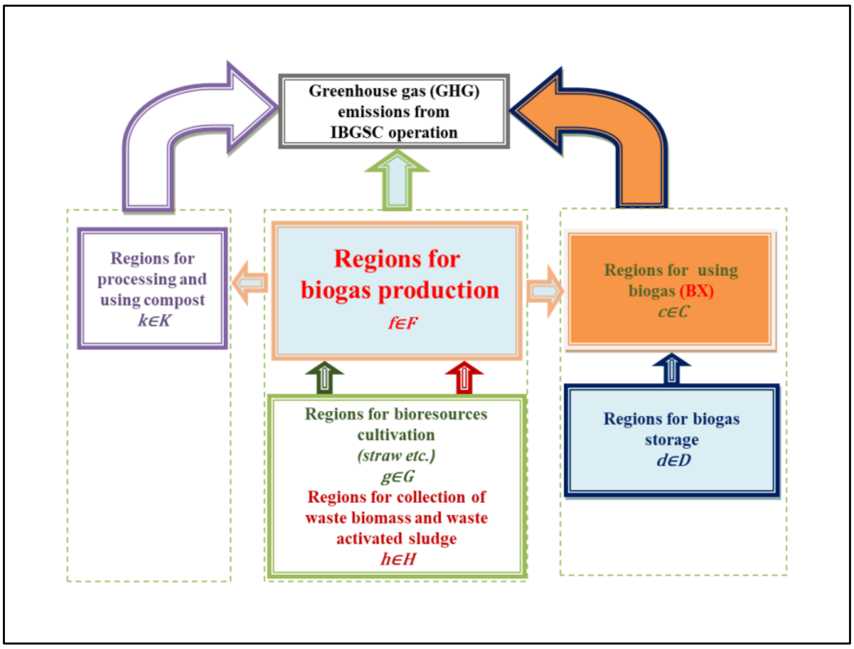

Figure 2. Superstructure of integrated biogas supply chain (IBGSC).

We look at IBGSC for a long planning horizon H (10 years). The whole time horizon H is subdivided in the set of discrete time intervals t. This time interval is divided into several equal time subintervals $t = \{0,1,2,\dots,T\}$, each of which lasts ∇t. It is assumed that during the planning horizon the value of biogas consumption will change with a predictable value. At the same time, it is assumed that the annual increase in biogas consumption is in accordance with the requirements of Regulation (EU) 2018/1999.

MODEL FORMULATION

This research describes a generic mathematical model to help decision makers in the design and planning of sustainable SC based on the LCA (life cycle assessment) methodology. The model establishes the link with the emission trading scheme to achieve sustainability objectives. Although SC sustainability recognizes the link between the economic, environmental, and social performance, an examination of social performances (labor equity, healthcare, safety) shows that they are dependent on the context of operation of the SC, the government policies, and cultural norms. Thus, without loss of generality, we do not include the social performance in the mathematical formulation [10].

MATHEMATICAL MODEL DESCRIPTION

To start with the description of the MILP model, we first introduce the parameters, that are constant and known a priori, and the variables that are subject to optimization. Then we describe step by step the mathematical model by presenting the objective function and all the constraints. First of all, we introduce the set of time intervals of the horizon of planning $t = \{0,1,2,\dots,T\}$. The subscript t indicates the variable or parameter corresponding to the t th interval of the planning [10].

BASIC RELATIONS FOR THE PROBLEM

The analysis related to the production and distribution of biogas will be performed according to three criteria, economic, environmental and social. The optimal solution would be a compromise between these three criteria (Figure 3).

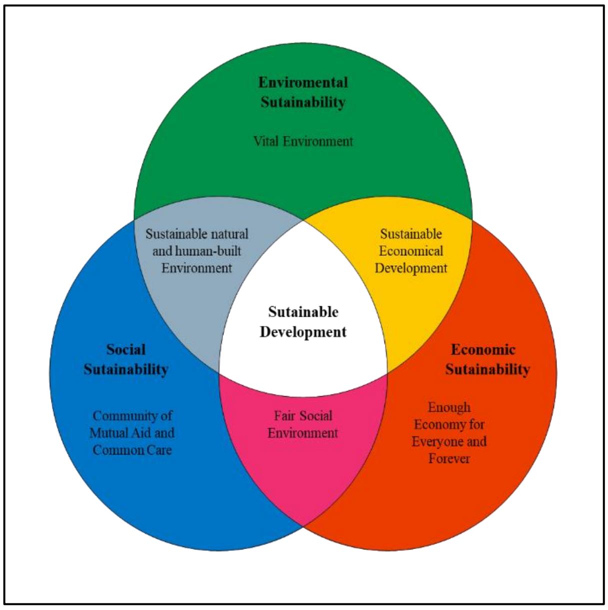

Figure 3. Sustainable development and management concept of IBGSC.

A) Basic relations for total environmental impact TEI_t, $\left[kg_{CO_2eq}/d\right]$

Among the different approaches available to assess the environmental impact of processes and organizations, the LCA method seems to be the most promising. It aggregates the results of different aspects of environmental studies including greenhouse gas (GHG) emissions that are recognized as the most harmful elements to the environment and responsible for climate change. The environmental impact of the IBGSC is measured in terms of total GHG emissions $\left[\mathrm{kg}_{\mathrm{CO_2eq}}\right]$, stemming from SC activities and the total emissions are converted to carbon credits by multiplying them with the carbon price (per $\mathrm{kg}_{\mathrm{CO_2eq}}$) in the market.

The environmental impact of IBGSC is assessed on the basis of total annual GHG emissions, such as carbon dioxide (CO_2), methane (CH_4) and nitrogen oxide (N_2O) resulting from supply chain activities. The greenhouse gases are grouped in a common indicator in terms of equivalent carbon dioxide emissions $\left[\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{y}\right]$ using their respective global warming potentials (GWPs) based on the recommendation of the Intergovernmental Panel on Climate Change (IPCC, 2007) [11] for a 100-year time horizon as follows: 1 for CO_2, 25 for CH_4 and 298 for N_2O.

An environmental objective is to minimize the total annual GHG emission resulting from the operations of the biogas supply chain. The formulation of this objective is based on the life cycle analysis, which takes into account the following stages of the fuel life cycle (Figure 4):

- The biomass production stage consists of different stages depending on the feedstock type and the subsequent use of it.
- The biomass transport stage refers to the supply of biomass to the conversion plant.
- The biomass conversion stage to biogas.
- The biogas transportation stage of facilities to the costumers zones and the cogeneration.
- The biofuel end-use stage is the stage where the biofuel is introduced in the cogenerator and burnt to provide electricity and heat energy.
- Environmental assessment criteria will be understood as the overall environmental impact during the operation of the IBGSC by the resulting greenhouse gas emissions at each time interval $t \in T$. These emissions are equal to the sum of the environmental impacts of each stage of the life cycle. Greenhouse gas emissions are usually determined as follows for each time interval $t \in T$:

$$TEI_t = ELS_t + ELB_t + ELD_t + ETT_t + ESW_t + ECOG_t, \forall t \qquad (1)$$

where all quantities are measured in $\left[\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{d}\right]$ as follows:

- TEI_t Overall environmental impact of the life cycle of IBGSC;
- ELS_t Biomass cultivation;
- ELB_t Biogas production;
- ELD_t Petroleum diesel production;
- ETT_t Raw material and product transportation;
- ESW_t Compost utilization (solid waste) for each time interval $t \in T$.
- $ECOG_t$ The use of biogas in co-generators.

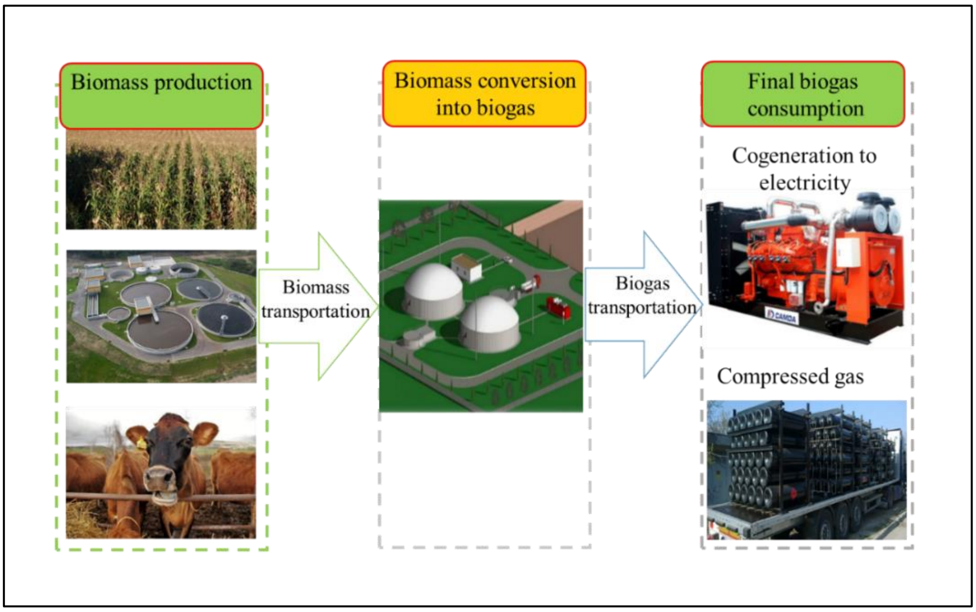

Figure 4. Biogas life cycle stages.

B) Basic relations for total cost TDC_t, [$\$/y$]

The annual operational cost includes the biomass feedstock acquisition cost, the local distribution cost of final fuel product, the production costs of final products, and the transportation costs of biomass, and final products. In the production cost, we consider both the fixed annual operating cost, which is given as a percentage of the corresponding total capital investment, and the net variable cost, which is proportional to the processing amount. In the transportation cost, both distance-fixed cost and distance-variable cost are considered. The economic criterion will be the cost of living expenses to include total investment cost of biogas production facilities and operation of the IBGSC [12]. This price is expressed through the dependence for each time interval $t \in T$:

$$TDC_t = TIC_t + TPC_t + TPW_t + TTC_t + TTAXB_t - TL_t - TA_t, \forall t \quad (2)$$

where all quantities are in [\$/y]:

TDC_t IBGSC total expenses for the year;

TIC_T Total investment cost for the production capacity of IBGSC compared to the operating period and the purchase of the plant per year;

TPC_T Production costs for biogas production;

TPW_T Production costs for solid waste disposal to compost;

TTC_T Total shipping costs of IBGSC;

$TTAXB_T$ Carbon tax calculated on the total amount CO_2, generated by the operation of the IBGSC;

TL_t Government incentives for biogas production and consumption;

TA_t Total value of by-products (compost).

C) IBGSC Social Assessment Model, [$Number\ of\ Jobs$]

The IBGSC Social Assessment Model defines the expected total number of jobs created (J_t) as a result of the operation of all elements of the system during its operation:

$$Job_t = NJ1_t + LT_t NJ2_t + LT_t NJ3_t,\ \forall t \quad (3)$$

where the components of (3) are determined according to the relations at each time interval $t \in T$, [Number of Jobs/y]:

$NJ1_t$ - the jobs created during the installation of biogas facilities and solid waste;

$LTNJ2_t$ - the jobs created during the operation of biogas facilities and solid waste;

$LTNJ3_t$ - the jobs created during biogas production.

Equation (3) represents a simplified model of the social assessment criterion used in [10].

MODEL CONSTRAINTS

For the MILP SC network design model, there are many constraints to be considered. These constraints are of many kinds including the balance constraints of all products, the capacity limit constraints, the minimum capacity occupation constraints, and the demand satisfaction constraint.

DISCUSSION

This study discusses the optimal location of biogas plants and the operation of the IBGSC. The MILP approach developed by us for the design and planning of IBGSC according to economic and environmental criteria is applied [10]. An optimization model has been developed to enable decisions to be made on biogas production infrastructure, including treatment points, volumes and logistics, both from biomass to biogas and to biorefineries to co-generation systems and markets. The development of a flexible optimization model makes it possible to solve a wide range of problems related to biofuels, as this area is changing rapidly (not only in economic but also in other dimensions, such as strategic decisions related to development and progress in this area). All of them can be included very easily in the optimization model, which would lead to significant benefits.

CONCLUSIONS

One of the valuable features of the approach is the ability to identify and solve a wide range of problems at different scales and levels such as the location of facilities and the choice of raw materials. In addition, the model itself could easily be extended to cover strategic planning issues, such as whether or not to invest in new production facilities, their location and the introduction of environmental and other external factors in the calculation of total costs.

The criteria for optimizing the model for each specific case will reflect the objectives of the stakeholder and may include maximum economic efficiency, best environmental behavior, minimum land usage, minimum total costs, etc.

Another feature of the proposed approach is that the model is not unnecessarily complicated and applying it, you can easily solve urgent problems without the need of developing new codes or optimization methods.

Acknowledgement: *The author kindly acknowledges the financial support of project № BG05M2OP001-*

1.002-0014 „Center of Competence HITMOBIL - Technologies and systems for generation, storage and consumption of clean energy", funded by Operational Programme "Science and Education For Smart Growth" 2014-2020, co-funded by the EU from European Regional Development Fund.

REFERENCES

1. T. Mizik, G. Gyarmati, *Clean Technol*., **3**, 19 (2021), https://doi.org/10.3390/cleantechnol3010002.
2. B. R. Sarker, B. Wu, K. P. Paudel, *Appl. Energy*, **239**, 343 (2019), https://doi.org/10.1016/j.apenergy.2019.01.216.
3. J. M. Egieya, L. Čuček, K. Zirngast, A. J. Isafiade, Z. Kravanja, *BMC Chem. Eng.*, **2**, 3 (2020), https://doi.org/10.1186/s42480-019-0025-5.
4. , T. Soha, L. Papp, C. Csontos, B. Munkácsy, *Renew. Sustain. Energy Reviews*, **141**, 110822 (2021), https://doi.org/10.1016/j.rser.2021.110822.
5. L. A. Díaz-Trujillo, F. Napoles-Rivera, *Renewable Energy*, **139,** 1227 (2019), https://doi.org/10.1016/j.renene.2019.03.027.
6. R. H. Gomes de Jesus, J. T. de Souza, F. N. Puglieri, C. M. Piekarski, A. C. de Francisco, *Energy Reports*, **7**, 3998 (2021), https://doi.org/10.1016/j.egyr.2021.06.090.
7. B. R. Sarker, B. Wu, K. P. Paudel, *Applied Energy*, **239,** 343 (2019), https://doi.org/10.1016/j.apenergy.2019.01.216.
8. I. G. Jensen, M. Münster, D. Pisinger, *European Journal of Operational Research*, **262,** 744 (2017), http://dx.doi.org/10.1016/j.ejor.2017.03.071.
9. I. Awudu, J. Zhang, *Renew. Sustain. Energy Reviews*, **16**, 1359 (2012).
10. E. Ganev, B. Ivanov, N. Vaklieva-Bancheva, E. Kirilova, Y. Dzhelil, *Energies*, **14**, 2261 (2021), https://doi.org/10.3390/en14082261.
11. ARC4 Climate Change 2007: Synthesis Report, Intergovernmental Panel on Climate Change (IPCC), Fourth assessment report. **2007**. Available online: https://www.ipcc.ch/assessment-report/ar4/ [Accessed 2022-02-23].
12. A. Ozlem, N. Shah, L Papageorgiou, *Biomass & Bioenergy*, **41**, 57 (2012).