

A methodological framework for achieving sustainable hydrogen supply chain produced via biogas-based steam methane reforming

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Abstract: Growing energy and environmental challenges highlight the need for a transition to sustainable supply chains. This paper presents a methodology for assessing a hydrogen supply chain based on steam reforming of biogas (SMR), as a low-carbon alternative to conventional natural gas. The framework covers the entire life cycle, from feedstock to end use. The proposed framework supports strategic planning and provides a basis for future modeling, optimization, and assessment of environmental and socio-economic benefits.

Keywords: HYDROGEN, BIOGAS, STEAM METHANE REFORMING, SUSTAINABLE, SUPPLY CHAIN

1. Introduction

Hydrogen is often described as the "green energy carrier of the future" because it can be used in fuel cells, where it produces electricity through oxidation without emitting carbon dioxide. This electricity could be used to power cars and buses, to carry out chemical processes, to provide backup or peak power in energy systems, etc. Unlike conventional resources such as natural gas, hydrogen does not occur freely in nature and must first be produced, which is why it is considered an energy carrier rather than a primary fuel [1]. Various feedstocks such as water, natural gas, coal, oil, biomass, biogas, waste, and industrial by-product gases can be used for hydrogen production through chemical, electrochemical, or thermochemical processes. The choice of source and method determines the efficiency, cost, and environmental impact of production. At present, the most widely used technology for industrial hydrogen production is steam methane reforming (SMR) from natural gas due to its technological maturity and economic efficiency [2]. However, the SMR process generates significant CO₂ emissions (approximately 9–12 kg CO₂-eq/kg H₂), which motivates researchers to explore the development of alternative feedstocks and processes [3]. This poses serious challenges to the sustainability of hydrogen supply chains.

One of the most promising low-carbon alternatives that is attracting increasing attention is the use of renewable gas feedstocks, among which biogas stands out as a technologically compatible substitute for natural gas in reforming processes. Analyses indicate that integrating biogas into reforming processes can reduce emissions and improve energy efficiency, particularly when the feedstock is derived from waste streams [3]. In addition, biogas quality and the degree of purification are critical factors for reforming efficiency and catalyst stability [4].

Another key aspect is the availability of biogas as a resource. Its potential is highly dependent on regional factors such as biomass waste availability, collection infrastructure, regulatory framework, and economic incentives. Therefore, the sustainability of biogas-based hydrogen systems cannot be assessed solely at the technological level but requires an integrated system analysis that includes the resource base, logistics, and market conditions.

The hydrogen supply chain is a complex system of interconnected stages, including feedstock supply, biogas production, biogas upgrading, hydrogen production and purification, transport, storage, and end use [5]. Each of these stages has specific technological, economic, and environmental characteristics that influence the overall sustainability of the system.

Modern scientific research emphasizes that the optimization of hydrogen supply chains (HSC) requires a systematic approach that considers all stages simultaneously [6]. Analyses indicate that solutions optimal for an individual stage (e.g., production) are not always optimal for the system as a whole. For example, centralized production may be more technologically efficient but can result in high transport costs and emissions. Conversely, decentralized systems reduce logistical costs but often require greater production capacity.

The main parameters influencing the configuration of hydrogen supply chains include the geographic distribution of resources, spatial distribution of consumers, transport distances, infrastructure availability, and economies of scale. Modeling such systems is often performed using optimization methods, including linear programming, mixed-integer models, and scenario analyses. These approaches enable simultaneous minimization of costs and emissions under given constraints, such as facility capacity or infrastructure limitations. A particularly important aspect is the choice of hydrogen storage and transport technology. Different options—compressed gas, liquefied hydrogen, ammonia, or liquid organic carriers—exhibit different energy losses, capital costs, and risks. Therefore, the optimal configuration of the supply chain depends on the combination of technology, distance, and production scale.

An additional factor is uncertainty in future hydrogen demand [7]. Many models show that investment decisions are highly sensitive to demand forecasts, which necessitates the integration of scenario analyses and probabilistic methods. This is especially relevant for emerging markets where stable historical data are lacking.

In this context, multi-criteria assessment methods are considered a promising tool for strategic planning, as they allow simultaneous consideration of economic, environmental, and social indicators. They support decision-making under conditions of uncertainty and complexity characteristic of the hydrogen economy.

Existing literature identifies three main limitations: the lack of integrated methodologies combining life cycle assessment (LCA) and supply chain analysis, the limited number of studies on biogas-based hydrogen, and the absence of multicriteria frameworks for strategic planning. Therefore, the development of a systematic methodological framework for assessing the sustainability of biogas-based hydrogen supply chains represents a timely and scientifically justified research need.

This study focuses on developing a methodology for evaluating the sustainability of a supply chain based on hydrogen production via biogas-based steam methane reforming. The object of the study is a hydrogen supply chain encompassing feedstock supply, biogas production, biogas upgrading, hydrogen production and purification, transport, storage, and end use. The approach adopted in this work is based on a systems-level consideration of the chain and life cycle analysis, integrated within a multicriteria framework for sustainability assessment. The aim of the developed methodological approach is to support strategic planning and provide a foundation for future quantitative modeling and optimization.

2. Hydrogen production via biogas-based steam methane reforming

Before considering the technological process of producing hydrogen based on biogas (biohydrogen), it is important to analyze the raw material itself (biogas) - composition, potential and challenges.

2.1 Biogas as a feedstock for hydrogen

Biogas is a biogenic gas produced through the anaerobic decomposition of organic matter by microbial cultures [8]. It is typically obtained from municipal solid waste landfills, wastewater treatment plants, agricultural facilities fermenting animal residues, and industrial and food-processing waste.

Biogas primarily consists of methane (CH₄) and carbon dioxide (CO₂), along with trace impurities such as hydrogen sulfide (H₂S), water vapor, nitrogen, and other volatile components. Table 1 presents the compositional profile of biogas as a feedstock for hydrogen production via SMR [9]. The high methane content in biogas makes it a suitable feedstock for hydrogen production.

Table 1: Component composition of biogas, [9].

Components of biogas	Molar Fraction	Mass Fraction
CH ₄	59.75%	35.05%
CO ₂	40.00%	64.60%
N ₂	0.20%	0.20%
O ₂	0.02%	0.05%
H ₂ S	725 ppmv	900ppm

The composition of biogas can vary depending on the source and production conditions, but it usually contains about 50-70% methane, 30-50% carbon dioxide and up to a few percent of impurities. Impurities such as hydrogen sulfide and siloxanes can be corrosive and reduce the efficiency of subsequent technological processes, requiring preliminary upgrading [4].

The use of biogas as a feedstock for hydrogen production offers several key advantages [10]:

- *Low-carbon profile*

Biogas can significantly reduce life cycle greenhouse gas emissions compared to natural gas, particularly when derived from waste streams that would otherwise release methane into the atmosphere.

- *Utilization of waste resources*

The use of biogas in hydrogen production turns an environmental problem associated with waste from landfills, farms and sewage treatment plants into a valuable resource. The conversion of organic waste into energy and hydrogen contributes to the development of a circular economy, while reducing the need for landfilling and open fermentation.

- *Use of existing infrastructure*

Hydrogen production from biogas is achieved using established and widely applied steam methane reforming technology. Since biogas (after upgrading to biomethane) is nearly identical to natural gas, existing facilities can be used without major new investments in technology.

- *Continuous production*

Unlike "green hydrogen", which is produced by electrolysis and is dependent on the availability of sun or wind, biogas-based hydrogen can be produced continuously. This makes hydrogen supplies predictable and stable for industry and transport.

- *Decentralization*

Biogas plants can be located close to waste sources, in agricultural areas or near urban centers. This allows hydrogen to be produced close to the point of consumption, reducing both transport costs and emissions.

- *Flexibility*

Biogas can be used either independently or blended with natural gas, allowing technological processes to be adapted according to feedstock availability.

According to the International Energy Agency (IEA) [10] and the International Renewable Energy Agency (IRENA) [11], biohydrogen provides reliable production with the potential for a negative carbon footprint, making it more environmentally friendly than gray hydrogen and more accessible than green hydrogen. Furthermore, biogas-based technology supports the circular economy by converting waste into a resource for clean energy. Table 2 presents a comparative profile of hydrogen production pathways.

Table 2: Hydrogen production pathways: a comparative profile

Characteristic	Grey Hydrogen (Natural Gas)	Bio-Hydrogen (Biogas/Bio methane)	Green Hydrogen (Electrolysis)
CO₂ Emissions	High (Fossil-based)	Neutral to Negative	Zero (Renewable-only)
Availability	Constant (24/7)	Constant (Base load)	Intermittent (Weather-dependent)
Production Cost	Low	Medium	High
Raw Material	Fossil Methane	Organic Waste / Biomass	Water + Renewable Electricity
Energy Cycle	Linear (One-way)	Circular (Closed-loop)	Circular (Closed-loop)

Despite the potential benefits of using biogas as a feedstock for hydrogen production, several technological and economic challenges exist, including the need for biogas upgrading, compositional variability, infrastructure requirements, and others [3]. These limitations could be addressed through the development of a methodological framework for achieving a sustainable hydrogen supply chain.

2.2 Hydrogen production from biogas

The conversion of biogas into hydrogen is a multi-step thermochemical process that integrates biogas production, gas upgrading, and subsequent catalytic conversion [3]. Biogas is typically produced through the anaerobic degradation of organic waste under mesophilic conditions.

The first technological step is the preliminary upgrading of biogas, which involves the removal of sulfur compounds, moisture, and silicon-containing components, as these can deactivate catalysts and reduce process efficiency. If necessary, CO₂ is partially removed to produce biomethane with a higher CH₄ content.

The main conversion step is steam methane reforming in which a mixture of methane and steam reacts catalytically at high temperatures (typically 700–900 °C) in the presence of a nickel catalyst, forming syngas—a mixture of H₂, CO, CO₂, CH₄, and water vapor. The reaction is highly endothermic and requires an external heat source. The composition of the resulting syngas depends on temperature, pressure, and the CH₄/CO₂/H₂O ratio in the feed.

After reforming, the gas mixture undergoes a water–gas shift (WGS) reaction, in which carbon monoxide reacts with steam to produce hydrogen and carbon dioxide. In industrial practice, this stage is carried out in two consecutive reactors—a high-temperature reactor (≈300–400 °C) and a low-temperature reactor (≈200–300 °C)—to maximize CO conversion and increase H₂ yield.

The final technological step is hydrogen purification. Methods such as chemical absorption of CO₂, methanation, membrane separation, or Pressure Swing Adsorption (PSA) are employed.

Modern systems often combine PSA and membranes, as this allows the production of high-purity hydrogen (over 99%) with relatively moderate energy consumption.

In addition to conventional SMR, biogas also allows the application of dry reforming, in which methane reacts directly with the CO₂ present in the feedstock. This approach is environmentally attractive, as it utilizes carbon dioxide as a reactant and potentially reduces overall emissions.

3. Hydrogen supply chain

The hydrogen supply chain for biogas-based hydrogen produced via steam methane reforming represents an integrated system of technological, logistical, and infrastructural stages. It covers the entire pathway—from feedstock to end user. The main stages are:

- *Feedstock supply*

This is the stage of waste biomass collection, transport to the anaerobic plant and preliminary preparation (grinding, homogenization, humidity control).

- *Biogas production and upgrading*

This stage includes the anaerobic digestion of biomass in the production of raw biogas and the subsequent biogas upgrading process.

- *Hydrogen production*

This is the stage of converting biogas into biohydrogen through a steam reforming process, in which the main process (SMR), Water-Gas Shift reaction and gas purification are carried out to obtain high-purity hydrogen.

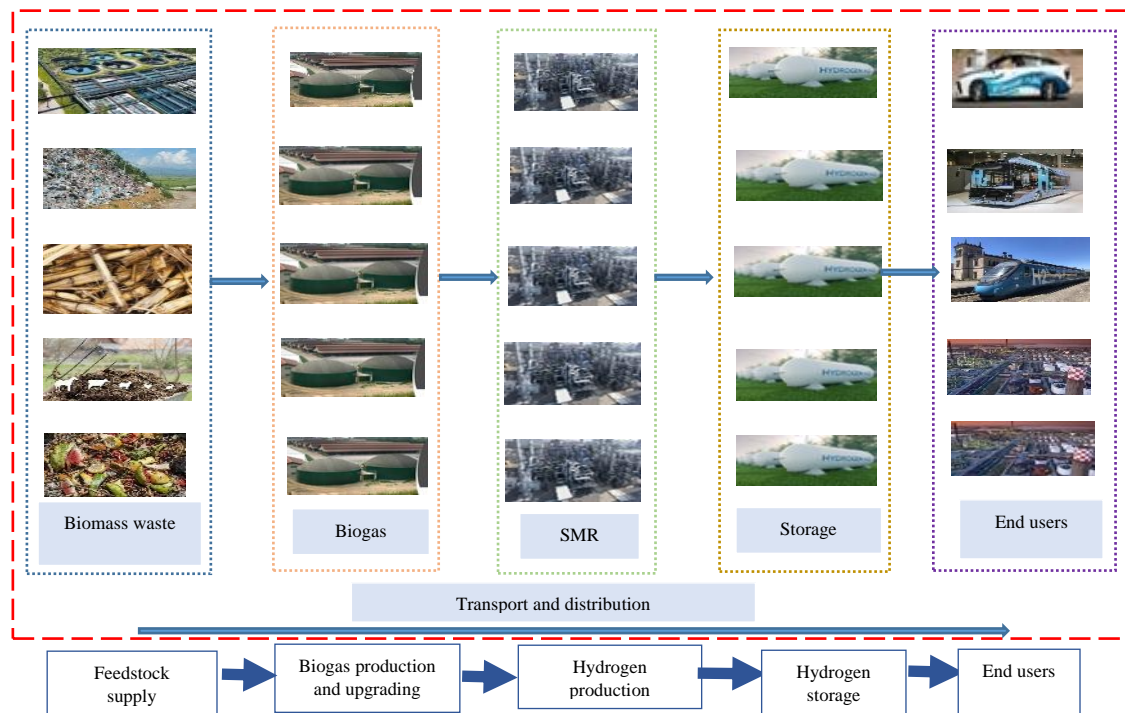


Fig. 1. Supply chain of hydrogen produced via biogas-based SMR

- *Hydrogen storage*

Hydrogen can be stored in liquid or gaseous form in buffer tanks at the production facility or at the end points of consumption.

- *Transport and distribution*

Transport and distribution of hydrogen can be carried out using specialized tube trailers or pipelines.

- *End use*

Biohydrogen can be utilized at hydrogen refueling stations for cars and buses, as well as in industry, energy systems, and other applications.

Fig. 1 presents the proposed superstructure of the hydrogen supply chain produced via biogas-based steam methane reforming, which considers the entire life cycle of the process—from feedstock to end user.

4. A methodological framework

The research methodological framework of the study is presented in Fig. 2 and is adapted from the framework proposed in [12]. The proposed in current work framework is structured into three main blocks: input data, optimization model, and output results, which together form a systematic architecture to support decision-making in the design and assessment of a sustainable hydrogen supply chain based on biogas resources. This framework allows for the integration of technological, economic, and environmental parameters, enabling a comprehensive evaluation of alternative configurations and their impact on overall system sustainability. By providing a structured approach, it facilitates strategic planning and supports the identification of trade-offs between cost, efficiency, and environmental performance.

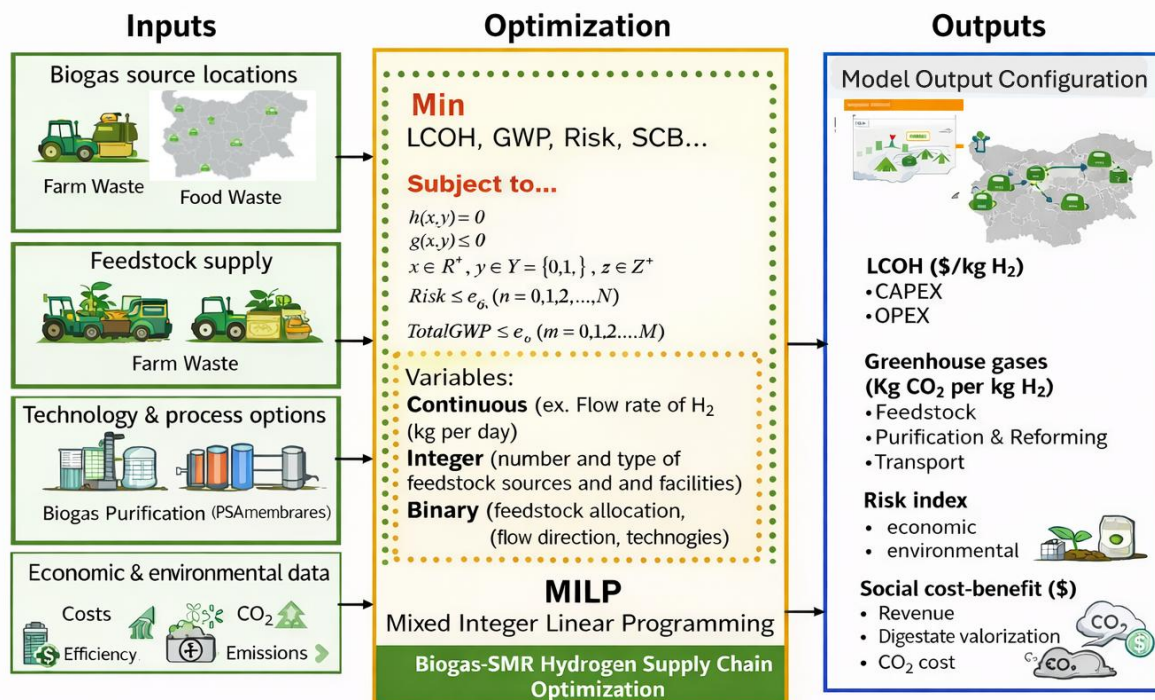


Fig. 2. Biogas-SMR hydrogen production methodological framework

The input block corresponds to all the databases, hypotheses, and scenarios. This stage collects the necessary information for system modeling, including the location of biomass waste sources, data on the quantity and type of available biomass, technological process parameters, as well as economic and environmental data. The purpose of this block is to initialize the model with consistent and realistic information, enabling both deterministic calculations and scenario-based analysis.

The optimization block integrates the mathematical model and the multi-objective optimization approach, constituting the core of the framework. The problem is formulated in terms of Mixed Integer Linear Programming (MILP). The proposed methodological framework aims to minimize key indicators such as economic efficiency, environmental impact, social benefits, and risks, while satisfying a set of constraints (e.g., technological, transport, material, environmental, logical, and others). This formulation allows for the analysis of trade-offs between conflicting objectives and helps identify optimal system configurations under different scenarios.

The outputs block corresponds to all results according economic, ecologic and risk and social benefits, so as to ensure a sustainable hydrogen supply chain. The set of results obtained allows a quantitative assessment of the sustainability of the system and supports decision-making processes.

5. Conclusion

This study presents an integrated framework for the analysis and design of the production and supply chain of hydrogen from biogas via steam methane reforming. The proposed approach combines resource assessment, process modeling, and systems analysis within a unified methodological structure, considering the entire system as an interconnected chain—from feedstock to end user. Sustainability is addressed comprehensively by simultaneously accounting for technological, economic, environmental, and social indicators. The developed framework can serve as a decision-support tool for planning, optimization, and scenario evaluation for the implementation of biogas-based hydrogen systems under varying regional and technological conditions.

Acknowledgments

The study has been carried out by the financial support of National Science Fund, Ministry of Education and Science of the Republic of Bulgaria, Contract № KII-06-H89/6/09.12.2024

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