Empowering rural districts with Urban-Industrial Symbiosis: A multi-objective model for Waste-to-Energy cogeneration and hydrogen sustainable networks

Neri A. [a,c)], Butturi M.A. [a)], Lolli F. [a,b)], Gamberini R. [a,b)]

a. *Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, Via Amendola 2, 42122 - Reggio Emilia - Italy (alessandro.neri@unimore.it, mariaangela.butturi@unimore.it)*

b. *Interdepartmental Centre En&Tech, Piazzale Europa, 1, 42124 - Reggio Emilia - Italy (francesco.lolli@unimore.it, rita.gamberini@unimore.it)*

c. *Department of Industrial Engineering, University of Bologna, Via Zamboni 33, 40126 - Bologna - Italy*

Abstract: The growing demand for sustainable energy sources and the need to mitigate greenhouse gas emissions have led to increased interest in developing efficient, cost-effective, and environmentally friendly industrial systems. This paper presents a multi-echelon multi-objective network design model for urban-industrial symbiosis, combining biogas and hydrogen production plants with locally sourced organic waste as feedstock. The integrated biogas-hydrogen system utilizes locally sourced agricultural and organic waste as feedstock, enhancing rural processes sustainability and resource efficiency. The model optimizes the location of industrial plants based on environmental and economic parameters, including transportation emissions, energy consumption, and carbon footprint. A case study set in Emilia Romagna validates the model, and a sensitivity analysis examines the impact of varying input parameters on the designed industrial park. Results demonstrate that the novel combined biogas-hydrogen system not only reduces greenhouse gas emissions but also produces hydrogen at a lower cost due to the utilization of excess power from the biogas cogeneration plant. This research has significant implications, offering a sustainable and cost-effective hydrogen source while promoting efficient supply chain management and strategic decision-making in the renewable energy sector. Further study might investigate system robustness against disruptive events, plant design, and the integration of additional renewable sources.

Keywords: Industrial Symbiosis; Waste-to-Energy; Hydrogen Production; Renewable Energy Sources; MILP

I. INTRODUCTION

The need for sustainable energy sources and solutions to mitigate climate change is increasing. Agriculture has the greatest environmental impact in developing nations [23]. The Emilia-Romagna region in northern Italy is characterized by a rich agricultural heritage and a strong industrial base. In 2021, Emilia-Romagna generated 2,839,452 tons of urban waste. The most commonly collected materials were organic and green waste (19% and 6% potentially recoverable). There are 451,423 tons of waste from the agricultural and forestry industries, of which 99,894 tons are destined for disposal [29]. Furthermore, Emilia-Romagna is interested in green hydrogen for mobility and energy production. The key issue for its development is economic sustainability due to considerable capital investments and high operational costs. The region's hydrogen transition can begin by mixing hydrogen into existing natural gas networks and progressively shifting to electrolysis driven by renewable electricity, especially for heavy transport and hard-to-abate industries. Thus, the proper management of municipal and rural waste, as well as the development of an efficient hydrogen supply chain, are areas of great interest for stakeholders in the region.

Waste-to-Energy (WtE) technologies are being explored to efficiently recover energy from waste [3]. Among the others, Anaerobic Digestion (AD) is a waste-to-energy technology with many benefits for solid waste and agriculture. AD produces biogas that can be used to generate renewable energy while also reducing waste volume. Biogas can be cleaned and utilized for heat and power generation [20]. This reduces dependence on fossil fuels and fosters a more cost-effective and sustainable energy supply [9]. Additionally, AD systems produce nutrient-rich digestate, a natural fertilizer that can enhance soil quality and crop yields, while decreasing reliance on chemical fertilizers [15].

Hydrogen can be used to store, transport, and produce electricity. Natural gas and coal generate most of the world's hydrogen [12]. Renewables are underutilized sources, accounting only 2% of overall output [14]. Low-carbon hydrogen is critical to achieving a sustainable energy system by 2050 [18]. The power to hydrogen process converts extra electricity into hydrogen using electrolysis, breaking water molecules into O_2 and H_2. The hydrogen produced is considered "green hydrogen" whenever electricity from renewable systems is exploited. Green hydrogen has a lower global warming potential than standard coal gasification and reforming systems [8]. Therefore, biomass-electricity-electrolysis route exhibits better environmental performance [13, 26]. Green hydrogen can promote low-carbon mobility through synergies between industrial clusters and communities [5]. Urban-Industrial Symbiosis (UIS) provides an innovative framework that seeks to foster synergies among industrial, urban and rural communities, paving the way for sustainable development and resource optimization [6].

The objective of this study is to propose a model for the design of an energy symbiosis that transforms biomass into biogas, heat, electricity, and hydrogen through electrolysis. Additionally, the model incorporates the utilization of by-products, specifically fertilizers generated during the anaerobic digestion process. The main aim is to optimize both the economic and environmental impacts of the entire system.

This paper includes a concise literature review in Section II, problem description and formulation in Section III, a detailed case study in Section IV followed by the sensitivity analysis, and conclusive remarks in Section V.

II. LITERATURE REVIEW

In recent years, WtE technologies have gained increased attention as a promising means of addressing waste management issues and promoting sustainable energy production. Several studies have employed various methodologies to optimize the selection and sizing of WtE technologies under different conditions, considering economic, environmental, and technical factors.

Waste management frequently employs Mixed Integer Linear Programming (MILP) models to support strategic decisions. This is caused by the flexibility and diversity of integrable decision factors and parameters. The MILP models mainly aim at designing the waste supply chain network considering the waste allocation, and the number, capacities, and locations of waste treatment plants, optimizing the economic and environmental impacts. For instance, Thiriet et al. (2020) [24] described an approach to design distributed micro-scale anaerobic digestion networks for the valorisation of urban bio-waste. Their MILP model aimed to minimize the total payload distances involved in transporting waste and digestate. Bijarchiyan et al. (2020) [4] modelled a biomass to bioenergy supply chain using the anaerobic digestion process maximizing economic profits and positive social externalities. Balaman and Selim (2014) [2] optimized biomass to energy supply chain networks at regional level in Turkey. Their MILP model considered economic and environmental criteria to identify the optimal number, capacities, and locations of biogas plants and biomass storages. Rahimi et al. (2021) [19] designed an electricity production supply chain from animal manure, minimizing SC costs. They determined the best locations for establishing facilities, optimal capacity levels, and material flow. In the context of Municipal Solid Waste (MSW) management, Abbasi et al. (2022) [1] considered the MSW management, comparing Anaerobic digestion and incineration processes to minimize environmental impact while maximizing profits.

III. PROBLEM DESCRIPTION AND FORMULATION

The proposed models are focused on designing a WtE system for organic rural waste, utilizing anaerobic digestors as a key component. In this section, we outline the challenge of creating a WtE system and offer a mathematical representation of the multi-tiered, interconnected biogas-hydrogen network.

A. Problem definition

The objective of the problem is to determine the optimal network design (i.e., location and size) to be exploited to convert organic waste to power, heat, and hydrogen. The proposed integrated biogas-hydrogen network consists of several interconnected facilities, which work in synergy to optimize the utilization of locally sourced agricultural and organic waste as feedstock to produce hydrogen, electricity, and heat.

According to Figure 1, the anaerobic digestors process the feedstock, converting it into biogas and producing fertilizer as a by-product.

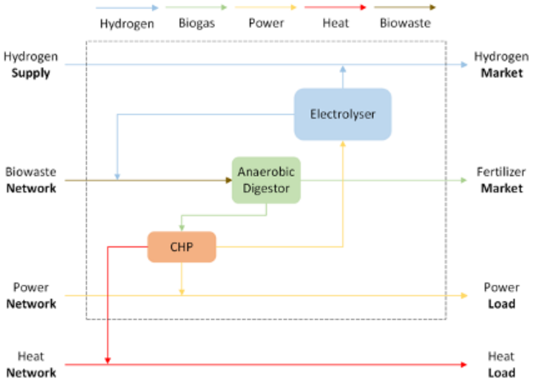

Figure 1 Problem boundaries and network structure

The biogas is then transported to cogeneration units, where Combined Heat and Power (CHP) systems generate electricity and heat for the outside market. A portion of the generated electricity is consumed by the electrolysers, which in turn produce hydrogen. The output hydrogen, as useful energy source, is supplied directly to hydrogen-powered vehicles for feedstock and biogas transportation or sold to market.

B. *Mathematical model notation*

This section describes the nomenclature that was used to express the problem, consisting of several key components, which can be classified into sets, parameters, and variables. The sets include F, representing feedstock sources, A which stands for anaerobic digestors, C that symbolizes cogeneration units, and E, denoting electrolysers. In addition to these sets, the model comprises numerous parameters that depict the characteristics and costs associated with each element within the sets. These parameters include various aspects like feedstock availability fs_i, treatment cost for organic waste cwo, distances between various units d_{ij}, their capacities a_j, investment costs ica_j, and the yield of energy products such as biogas γ^b, fertilizer γ^f, and hydrogen η^e. Additionally, they also encompass costs related to hydrogen transportation tc, rates of consumption β^f, unit prices for fertilizer pa, electricity pp, heat ph, and hydrogen pe, and the emission factors associated with each stage of the process $(ef\,a, ef\,f, ef\,c, ef^{f}, ef^{ng})$. Lastly, the variables in the model are indicative of the quantities of different elements being transported $\left(x_{ij}, y_{jk}, f_i\right)$, generated $\left(e_k, q_k, w_l\right)$, or consumed throughout the network $\left(z_{kl}, v_l\right)$. These elements can range from feedstock and biogas to heat, electricity, and hydrogen. Additionally, the variables also include binary values representing the existence or non-existence of an anaerobic digestor ba_j, a cogeneration unit bc_k, or an electrolyzer be_l. By integrating these sets, parameters, and variables, the primary objective is to identify the optimal size of the required components in order to economically valorise the waste and by-products into energy and hydrogen. Simultaneously, the models aim to minimize the total amount of carbon emissions generated by the processes, ensuring a sustainable and environmentally friendly solution for waste management and energy production.

C. *Objective functions*

The proposed multi-objective optimization model will simultaneously optimize two objective functions, aiming to identify a set of non-dominated solutions that strike a balance between minimizing economic costs and environmental impacts.

The first objective function seeks to reduce the system's overall economic expenses. This covers the expenses of installing anaerobic digesters, cogeneration systems, and electrolysers as well as the costs of operating and maintaining them, transporting feedstock and biogas, and producing hydrogen. The revenues are generated from the sale of electricity, heat, hydrogen, and fertilizer produced within the system. Equation 1 expresses the mathematical formulation of this objective function.

$$\begin{aligned} Z_1 = {} & \left(\sum_j ica_j ba_j + \sum_k icc_k bc_k + \sum_l ice_l be_l\right)(1+op) + \\ & + tc\left[\left(\frac{\sum_i \sum_j x_{ij} d_{ij} + \sum_j \sum_k x_{jk} d_{jk}}{tk \cdot ac}\right) - \sum_l v_l\right] + cwo \sum_i \left(fs_i - \sum_j x_{ij}\right) \\ & - \left[pa \sum_i f_i + pp \sum_k \left(e_k - \sum_l z_{kl}\right) + ph \sum_k q_k + pe \sum_l \left(w_l - v_l\right)\right] \end{aligned} \tag{1}$$

The second objective function aims to minimize the emissions generated by the symbiosis and its associated network. In this paper, only is considered among the air pollution emissions. The primary sources of emissions only include anaerobic digestion and cogeneration. Equation 2 presents the carbon footprint objective function.

$$\begin{aligned} Z_2 = {} & ef\,a \sum_i \sum_j x_{ij} + ef\,c \sum_j \sum_k y_{jk} \\ & + ef\,f \sum_i \left(fs_i - \sum_i x_{ij}\right) - ef^{f} \sum_j f_j - ef^{ng} \sum_k e_k \end{aligned} \tag{2}$$

In this study, we have chosen the ε-constraint method to solve the multi-objective optimization problem for the integrated biogas-hydrogen system. This method effectively balances the competing objectives of minimizing net economic costs and environmental impacts by transforming the multi-objective problem into a series of single-objective problems with varying constraints. The ε-constraint method proceeds by selecting one objective function to optimize (i.e., Z_1) while treating the remaining objective function (i.e., Z_2) as a constraint with a specified limit ε (level of satisfaction of the objective function) in the first function feasible space. By employing the ε-constraint method, we can systematically explore the trade-offs between the objectives and obtain a diverse set of solutions that cater to various priorities and preferences of decision-makers.

D. *Constraints*

Depending on the elements and operations of the system, it is possible to segment the constraints of the optimization problem into several stages.

Feedstock collection Constraint 3 ensure that the total amount of feedstock collected by sources does not exceed the available supply.

$$\sum_j x_{ij} \leq fs_i \quad \forall i \tag{3}$$

Biogas production Constraint 4 guarantees that the total amount of feedstock used during anaerobic digestion must not be greater than each digestor's capacity.

$$\sum_i x_{ij} \leq a_j \cdot ba_j \quad \forall j \tag{4}$$

Constraints 5 and 6 ensure that the biogas and fertilizer production rate is consistent with the feedstock processed in the anaerobic digestor.

$$\sum_k y_{jk} = \gamma^b \sum_i x_{ij} \quad \forall j \tag{5}$$

$$f_j = \gamma^f \sum_i x_{ij} \quad \forall j \tag{6}$$

Cogeneration Constraint 7 guarantee that the total amount of biogas utilized does not exceed the capacity of each cogeneration unit.

$$\sum_j y_{jk} = c_k \cdot bc_k \quad \forall k \tag{7}$$

Electricity and heat produced by the cogeneration units must be consistent with the biogas input and CHP conversion efficiencies (constraints 8 and 9).

$$q_k = \eta^h \sum_j b \cdot y_{jk} \quad \forall k \tag{8}$$

$$e_k = \eta^p \sum_j b \cdot y_{jk} \quad \forall k \tag{9}$$

Hydrogen production Constraint 10 states that the electricity sent to each electrolyser must be limited to the amount produced by the CHP plant.

$$\sum_l z_{kl} \leq e_k \quad \forall k \tag{10}$$

Total amount of electricity consumed does not exceed the capacity of each electrolyzer and that the hydrogen production rate is consistent with the electricity input and electrolyzer conversion efficiency (constraints 11 and 12).

$$\sum_k z_{kl} \leq g_l \cdot bl_l \quad \forall l \tag{11}$$

$$w_l = \eta^e \sum_k z_{kl} \quad \forall l \tag{12}$$

Additionally, constraint 13 states that hydrogen used in fuel cell vehicles must be less than the total amount of hydrogen produced.

$$v_l \leq w_l \quad \forall l \tag{13}$$

$$x_i j, y_j k, f_j, e_k, z_k l, q_k, w_l, v_l \in \mathbb{R}^+ \quad \forall i, j, k, l \tag{14}$$

$$ba_j, bc_k, be_l \quad \forall i, j, k, l \tag{15}$$

IV. CASE STUDY

Our case study focuses on the Emilia-Romagna region in Italy for the following key reasons: (1) Emilia-Romagna exhibits a high potential for biogas production from biomass energy sources, particularly agricultural waste, which is abundant in the region [16]. (2) A large quantity of biomass is produced as a result of agricultural activities, including crop leftovers, animal manure, food and agro-industrial wastes, and organic waste [10]. (3) Emilia-Romagna has adopted a Regional Energy Plan (REP) to 2030, aiming at GHG emissions reduction, energy consumption control, and enhanced use of bioenergy. This plan, combined with Italy's incentive programs for renewable energy projects, boosts the profitability of the supply chain [23]. REP predicts a significant increase in energy output from biogas. The current 234 MW of installed capacity could rise 320 MW [16].

A. *Assumptions*

The following assumptions and data are applied in this study.

This case study is situated in Emilia-Romagna, specifically the countryside between Modena and Reggio Emilia. The time horizon for this study is a single aggregated year. The feedstock used consists of agricultural waste and biomass from local municipalities in Emilia-Romagna. Thus, each source has an available feedstock biomass already sorted ranging from 2,000 to 10,000 tonnes per year. We consider 10 potential sites for anaerobic digestors to process the feedstock. These sites are selected considering proximity to feedstock sources. Each potential site can host an anaerobic digestor with a capacity ranging from 30,000 to 75,000 tonnes per year. The investment cost for building a digestor ranges from € 500,000 to €3,000,000, depending on the capacity and site-specific installation costs [7]. The model assumes a biogas yield of 150 Sm^3/t and a fertilizer yield of 200 kg/t of feedstock. The biogas produced by the digestors can be used to generate heat and electricity in cogeneration units. We consider 10 potential sites for these units, located near industrial parks and residential areas with high energy demand. The cogeneration units have capacities ranging from 5,000,000 to 3,500,000 per year, and their investment costs range from € 200,000 to € 14,000,000, reflecting differences in technology and scale. The cogeneration units have a heat conversion efficiency of 80% and a power conversion efficiency of 30%. To boost the supply chain's sustainability, we include 10 prospective locations for Alkaline Electrolyzers (AEL), the most mature and cost-effective technology at the moment, that produce hydrogen from surplus power provided by cogeneration units. These electrolysers have capacities ranging from 500 kW to 5 MW (production rate 5.5 kWh/Sm^3H_2 max) and their investment costs range from € 500,000 to € 3,000,000 [25]. The transportation of hydrogen is considered with a cost of 5 , reflecting current market price for hydrogen transport [22]. We assume a 180 truck capacity and an average hydrogen consumption across the network of 0.08 [11, 21]. The supply chain is expected to generate revenue through the sale of fertiliser (6 $€/t$), electricity (0.157), heat (0.075 $€/kWh$), and hydrogen (3). The unit prices for these products are based on current market conditions in Italy [27, 28]. Finally, we include emission factors in the model to capture the environmental impact of the supply chain. The environmental impact is quantified using several emission factors: anaerobic digestion (1.9 $kgCO_2eq/kg\ feedstock$) [17], fertilizer production (4.20 $kgCO_2eq/kg\ N$) [23], northern Italy electricity emission factor (0.548 $kgCO_2eq/Sm^3$), and cogeneration (0.137 $kgCO_2eq/kWh$). These factors reflect the carbon intensity of different stages of the process, from feedstock digestion to energy generation and hydrogen production.

B. Model results

As previously stated, the methodology used to solve this model employs an ε-constraint approach. This technique facilitates the determination of an array of efficient solutions, which may be conveniently represented graphically using a Pareto chart. The primary goal of such solutions is to establish a balance between the model's two objectives. The model was resolved using MATLAB R2023a and its Optimization Toolbox.

We focused on the first objective function as the major goal. The zone of feasibility for the issue, indicated as **S**, includes model constraints 3-15, while adding a constraint $Z_2(\vec{x}) \leq \varepsilon_2$. Then, the boundaries are selected by exploring the extreme values of the Z_2 whilst the Z_1 is optimised. To find the upper limit of ε_2 , we find the value of Z_2 by minimizing the Z_1. Conversely, for determining the lower limit of ε_2 , we solve the same problem but this time minimizing and evaluating Z_2.

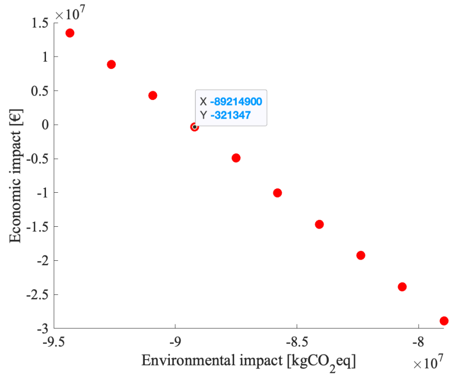

Figure 2 Pareto front

The Pareto diagram (Figure 2) demonstrates that when the environmental impact function ranges from -78,961,025 and -94,341,839 $kgCO_2eq$, the economic function varies between € -23,849,595 to € 13,465,601. The graphic shows a pattern in which the first goal function raises profits while the second function diminishes its impact. The importance of income above expenditures determines the negative values of Z_1. The ε_2 = -89214901.88 is chosen as the best to offer a good supply chain design for both target functions. Results are shown in Figure 3.

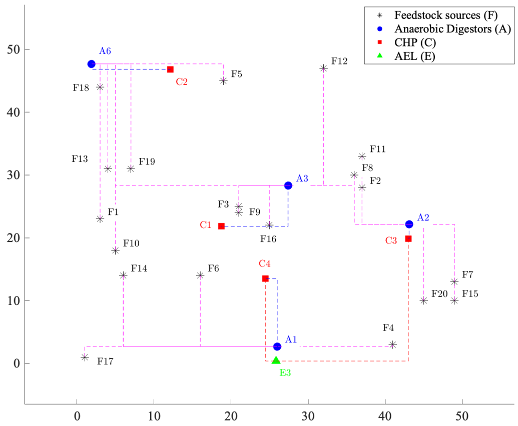

Figure 3 Optimal design with ε_2= -89214901.88

We performed a sensitivity study to determine the sensitivity of the optimisation outcomes to various factors.

C. *Sensitivity analysis*

The investigation focused on a pair of significant categories of parameters: investment costs and operating expenses. The research investigated the capital expenditures (CAPEX) of anaerobic digestors, CHP units, and electrolyzers, as well as the expenses of operation and maintenance, hydrogen transport, and landfill waste disposal. The sensitivity study intended to determine how changes in these parameters effect the optimisation outcomes by adjusting these parameters throughout an established range (0.5, 1, and 1.5 times the initial value). The investigation gave useful insights into the optimisation model's resilience and responsiveness, revealing light on the impact of various cost components on overall outcomes. Investment costs for cogeneration plant and anaerobic digestion can vary depending on factors such as the brand, technology, and production procedures of the capital equipment manufacturer. These factors, coupled with geopolitical considerations, can influence the overall investment cost. It is important to carefully assess and account for these factors when evaluating the economic feasibility of the project. Figure 4 illustrates the relationship between investment costs and resulting profits within the range considered for the analysis. It highlights the significant impact of cost variations on the total profit.

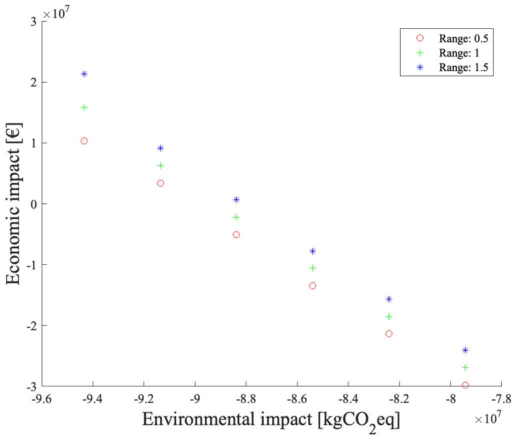

Figure 4 Sensitivity analysis of CHP plants investment cost

Furthermore, it is essential to examine the impact of changes in other costs. Among the various costs considered, it is worth noting that transportation hydrogen costs emerge as a significant factor influencing the overall profitability of the project (Figure 5). The transportation of hydrogen plays a crucial role in the efficient distribution and utilization of this energy carrier. Transportation costs can be influenced by factors such as the distance between the production site and the end-users, the infrastructure required for hydrogen transport, and the prevailing market rates. Fluctuations in transportation costs can have a substantial impact on the economic viability of the project and should be carefully analysed.

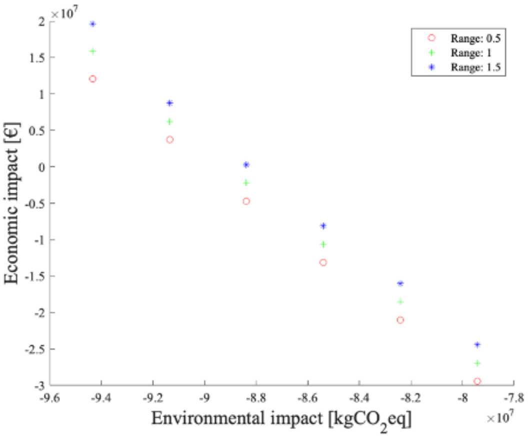

Figure 5 Sensitivity analysis of transportation costs

Based on the above discussions, Organizations must make several key management decisions to effectively manage and optimize investment expenditures, such as exploring cost-effective capital equipment options, researching multiple suppliers, and negotiating favourable costs. Additionally, geopolitical factors should be considered. To optimize operational costs, organizations should ponder alternative transportation methods and negotiate competitive rates. These decisions can help organizations improve cost-efficiency and overall performance in waste management processes.

V. CONCLUSIONS

This research aimed to develop a supply chain model for the conversion of biomass into energy using green technologies in Emilia-Romagna. The outcomes of this research have implications for the sustainable and efficient utilization of biomass resources, addressing environmental challenges, and contributing to the development of renewable energy systems. Renewable energy sources in UIS scenarios offer the potential to reduce greenhouse gas emissions, mitigate climate change, and promote a greener and more sustainable future. The developed supply chain model considers factors such as feedstock availability, technological advancements, and logistical considerations to optimize the entire biomass-to-energy and biomass-hydrogen supply chain. This multi-objective optimization problem provides a balanced decision-making process to tackle both challenges (i.e., economic, and environmental sustainability) and allows for scenario analysis and sensitivity studies, enabling decision-makers to assess the impact of different parameters and variables on the overall outcomes. This research on the biomass-to-energy supply chain model has provided valuable insights into its economic, operational, and environmental aspects. However, there are several areas for future development, such as conducting uncertainty and sensitivity analyses, integrating social and environmental factors, exploring advanced optimization algorithms and decision support systems, and combining GIS and multi-criteria decision making techniques. These future directions will enhance the robustness, sustainability, and practical applicability of the model, contributing to the advancement of renewable and sustainable energy systems.

VI. REFERENCES

[1] Abbasi, G., Khoshalhan, F., Javad Hosseininezhad, S. (2022): Municipal solid waste management and energy production: A multi-objective optimization approach to incineration and biogas waste-to-energy supply chain. Sustainable Energy Technologies and Assessments. Vol. 54, S. 102809.

[2] Balaman, Ş.Y., Selim, H. (2014): A network design model for biomass to energy supply chains with anaerobic digestion systems. Applied Energy. Vol. 130, S. 289–304.

[3] Beyene, H.D., Werkneh, A.A., Ambaye, T.G. (2018): Current updates on waste to energy (WtE) technologies: a review. Renewable Energy Focus. Vol. 24, S. 1–11.

[4] Bijarchiyan, M., Sahebi, H., Mirzamohammadi, S. (2020): A sustainable biomass network design model for bioenergy production by anaerobic digestion technology: using agricultural residues and livestock manure. Energy, Sustainability and Society. Vol. 10, Nr. 1, S. 19.

[5] Butturi, M.A., Gamberini, R. (2022): The potential of hydrogen technologies for low-carbon mobility in the urban-industrial symbiosis approach. Int. J. EQ. Vol. 7, Nr. 2, S. 151–163.

[6] Butturi, M.A., Gamberini, R. (2020): Urban–industrial symbiosis to support sustainable energy transition. International Journal of Energy Production and Management. Vol. 5, Nr. 4, S. 355–366.

[7] Cecchi, F. u. a. (2005): Digestione anaerobica della frazione organica dei rifiuti solidi.

[8] Cho, H.H., Strezov, V., Evans, T.J. (2023): A review on global warming potential, challenges and opportunities of renewable hydrogen production technologies. Sustainable Materials and Technologies. Vol. 35, S. e00567.

[9] Ferraz de Campos, V.A. u. a. (2021): A review of waste management in Brazil and Portugal: Waste-to-energy as pathway for sustainable development. Renewable Energy. Vol. 178, S. 802–820.

[10] Greggio, N. u. a. (2019): Theoretical and unused potential for residual biomasses in the Emilia Romagna Region (Italy) through a revised and portable framework for their categorization. Renewable and Sustainable Energy Reviews. Vol. 112, S. 590–606.

[11] Heid, B., Martens, C., Wilthaner, M. (2022): Unlocking hydrogen's power for long-haul freight transport | McKinsey, https://www.mckinsey.com/capabilities/operations/our-insights/global-infrastructure-initiative/voices/unlocking-hydrogens-power-for-long-haul-freight-transport, (17.05.2023).

[12] Khan, I. (2020): Waste to biogas through anaerobic digestion: Hydrogen production potential in the developing world - A case of Bangladesh. International Journal of Hydrogen Energy. Vol. 45, Nr. 32, S. 15951–15962.

[13] Koroneos, C., Dompros, A., Roumbas, G. (2008): Hydrogen production via biomass gasification—A life cycle assessment approach. Chemical Engineering and Processing: Process Intensification. Vol. 47, Nr. 8, S. 1261–1268.

[14] Lepage, T., Kammoun, M., Schmetz, Q., Richel, A. (2021): Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment. Biomass and Bioenergy. Vol. 144, S. 105920.

[15] Malode, S.J. u. a. (2021): Recent advances and viability in biofuel production. Energy Conversion and Management: X. Vol. 10.

[16] Mattias, G., Elena, T., Giuseppe, C., Anna, F.E. (2021): Modeling the ecosystem service of agricultural residues provision for bioenergy production: A potential application in the Emilia-Romagna region (Italy). Ecological Modelling. Vol. 451, S. 109571.

[17] Mostafavi Sani, M., Afshari, H., Saif, A. (2023): A robust framework for waste-to-energy technology selection: A case study in Nova Scotia, Canada. Energy Conversion and Management. Vol. 284, S. 116965.

[18] OECD (2021): Global Hydrogen Review 2021. Organisation for Economic Co-operation and Development. Paris.

[19] Rahimi, T., Babazadeh, R., Doniavi, A. (2021): Designing and planning the animal waste-to-energy supply chains: A case study. Renewable Energy Focus. Vol. 39, S. 37–48.

[20] Rasheed, T. u. a. (2021): Valorisation and emerging perspective of biomass based waste-to-energy technologies and their socio-environmental impact: A review. Journal of Environmental Management. Vol. 287.

[21] Shamsi, H. u. a. (2021): Macro-Level optimization of hydrogen infrastructure and supply chain for zero-emission vehicles on a canadian corridor. Journal of Cleaner Production. Vol. 289, S. 125163.

[22] Spazzafumo, G., Raimondi, G. (2023): Economic assessment of hydrogen production in a Renewable Energy Community in Italy. e-Prime - Advances in Electrical Engineering, Electronics and Energy. Vol. 4, S. 100131.

[23] Tamburini, E., Gaglio, M., Castaldelli, G., Fano, E.A. (2020): Biogas from Agri-Food and Agricultural Waste Can Appreciate Agro-Ecosystem Services: The Case Study of Emilia Romagna Region. Sustainability. Vol. 12, Nr. 20, S. 8392.

[24] Thiriet, P., Bioteau, T., Tremier, A. (2020): Optimization method to construct micro-anaerobic digesters networks for decentralized biowaste treatment in urban and peri-urban areas. Journal of Cleaner Production. Vol. 243, S. 118478.

[25] Vidas, L., Castro, R. (2021): Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis. Applied Sciences. Vol. 11, Nr. 23, S. 11363.

[26] Wilkinson, J., Mays, T., McManus, M. (2023): Review and meta-analysis of recent life cycle assessments of hydrogen production. Cleaner Environmental Systems. Vol. 9, S. 100116.

[27] ARERA, https://www.arera.it/it/index.htm, (16.05.2023).

[28] Il mercato del Compost, https://www.compost.it/il-compost-e-il-marchio-compost-di-qualita-cic/il-mercato-del-compost/.

[29] (2023): La gestione dei rifiuti in Emilia-Romagna: Report 2022. Regione Emilia-Romagna, Arpae Emilia-Romagna.