Economic and Environmental Performance of Biowaste-to-energy Technologies for Small-scale Electricity Generation

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***Abstract*—Electricity is predicted to be the energy vector that will undergo major changes in the future, and a transition would be observed in the resources such as waste and residual biomass that we use to satisfy the energy demand. Therefore, this study aims to highlight the main economic and environmental performances of different biowaste-to-energy technologies for small-scale electricity generation by comparing the direct combustion of refined vegetable oil obtained from waste cooking oils (thermal pathway), anaerobic digestion of biowaste (biochemical pathway), and gasification of wood residues (thermochemical pathway). The economic analysis is mainly based on personal experiences in the energy sector and shows an overview of the performance in investment of combined heat and power (CHP) systems, ranging from 100 to 500 kW for a period of 20 years. The environmental assessment is conducted considering the life-cycle thinking approach using support from the openLCA software, product environmental footprint (PEF) database, and previous studies that have reported environmental inventory data from real industrial cases.**

***Index Terms*—Biowaste-to-energy, small-scale generation, economic assessment, environmental assessment.**

I. Introduction

THE global energy system undergoes a constant transformation; as such electricity will be the energy vector that will experience major changes in the future [1], [2]. This transformation also includes a transition in the resources used for covering the energy demand. For example, in 2015, the world generation of electricity provided by renewable energy resources was approximately 23%, with a hydroelectricity share of 16% and nonconventional renewable sources of 5% [3]. It is estimated that by 2050, renewable energy resources will be the main resources used in energy production. Waste and biomass will play a significant role, owing to their importance in recycling processes and their potential as zero-emission fuels [4].

According to the Italian Legislative Decree 156/2006, waste is defined as "any substance or object that an owner discards or has an intention or obligation to discard" [5]. Moreover, biowaste is defined as biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and wastes from food processing plants [6]. Biowaste is an important fraction of municipal solid waste (MSW). In Organization for Economic Co-operation and Development (OECD) countries, this fraction varies significantly, from 14% to 56% of total MSW, with an average of 27%; in 2013, the yearly generation rate was approximately 177 million tons. However, only a limited part of this amount (37% in OECD countries, i.e., 66 million tons) is directed to biological treatments [7]. Furthermore, residual biomass is not classified as waste and typically includes lignocellulosic materials generated by the agricultural, forest, and agro-industrial sectors. Italy has been estimated to produce approximately 22 million tons of residual biomass per year; this is equivalent to 4.6 Mtoe, which is nearly 2.7% of the gross Italian energy consumption in 2013 [8]. The installed power of biomass plants (MSW, biogas, vegetable oils, and agroforestry biomass) used in the production of electricity exceeded 4.3 GW at the end of 2018; however, this amount has practically not changed since 2014 (approximately 4 GW) [9]. Although electricity plays an important role in the industrial sector, a high percentage (63%) of Italian small- and medium-sized enterprises (SMEs), which are characterized by an electricity demand between 430 and 1600 MWh per year, does not use renewable energy resources for the electricity generation [10].

The capability to manage the use of biowastes and residual biomass into a wide range of marketable products and energy is essential for the improvement of the current industrial systems and development of a sustainable economy. Therefore, the use of biowastes and residual biomass in small-scale combined heat and power (CHP) systems can be highly advantageous for SMEs in Italy and worldwide. According to the European Directive 2004/8 EC, a small-scale CHP system is characterized as that with electricity capacities between 50 kWh and 1 MWh [11] and comprising two modules. In the first module, based on a primary process, the starting raw material (RM) is converted into a suitable fuel for the second module, which generates electricity. Depending on the type of biowaste or residual biomass, primary processes can include thermal (combustion), thermochemical

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(pyrolysis, gasification, liquefaction, torrefaction), and biochemical (anaerobic digestion, transesterification) pathways [12]. Combustion technologies, including boilers, dryers, kilns, furnaces, and ovens, can generate a few kilowatts to several megawatts of heat, which can be used directly or can be alternatively converted into electricity using secondary conversion technologies. The choice of the combustion system depends on the energy demand as well as on the fuel characteristics, cost, and performance of the technologies. Combustion boilers are the most commonly used technology for the conversion of solid biomass into thermal energy in most industries. In general, fixed bed boilers are used for systems with low capacities (< 20 MWh), while for high capacities, fluidized bed boilers are commonly used (20-30 MWh) [13]. Additionally, internal and external combustion technologies can be used to generate electricity. Currently, internal combustion engines (ICEs) are the main internal combustion devices used for electricity generation. ICEs are simpler and cheaper cleaning systems compared with other systems. They can burn different types of biofuels such as refined vegetable oil (RVO), biogas, and syngas, because they are relatively robust to their impurities. Other external combustion technologies include Rankine cycle technologies, steam turbines, and Stirling engines. They operate with a working fluid, i. e., water or an organic fluid that is heated using an external heat source [11]-[13].

Despite direct combustion being the most widely applied process, its thermal efficiency is significantly low. Therefore, the gasification process was developed and has been considered a more attractive thermochemical process with considerably higher efficiency, lower emission of NO_x and SO_x, and a lower reaction temperature. Unlike combustion, in gasification, partial oxidation of organic residues occurs, with syngas as the main byproduct. Other processes also occur during gasification such as drying, pyrolysis, combustion, and gasification. During drying, which occurs between 100 and 150 °C, the biomass moisture is reduced, and during pyrolysis (200-700 °C), the volatile components of the biomass are vaporized. Thereafter, oxygen supplied to the gasifier reacts with the fuel substances, resulting in CO_2 and H_2O, which subsequently undergoes reduction upon contact with the char produced from pyrolysis to produce a mixture of carbon monoxide and hydrogen (syngas) [14].

Anaerobic digestion consists of natural degradation of organic materials in biogas by the action of microorganisms. In developing countries, biogas is mainly produced in small or domestic-scale digesters to provide fuel for cooking or even lighting. In contrast, in developed countries, biogas is used to produce electricity and heat, mostly on a larger scale. Biogas can be produced from a wide range of diverse feedstocks, including agricultural residues (livestock manure, crop residues, and energy crops), industrial residues from the food and beverage industry, and municipal organic waste. In particular, the co-digestion of manure with various substrates is used to increase the biogas yield, and consequently the energy output, providing significant economic improvements. In addition, the biomethane obtained through biogas purification processes can be used as fuel in vehicles, and thus constitutes an important alternative in the field of eco-sustainable mobility [15]. Furthermore, small-scale biomass CHP systems can use locally available biowastes and residual biomass, thus reducing transportation costs and providing users with the possibility of producing their own electricity and heat [16]. Therefore, this study aims to highlight the main economic and environmental performance of the use of different biowaste-to-energy technologies for small-scale electricity generation. The evaluated technologies represent each type of primary process used by CHP systems: the direct combustion of RVO is obtained from waste cooking oil (WCO) (thermal pathway), anaerobic digestion of biowaste (biochemical pathway), and gasification of wood residues (thermochemical pathway).

II. Methodology

The economic analysis conducted in this study is mainly based on personal experiences in the energy sector, and shows an overview of the performance in investment of CHP systems ranging from 100 to 500 kW for a period of 20 years, with a capital contribution of 20% and financing of 80% (with an interest rate of 5%). The costs of the RMs considered in the economic analysis are 600, 25, and 60 €/t for RVO, biowaste, and wood residues, respectively. Additional operation and maintenance costs, which include the costs for maintenance, insurance, electricity, personnel, and waste disposal, are estimated at 0.02, 0.03, and 0.04 €/kWh produced using RVO, syngas, and biogas, respectively (for example, the operation and maintenance costs, excluding the cost of RMs, for a plant of 100 kW, which uses RVO and works 8000 hours per year, are estimated at €16000 per year). However, to calculate the possible savings, the electricity price of the power grid of 0.20 €/kWh and the cost of the heat of 0.08 €/kWh are considered. Furthermore, we hypothesize that all plants work the same number of hours per year (8000 hours), producing the same amount of electricity, and after discounting the self-consumption of 10% of different processes, the electricity is fully used by the user. The amount of available heat varies depending on the self-consumption of each of the technologies, and it is hypothesized to be consumed entirely by the user.

Environmental assessments are conducted by considering a life-cycle thinking approach. The model of the life-cycle systems is built based on the reports by previous studies on the environmental inventory data obtained from real industrial cases and the product environmental footprint (PEF) database, by using the openLCA software. To allow a consistent comparison among different technologies shown in Fig. 1, the production of 1 kW electricity is established as a functional unit, considering a cradle-to-grave approach. In Fig. 1, low calorific values of WCO, wood residue, syngas, and biogas are 37.60 MJ/kg, 19.00 MJ/kg, 5.2 MJ/m^3 [17], and 18.20 MJ/m^3 [7], respectively. The water content in wood residues from PEF database is 0.15 (dimensionless); therefore, the input heat and electricity in the gasification process do not consider the heat (0.47 kWh, hypothesizing an initial humidity of 50%) and electricity (0.02 kWh) required for drying the biomass. Heat for drying can also be supplied by waste heat from the gasification process (3.84 MJ/m^3 syngas produced); thus, the net heat consumption for drying can be considered as zero [17]. Additionally, the electrical and heat efficiencies of ICEs are taken as 37% and 47%, respectively.

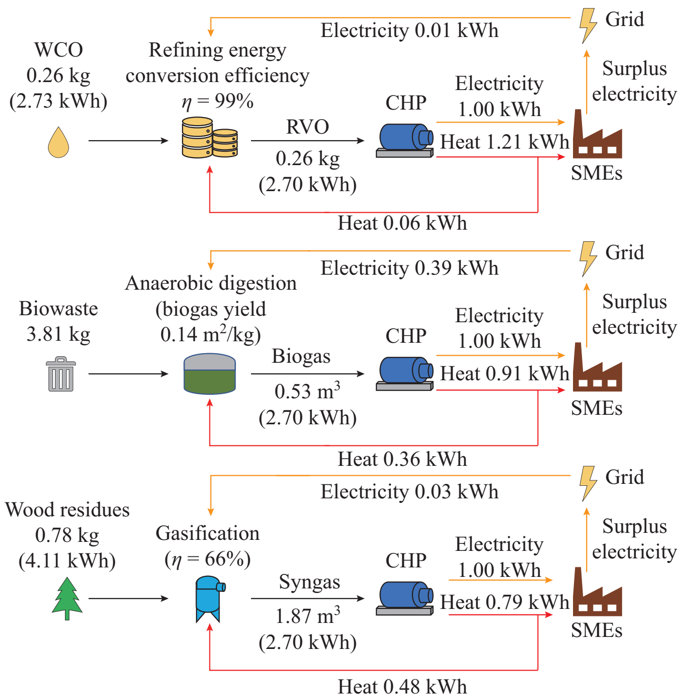

Fig. 1. Graphic scheme of systems under evaluation.

The data inventory for the treatment of the WCO is based on the "vegetable oil from WCO" process reported by [17]. This process consists of the purification, water removal, and further esterification of the free fatty acids (6.5 wt.%) contained in the WCO using technologies such as the transesterification of vegetable oil into biodiesel. CO_2 emissions from the combustion of the regenerated oil from WCOs are based on the results obtained by [18], which reported on the exhaust emissions of a 50 kW diesel power generator fueled by biodiesel. Further, the CO, NO_x, and particulate matter (PM) emissions are based on the results obtained by [19], which reported on the comparison of exhaust emissions from the combustion of biodiesel, vegetable oil, gas-to-liquid, and diesel fuels in an engine with a rated power of 205 kW.

On the other hand, the data inventory of the anaerobic digestion of biowaste is based on the study reported by [7], which compared the environmental sustainability of energy generation in a CHP system fed with biogas as fuel and the use of biomethane in the road transport sector. Additionally, the data inventory of the life-cycle assessment (LCA) project for the gasification of residual biomass is based on the unit process "synthetic gas from wood" reported by [17]. In addition, the exhaust emissions from syngas combustion in a power generator are based on the dataset "combustion of gas from wood" of Bionergiedat database. The electricity generated by three primary technologies under evaluation are compared with the electricity generated from the direct combustion of crude rapeseed oil, which is one of the frequently used RMs in biodiesel production in Europe and Italy [20], [21], and the direct use of electricity from power grid, according to the datasets available in the PEF database. Additional information about the inputs and outputs to produce RVO, Syngas, and Biogas can be found in Table SI of the Supplemental Material, while inputs and outputs for the energy generation in ICEs using these fuels can be found in Table SII of the Supplemental Material.

III. Results

A. Combustion of RVO

The use of straight vegetable oils (SVOs) as an alternative fuel to diesel and their mixtures has been extensively studied in the past several years [22]-[24]. Currently, it is possible to obtain small-size CHP systems based on the direct combustion of SVO and other types of liquid biofuels such as biodiesel and bio-oils [25]-[29]. Biodiesel is produced through transesterification and is one of the most widely used biofuels globally [30], [31]; however, its use has been limited in the transport sector to a maximum of 7 vol.% by the Fuel Quality Directive 2009/30/EC [32]. Bio-oils are typically produced by pyrolysis; however, this process can be categorized into various types such as torrefaction [33], carbonization [34], and fast pyrolysis [35], [36]. Torrefaction and carbonization are used to obtain a solid product, whereas fast pyrolysis is used to obtain high amounts of bio-oil. Both biodiesel and bio-oil are significantly important biofuels for the transport and energy-generation sectors; however, in this research, the focus is on the use of WCO. In particular, Italy is one of the countries with the highest average oil consumption in Europe [37], and a significant amount of the WCOs is discarded without any treatment after the cooking process, thus creating several disposal problems such as pollution of rivers, lakes, seas, and underground water, which are harmful to the environment and human health [38].

The use of WCO has been verified in small ICEs with an electrical generation capacity of 6-53 kW, both for transport applications and energy generation [39]-[49]. It is necessary to consider that during cooking, SVO undergoes thermochemical transformations that cause various physical and chemical changes such as an increase in the viscosity, which contributes to a high pressure loss and poor atomization in the engines. This can be done by increasing the cost of the equipment and utilizing a high carbon residue, which causes the formation of carbon deposits in the combustion chambers, and a high water content, which reduces the calorific value and contributes to an increase in the ignition delay period [50]. Consequently, WCO should be treated to remove water and impurities before they can be used as alternative fuels in small-size ICEs.

B. Anaerobic Digestion of Biowaste

During the anaerobic digestion process, microorganisms break down organic material under oxygen-free conditions to produce biogas, which is mainly composed of methane, carbon dioxide, and trace amounts of other gases. This process can be divided into four main stages: hydrolysis, acidogenesis (fermentation), acetogenesis, and methanogenesis [12], [51], [52]. In addition, it can be classified into different types based on the type of reactor (continuous and batch), moisture content of the substrate (dry and wet), and temperature of the digestion process (mesophilic and thermophilic) [53]. Anaerobic digestion is one of the most diffusive biochemical processes worldwide, with Europe being the leader in biogas electricity production, with 17400 biogas plants and more than 10 GW of plants installed in 2015, mainly in Germany (with more than 50% of the total production), and in the UK and Italy (with 14% each) [7], [54], [55]. The greatest growth was evidenced in plants using agricultural substrates, from 4797 units in 2009 to 12496 installations in 2016, followed by plants using sewage sludge (2838 plants), landfill waste (1604 units), and various other types of waste (688 plants). In addition, more than 70% of the European biogas plants for electricity generation operate using agricultural RMs, mainly maize, which provides approximately half of the biogas production, followed by landfill, organic waste (including municipal waste), sewage sludge, and manure [15]. Moreover, anaerobic digestion is a technology widely used in SMEs, which operate mainly in the agricultural and food industries as well as waste management sectors, thus further promoting the diffusion of additional SMEs involved in the construction, monitoring, management, and maintenance of biogas plants. Therefore, anaerobic digestion has an important effect on the local economy and occupation [56].

C. Gasification of Wood Residues

The gasification process is performed in an oxygen-poor environment, where the biomass is transformed into syngas (synthesis gas), which is mainly composed of carbon monoxide, hydrogen, and a limited amount of carbon dioxide. Syngas can later be used as fuel in ICEs to produce electricity and heat. Power generation systems based on the gasification process can be scaled to generate from a few kilowatts to several megawatts of electricity and heat. Large-scale gasification systems, with capacities greater than 2 MW, are preferably chosen owing to their efficiency to the investment ratio. To effectively utilize the biomass resources in local areas, a small-scale biomass gasifier with a capacity of less than 200 kW is expected to be utilized, which has been proven to be economical and feasible [57], [58]. However, few small-size CHP systems based on the gasification process are currently available in the market [59] - [63], and other technologies have been analyzed. As such, there are great interests in gasification owing to its benefits in energy decentralization. Small-sized CHP systems based on the gasification process can be used in different sectors such as agriculture (greenhouses, cattle breeding, wine-growing, etc.), agri-food, tourism (agri-tourism), residential (buildings with several users or in small district heating networks), wood industry, and other energy-intensive industries. Additionally, gasifiers can be classified into two types, namely fixed and fluidized bed gasifiers, with variations within each type. Fixed bed gasifiers are operated at temperatures of approximately 1000 °C, and depending on the direction of air flow; they can be classified as downdraft (commonly referred to as co-current), updraft (also termed counter-current), or cross-flow. Fluidized bed gasifiers use a bed of fine-grained material, into which air is introduced to uniformly distribute the temperature in the gasification zone. Typically, a fixed bed reactor is more appropriate for low capacity (< 10 MWh), whereas fluidized bed gasifiers are more adapted to larger capacities (> 10 MWh) [15].

D. Economic Performance of Small-scale CHP Systems

Figure 2 shows that electricity generation based on gasification is the technology with the highest investment cost, followed by the anaerobic digestion and the use of RVO as fuel, where OC stands for operation cost. The investment for a CHP system, including the cost for a gasification plant, can be approximately 7×10^6 €/MW, while for a CHP system, including an anaerobic digestion plant, the investment cost is approximately 4×10^6 €/MW. Further, for a CHP system using RVO, the investment cost is approximately 2.5×10^6 €/MW. For the RVO-based technology, an investment in the WCO treatment plant is not considered because RVO is commercially available. Regardless of the type of technology used, the savings obtained from the electrical energy available for self-consumption range from €144000 to €720000 depending on the power of the plant (from 100 kW to 500 kW). The savings obtained from the thermal energy available for self-consumption range from €61808, €46356, €31806 to €309041, €231781, and €159032, when using RVO, biogas, and syngas, respectively. Although RVO has the highest cost compared with other materials, its great calorific value (37.6 MJ/kg) and great efficiency in the use of the energy contained during the electricity-generation cycle allow for substantial savings in the cost of RMs. All the technologies show a positive net profit average; however, for low investment and RM costs, RVO is ideal for the electricity generation from an economic point of view. These results should be considered with caution because they are based on the hypothesis that both electricity and heat are fully used; however, if heat is dissipated in the environment, the net profit can be dramatically reduced.

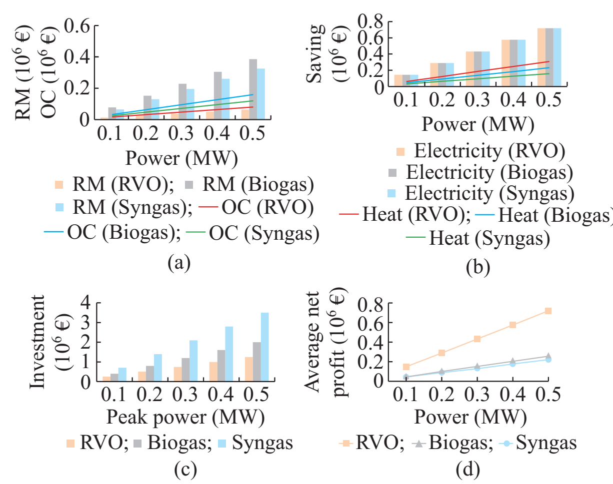

Fig. 2. Economic performances for investments in small-scale CHP systems. (a) RM and OC. (b) Saving. (c) Investment. (d) Average net profit.

E. Environmental Performance of Small-scale CHP Systems

Figure 3 shows the results of the environmental assessment according to the environmental footprint method, where for each indicator, the maximum result is set to be 100% and the results of the other variants are presented in relation to this result; the No. 1 to No. 18 for indicators represent acidification, climate change, climate change (biogenic), climate change (fossil), climate change (land use and land use change), ecotoxicity (freshwater), eutrophication (marine), eutrophication (freshwater), eutrophication (terrestrial), human toxicity (cancer), human toxicity (non-cancer), ionizing radiation (human health), land use, ozone depletion, particulate matter, photochemical ozone formation, resource use (fossils), resource use (minerals and metals). For the analyzed life-cycle systems, of all the environmental categories, the most significant impacts have been shown to be caused by the acidification of the environment, climate change, and land use. The use of SVO has a greater impact on most of the environmental categories, particularly the three aforementioned categories, even more than the use of grid electricity. The value obtained for the concentration of equivalent hydrogen ions (mol of H+) adopted to measure the acidification potential is higher with the use of SVO for the production of electricity than that of the other resources studied, mainly owing to the emission of NH_3 and NO_x in the rapeseed cultivation phase (equal to 1.19×10^{-2} mol of H+). This value decreases with the use of biogas, RVO, grid electricity, and syngas, or 1.82×10^{-3}, 1.49×10^{-3}, 9.00×10^{-4}, and 5.23×10^{-4} mol of H+, respectively.

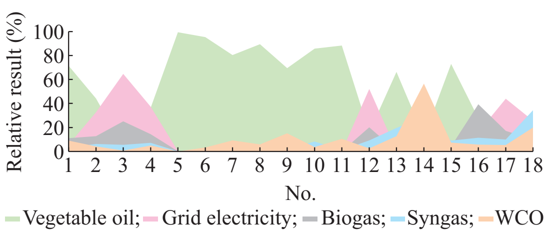

Fig. 3. Relative results according to environmental footprint method of production of 1 kWh of electricity using biowaste and residual biomass.

Regarding the total impact on climate change (owing to biogenic and fossil emissions, and from land use and its modification), the results are higher for the use of SVO (equal to 0.65 kg CO_2), followed by the use of grid electricity (equal to 0.48 kg CO_2). These results are mainly obtained by the emissions of CO_2, NO_x, and CH_4 generated in the vegetable-oil production chain, and from the use of the soil and modification of its destination during the rapeseed cultivation phase. As expected, the values are lower when biowaste and wood residues are used as RMs, and decrease to 0.19, 0.09, and 0.06 kg CO_{2eq}, when using biogas, syngas, and RVO, respectively. The impact on climate change when biowaste or wood residue is used as RM is mainly due to the emissions of CO_2, CH_4, and NO_x produced during the generation of grid electricity, which is used during the anaerobic digestion process, and the preliminary treatment of wood residues used in gasification, or in the production of glycerin, which is one of the inputs of the WCO refining process. Owing to the greater impact on acidification of the environment and climate change, the use of SVO for electricity production can cause significant damage to the quality of ecosystems, decrease in biodiversity, and global temperature disturbances and anomalies of the climatic phenomena with respect to the other studied resources. The greater impact on the use of SVO is also evident in the category that concerns the use of the soil (occupation), owing to the large areas of land used in the agricultural phase.

Furthermore, owing to the release of potentially toxic substances, the use of SVO shows a higher impact on other environmental categories such as ecotoxicity, eutrophication, and human toxicity. This result implies the damage to individual species and changes in the structure and function of ecosystems, and causes negative effects on human health such as cancerous or non-cancerous effects. However, the environmental impact is different when analyzing the decrease in the stratospheric ozone layer although the values in this environmental category are significantly low. The use of RVOs has a higher impact (equal to 1.82×10^{-9} kg CFC-11) than that of the other analyzed resources such as syngas (equal to 9.38×10^{-10} kg CFC-11), SVO (equal to 3.95×10^{-10} kg CFC-11), grid electricity (equal to 4.62×10^{-11} kg CFC-11), or biogas (equal to 1.79×10^{-11} kg CFC-11), because of the emissions of fluorocarbons (CFC-10) and hydrofluorocarbons (HCFC-20) during the glycerin-production process. Consequently, the use of RVO can contribute in the reduction of the ability of the ozone layer to preventing the penetration of ultraviolet (UV) light into the earth's atmosphere, thus increasing the amount of ultraviolet B (UVB) carcinogenic light that reaches the earth's surface.

For the impact categories that affect human health such as ionizing radiation, particulate matter, or photochemical ozone formation, the results are variable. Regardless of the production process, the highest impact on human health from ionizing radiation (radioactive emissions) is caused by the consumption of grid electricity, owing to the import of electricity from countries such as Switzerland or France, where it is being produced in nuclear power plants. The highest value corresponds to the use of only grid electricity (4.45×10^{-2} kBq). The use of SVOs has the highest emissions of particulate matter (8.47×10^{-8} items). The photochemical ozone formation is high when biogas (equal to 1.52×10^{-3} kg of non-methane volatile organic compound (NMVOC)) and SVO (equal to 1.07×10^{-3} NMVOC) are used, followed by grid electricity (equal to 6.19×10^{-4} NMVOC), syngas (equal to 4.39×10^{-4} NMVOC), and RVO (equal to 2.18×10^{-4} NMVOC). High concentrations of ozone at the ground level of the troposphere damage vegetation and human respiratory tract. Considering the above results, the lowest impact is confirmed to be obtained when biowaste and wood residues are used as RMs. Although the differences between resources could be small, the lowest impact on environmental acidification occurs when syngas is used, while the use of RVO has a lower impact on climate change. The use of biogas shows a lower impact on the use of the soil (occupation).

IV. Conclusion

Depending on the type of waste and residual biomass, thermochemical and biochemical primary processes are used to convert them into fuels that are adapted to small-size CHP systems, which are commercially available. Small CHP systems can be used in different sectors such as agricultural, agri-food, tourism, and other energy-intensive industries, promoting energy decentralization. However, their management can be complex owing to the wide variety of physicochemical characteristics of RMs and process conditions that can be used to obtain high-quality fuel. From an economic point of view and according to the hypothesized scenarios, the use of the RVO is revealed to be the best alternative for the electricity generation at a small scale. However, from an environmental point of view, the use of first-generation RMs such as SVO to generate electricity is determined to have a higher impact on most of the environmental categories, particularly on the acidification of the environment, climate change, and land use, compared with other analyzed materials; even higher than the use of grid electricity.

As expected, the environmental impact is lower when biowaste and wood residues are used as RMs. This is because the emissions of CO_2, CH_4, and NO_x during the generation of grid electricity are used to convert the starting RMs into fuels adapted to small-size CHP systems. The findings also show that the use of RVOs affects the decrease in the stratospheric ozone layer owing to the emissions of CFC-10 and HCFC-20 produced during the synthesis of glycerin.

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