Overview on Bioconversion of Domestic Wastewater Sewage Sludge into Green Energy: Biogas and Hydrogen

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***Abstract*—Municipal wastewater treatment plants generate large amounts of sludge after a set of unit processes. The sewage sludge is an important resource for energy production because of its high level of biodegradability. Sewage sludges are generally made of non-toxic and biodegradable organic compounds mixed with a small fraction of non-toxic and toxic inorganic compounds having a very low biodegradability. The large fraction of biodegradable matter constitutes a pool for green/clean energy to be used for industrial and domestic applications. The generated energy can also be used in the wastewater treatment plant. Currently, fossil fuels are leading the energy world, however, they are being depleted and are considered to be among the main causes contributing to climate change and global warming. Domestic sewage sludge can be converted sustainably into bio-hydrogen and bio- methane. This conversion is achievable through anaerobic digestion, combustion, pyrolysis and gasification. With regard to the last three conversion processes, the organic and inorganic toxic compounds are eliminated. Production of biogas from sewage sludge is being undertaken worldwide on small, medium, and large scales. However, hydrogen production from sludge is still developing. There is an existence of substantial knowledge in this field, the production of hydrogen and biogas from sewage sludge is gaining interest. This study analyses various possibilities of sewage sludge conversion into clean energy. The analysis focuses on the technology strengths, weaknesses and gaps to be improved in future studies.**

***Index Terms*—Domestic sewage, sludge, biogas, bio-methane, bio-hydrogen, anaerobic digestion.**

I. Introduction

The demand for energy is currently on the increasing trend due to the fact that energy is an important ingredient for a successful economic development.

On the other hand, the fossil fuel reserves are currently in a decreasing trend. Fossil fuels are known as the dominant source of energy because 87% of energy users are consumers of fossil fuels [1]. Other sources of renewable energy such as solar energy and hydroenergy are being used for many applications, they are environmentally friendly with low maintenance costs, reliable, safe and flexible. However, they are weather dependent or the storage of energy is expensive. Considering the large amounts of sludge generated from wastewater treatment plants on a daily basis in many countries, it is a necessity to convert the biodegradable sewage sludge with the aim to produce cost effective and clean energy including hydrogen and biogas. As the demand for environmentally friendly and sustainable energy sources is increasing, the implementation of waste-to-energy technologies has started gaining more interest and particular attention. It is therefore an advantage to produce green energy from the sludge which is a highly biodegradable waste. Consequently, this option will assist in reducing the burden related to the management of sludge from wastewater treatment plants. Hydrogen and biogas can be the key alternative sources of energy which are non-polluting, renewable and sustainable. It is therefore pertinent to find out on various ways to produce clean energy resources which are ready to be used as substitutes for fossil fuels in the near future. The burning of fossil fuels has a negative environmental impact due to their significant input toward climate change and global warming. Several studies have reported that there is a possibility to develop reliable, costs effective and sustainable processes in order to generate clean energy from biodegradable solid wastes with lower negative environmental impact. Hydrogen and biogas might be considered as viable alternatives in replacement to fossil fuels, however, there are many challenges to be overcome in terms of production scale and availability of raw materials [2]-[4]. Hydrogen and biogas can be produced from several options such as thermochemical, biological and electrochemical processes. The biological process uses microorganisms for dark and photo fermentation, it is considered as the most affordable option [5]. The dark fermentation using wastewater with carbohydrates mainly the sugars as a feedstock have different yields for each kind of substrate presented in two metabolic routes with generations of acetic and/or butyric acids [6]. Therefore, glucose, fructose (glucose isomer), sucrose and xylose can be converted. The combustion of hydrogen and biogas generates water and energy. This is an added advantage for hydrogen and biogas because of a significant reduction of carbon emissions. It is reported that fossil fuels generate significant amounts of carbon emissions [7]. Pyrolysis and gasification are reported to be environmentally safe and costs effective options for sewage sludge treatment [8]. Pyrolysis allows a conversion of various types of sewage sludge such as raw, digested and waste-activated into biogas and oil, a stabilized residue known as biochar is collected as by-product. It is reported that anaerobic digestion followed by sludge pyrolysis yields significant amount of energy recovery compared to a stand-alone anaerobic digestion or pyrolysis [8], [9]. The gasification of sewage sludge, on the other hand, yields biogas that can fuel gas burners, cogeneration (CHP) systems, gas turbines and internal combustion engines. The generated heat and electricity can partially meet the demand of wastewater treatment plants. Gasification of sewage sludge for generation of biogas is economically viable and an

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environmentally friendly option [10]. Furthermore, considering a sample data represented in Table I, it is possible that the global production of sewage sludge can be beyond 50 MTds/annum. Furthermore, an increase of domestic sewage sludge production is certain as lifestyle changes and the population increases at a fast rate in many countries. Table I presents a sample of some countries sewage sludge production.

TABLE I: SAMPLE OF SEWAGE SLUDGE PRODUCTION 2010 AND 2020 ESTIMATES [11], [12]

Countries	2010 Sludge production estimates in tons of dry sludge/annum [Tds/ a]	2020 Sludge production estimates in tons of dry sludge tons of dry sludge/annum [Tds/a]]
USA	7.000.000	10.000.000
Austria	273.000	280.000
UK	1.640.000	1.640.000
Scotland	200.000	200.000
Spain	1.280.000	1.280.000
Sweden	250.000	250.000
France	1.300.000	1.400.000
Germany	2.000.000	2.000.000
Italy	1.500.000	1.500.000
Romania	165.000	520.000
Portugal	420.000	750.000
Poland	520.000	950.000
Hungary	175.000	200.000

The analysis of the data in Table I indicates that sewage sludge production has been on the increasing trend for the last decade. It can be predicted that more sewage sludge will be generated in the future because of many reasons mentioned before including the lifestyle, fast increase of population and industrialisation.

This study analyses various production options for conversion of sewage sludge to hydrogen and biogas, their strengths and weaknesses, the possibility for improvement for the existing processes. The operating conditions for effective conversion are also discussed.

A. Overview Analysis on Previous Studies on Biogas and Bio-hydrogen

Biogas is a promising source of renewable energy, and can become one of the best substitute for fossil fuels in the near future. Some of the previous studies have reported that through the promotion of sustainable clean energy, biogas and hydrogen may become one of the sources that can replace non –renewable sources of energy, however, many barriers related to costs and yields including technological, economic, market, institutional, socio-cultural and environmental challenges should be eliminated [13]-[15]. Optimization and technology improvements will play a major part in this type of situation. Biogas and hydrogen can be used to produce electricity and heat generation. It is also reported that through the production of biogas/hydrogen from sewage sludge, the solid waste will be managed efficiently while at the same time developing energy to sustain the increasing demand. Large-scale production of biogas is a promising route by the fact that there is an increasing amount of sewage sludge and agricultural wastes that have a significant potential for energy production. These wastes have high content of organic wastes and high level of biodegradability which are among the key aspects needed for wastes to generate energy (biogas and hydrogen) [16], [17]. The increase of wastes is due to the level of industrialization, rapid population increase and lifestyle of our modern society. Therefore, effective technology and logistics including best practices for the management of biodegradable wastes can be a stepping stone toward sustainable conversion of energy to wastes. Countries that have implemented effective strategies in this area have achieved economic benefits. Currently, there are many countries making efforts to convert their wastes into energy [18] From many studies completed previously it is reported that there are several ways of generating biogas from sewage sludge. One of the main methods is the conversion of sewage sludge through anaerobic digestion [17], [18]. This option has been used in many applications regarding the conversion of biodegradable wastes into energy. From that time, the application of biogas digestion has significantly increased. Previous studies have focused at the stages through which the biological wastes are decomposed to come up with the right and high quality biogas [18]-[20]. During the decomposition process, some metabolically generated products are used. The biodegradation time is also crucial when there is a need for quality. The first stage of decomposition mainly occurs in a period of less than a week. In this stage, oxygen is mainly removed from the wastes. The production of clean energy through organic waste materials is an approach that has the potential to meet the increasing demands of energy and replace fossil fuels in the future. The availability of raw materials is one of the elements that have to be considered. The costs of production are also another important element to be considered. The scale of production will dictate the costs to be incurred for an effective production of hydrogen and biogas [19]. The carbohydrate content of the materials that are used in the production ensures that the costs of production are not more than the amount of hydrogen and biogas produced [20].

II. TYPES OF SEWAGE SLUDGE AND SEWAGE SLUDGE CONTENT

Sewage sludge in a wastewater treatment plant is collected after primary and after secondary treatment. Different criteria may be applied to choose the type of domestic sewage sludge for the production of biogas. The factors that are mainly considered in this choice may include costs, availability, biodegradability and the carbohydrates content [21]-[25]. Most of the time, elements with simple sugars are easily biodegradable, and they are also essential in the production of biogas. In addition, carbohydrate sources can be also used, this has a positive impact on the biodegradability of sewage sludge and it may also add up on the productivity rate of biogas and hydrogen. One type of material that is used in the production of biogas is food, industrial and agricultural wastes that contain cellulose and starch. These types of wastes have high biodegradability while at the same time they can generate high amount of biogas and hydrogen. However, when the components are made with complex molecules, they could affect the biodegradability. They are easy to process and generate the needed amount of hydrogen. Most of the sewage sludge that is generated from activated sludge process contains large amounts of protein and carbohydrates. Therefore, the presence of these compounds in sewage sludge represents a great advantage for the production of hydrogen and biogas. Their presence is an indication that sewage sludge has an acceptable level of biodegradability that can be explored for clean energy production. The chemical and physical characterizations that are related to domestic sewage sludge depend on the geographical allocation of the wastes, the domestic sources and the country of origin for the sewage sludge. Domestic sewage can be solid, semi-solid matter, or a muddy residue. Physical characteristics of the sewage sludge have played an important role in allowing an effective anaerobic decomposition. Domestic sewage sludge is mainly made of sugars, proteins, detergents, lipids, and phenols [21-25]. There are cases where the sewage from the households may contain toxic inorganic and organic compounds. Again, the sludge may contain a wide range of harmful compounds and substances such as polychlorines and dioxins. The inorganic fraction of the sewage sludge contains compounds of calcium, phosphorus, aluminum. Again, the compounds may contain traces of heavy metals such as zinc and copper or any other heavy metal. From the household wastes, it is generally reported that copper, lead, and zinc are common heavy metals in the sludge, but there are also other materials depending on many factors which are related to the type of wastes generated by household activities. Phosphorus and potassium that are derived from the sewage sludge have a high value of fertility [21]-[25]. Generally, sewage sludge is made up mainly of high water content around 98%. The sludge is firstly removed by mechanical dewatering to get up to 25 wt % solid matter in humid phase sludge. Further removal is completed via thermal drying to get less than 10 wt% moisture content in dried granular sludge [21]-[25]. Non-toxic organic compounds are also found in sewage sludge, they account for up to 48% of the dry solid and are originating from plant sources. These compounds account for almost 60% of the energy content in the raw wastewater with a heating value of 11.10–22.10 MJ/Kg. [21]-[25] The third group of contents is made of biological pollutants such as micro-organisms and pathogens. The fourth group of sewage sludge content is made of non-toxic inorganic compounds, these include aluminium-, silicon-, iron- and calcium-containing compounds. Toxic inorganic compounds such as zinc, nickel, mercury, chromium and, arsenic, mainly from industrial wastes and corroded sewers form the fifth group of compounds found in sewage sludge. These compounds are in higher concentrations in sewage sludge compared to other solid fuels. Toxic organic pollutants like dioxins and polycyclic aromatic hydrocarbons are also part and parcel of the sewage sludge content [21]-[25].

Finally, phosphorus and nitrogen containing compounds sourced from peptides, proteins, sugars and fatty acids are also reported as part of sewage sludge content. Most of these compounds are subjected to changes at physical or chemical level with each energy recovery [21]-[25]. Changes involve decrease in organic content, fluctuations in pollutants stability and toxicity, densification of sludge and transformation of sludge into inorganic compounds mainly. Such changes should be correctly checked during all reaction stages [21]-[25]. Overall, sewage sludge is made of pathogens, organic matter which is biodegradable and inorganic substances that are known to be non-biodegradable. Also, it is important to mention the presence of small amount of toxic substances.

Table II presents an overview of the sludge characterization from primary and secondary treatment in a activated sludge process.

TABLE II: AN EXAMPLE OF SEWAGE SLUDGE CHARACTERIZATION [26], [27]

Parameter	Primary sludge	Activated sludge
Total dry Solids TS [%]	5 – 9	0.8 – 1.2
Volatile solids, VS [%]	60 – 80	59 – 88
Grease and fates (% TS)	7 - 35	5 - 12
Protein (%of TS)	20 – 30	-
Nitrogen (N, % of TS)	1.5 – 4	2.4 – 5.0
Phosphorus (P2O5, % of TS)	0.8 – 2.8	2.8 – 11
Potash (K2O, % if TS)	0 – 1	0.5 – 0.7
Cellulose (% of TS)	8 – 15	-
Iron (not as sulphide)	2.0 – 4.0	-
Silica (SiO2, % of TS)	15 – 20	6.5 – 8.0
pH	5.0 – 8.0	6.5 – 8.0
Alkalinity (mg/L as $CaCO_3$)	500 - 1500	580 – 1100
Organic acids (mg/L as HAc	200 - 2000	1100 – 1700
Energy content, kJ/kg	23,000	19,000-23,000
Total suspended solids TSS (mg/l)	29,000	

The general analysis of the data in presented in table 1 shows the potential of sewage sludge to produce clean fuel or energy source such as hydrogen and the biogas. This is supported by the amount of organic matter and the energy content of sewage sludge.

III. CONVERSION OF SEWAGE SLUDGE USING ANAEROBIC DIGESTION

There are four major processes used in the conversion of wastes into biogas from anaerobic digestion as indicated in Fig. 1. However, prior to anything there is a step involving the preparation of input material such as the removal of physical contaminants. Some compounds may not be biodegradable; they have to be removed from the waste to ensure the success of the conversion process into biogas or hydrogen. Some biological reactions can take place to ensure that there is an efficient production of biogas of biogas or hydrogen from sewage sludge.

Anaerobic digestion (AD) is a biological degradation of complex organic substances in the absence of oxygen. During biodegradation, energy is released and much of the organic matter is converted to methane, carbon dioxide, and water [28]-[30]. Currently, sludge stabilization by anaerobic digestion is used extensively on municipal wastewater sludge. High rate of anaerobic digestion slightly depends upon sludge type, mesophilic digestion and thermophilic digestion, for instance chemical sludges have been successfully digested anaerobically, although in several cases, volatile solids reduction and gas production were low when compared to conventional sewage sludge. Anaerobic digestion is a feasible stabilization method for sewage sludge that have low concentration of toxins and a volatile solid content above 50%. Consequently, AD offers several advantages over other methods of sludge stabilization, specifically, the process of producing methane known as a usable source of energy. Surplus of methane is frequently used for heating buildings, running engines, or generating electricity. It reduces total sludge mass through the conversion of organic matter primarily to methane, carbon dioxide, and water. Commonly, 25 to 45 % of the raw sludge solids are destroyed during AD; yields solids residue suitable for use as a soil conditioner; and inactivates of pathogens [31].

The processes include hydrolysis, acetogenesis, methanogenesis, and aciodogenesis as presented in Figure 1 After the hydrolysis of the wastes, they undergo the steps of acetogenesis and acidogenesis which lead to the creation of precursor molecules that are used in the process of methanogenesis. During the process of digestion, the methanogens act on them to produce methane as a waste product. The biogas is stored in a tank, the storage tank acts as a buffer, there is a balance of fluctuations taking place during the storage in the tank. In cases where the levels are low or when they are highly variable, dual fuel mixing is applied to supplement the gas produced with natural gas that comes from the distribution network at the mains.

Furthermore, there is a possibility to combine AD with gasification to provide additional benefits [32]. For instance, digestate from anaerobic digestion can be used as a gasification feedstock or the biochar co-produced in gasification can be used for the stabilization of AD and the improvement of nutrients retention in the digestate for fertilizers production. Integrated waste management technologies generate higher value from mixed wastes by processing a larger amount of the feedstock. Therefore, the technologies are an indispensable for a circular economy [33].

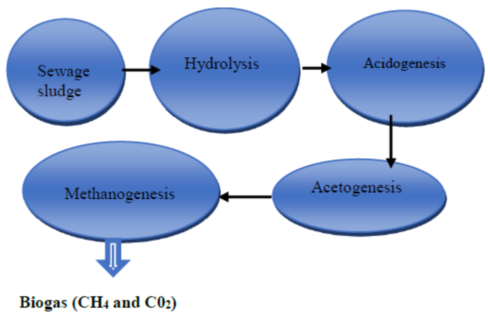

Fig. 1. Steps involved in the anaerobic digestion of sewage sludge for biogas production.

IV. Biogas Production Rate in Anaerobic Digestion of Sewage Sludge

Successful anaerobic digestion of sludge will never take place without the production of the correct biogas volume. Production of biogas through AD is one of the best available options due to low energy requirements and eco-friendly nature compared to other methods [34].

The conversion of organic matter from sewage sludge to biogas is an appropriate indicator that provides an early warning of upset conditions or problems in the digester. Measurement of the daily volume of produced biogas can be a substitute for all process control indicators when the feed loading is uniform and process upsets are intermittent [35]. It is reported from various experimental studies that 1 m^3 of biogas can be generated per kg of volatile solids biodegraded over a period of 20 days at the temperature of 35°C. It is therefore possible to determine the amount of biogas produced based on the daily feed loading to the digester [35]. A decrease in gas production is an evident sign of digester operation failure in case there was no disruption in terms of digester feeding and digestion temperature. Producing biogas from domestic sewage sludge via AD can be a promising and well-established technology for bio-energy or clean energy [36]-[40]; however, this process in many circumstances is unable to be costs competitive with natural gas [41]-]45]. Various recent studies have reported that the microbial communities and metabolic pathways involved in anaerobic digestion of sludge are mainly influenced by temperature [46]-[49]. It is reported that their metabolic activities increase significantly with the increase in temperature. Furthermore, temperature is a critical parameter for the AD process regarding the survival of microbial consortia and the consistent production of biogas, as it is reported that for each 6 °C decrease, the biogas production falls by 50% [46], [48], [49]. Therefore, temperature is considered as an important parameter for biogas production due to its influence on metabolic activities involved in anaerobic digestion. Hence, there is a need for insulation as well as external heating to maintain temperature stability and to avoid temperature fluctuations [46], [47], [49]. Also, there are other operating factors affecting the production of biogas in the AD process. These mainly include hydraulic retention time (HRT), organic loading rate (OLR), pH, tank volume, feedstock type, feeding pattern, and carbon to nitrogen (C/N) ratio. Longer HRT provides enough time for the biodegradation of organic matter depending on the microbial consortia living in the sludge at different rates and times. Shorter retention times can inhibit methanogenesis while longer retention times can lead to inadequate use of components. Biogas production increases with higher OLR; however, it destroys the bacterial population, leading to higher hydrolytic bacteria and acidogens. It may lead to lower methanogen population needed for biogas production. pH is also an important parameter that affects the production of biogas because it has an impact on bacterial activity and on methanogens which are known to be very sensitive in acidic environments. The optimal pH for acidogenesis is between 5.5 and 6.5 while methanogenesis is most efficient between pH 6.5 and 8.2 [50], [51]. Therefore, it is important to maintain pH between 6.5 and 7.5 to sustain an optimal concentration of acidogens and methanogens in the digester for higher biogas yields. The tank volume helps in the determination of HRT while the C/N ratio assists in the replication of nutrient levels in the digester [52].

V. Levels of CO_2 and Methane in Biogas

Biogas produced from a successful anaerobic digestion of sewage sludge may contain between 25 to 40% of Carbon Dioxide (CO_2) and 60 to 70 % of bio-methane by volume [30], [35], [53]. In overloading conditions occurring during digestion, the CO_2 content from biogas will increase while the bio-methane will be in the decreasing trend. This has been reported by many studies previously, it is due to the inhibition of methane producing microorganisms that takes place when the pH of the digested environment is lower [35], [53]. The lower values of pH are caused by the increase of both CO_2 and volatile acids. The increase of CO_2 content in the biogas is an early sign of the digestion failure [53]. Furthermore, the higher concentration of CO_2 in the biogas will generate a lower heat of combustion for the biogas. Therefore, the burning power of the biogas will be very low or even inexistent [53], [54].

VI. Conversion of Domestic Sewage Sludge Using Thermochemical Processes: Gasification, Combustion and Pyrolysis

Thermochemical methods for the conversion of sewage sludge into biogas such as combustion, pyrolysis and gasification are characterised by small reaction times generally in portion of seconds [31], [55]. Gasification is a process of heating biomass at a high temperature (> 700 ℃) without combustion under a meticulous supply of oxygen. The process leads to the production of syngas (CO_2, CO, and H_2). The biogas produced can retain between 70 to 80% of the energy content of the initial material. Biomass or sludge in the form of char is usually used rather than in its dried form because the produced gases are relatively free of tar, water, and corroding components. Downdraft gasification is a technological option for gasification in which the tar is eliminated. Another gasification type is termed fixed bed gasification. In this case the moisture is normally directed at the top drying zone before reaching the pyrolysis zone. The tars and oils move across the bed of hot char where the synthesis of biogas is occurring. [55]-[60]. The velocity of the biogas is generally low in the downdraft gasifier and the ash settles through the bottom grate to allow a very little amount of ash to be carried over with the gas. Gasification is generally effective with the action of catalysts. The use of nanocatalysts has generated conclusive outcomes from many studies with improved biogas yields at mild operating conditions when compared to ordinary catalysts. Also, nanocatalysts are economically realistic on large scale gasification compared to heterogeneous catalysts [55]-[60]. Nanocatalysts such as NiO, CeO_2, ZnO, SnO_2 are effective in the reduction of tar formation during gasification. Nanocatalysts known as nanoalloys including CeZr, XO_2, $Ni_3Cu(SiO_2)6$ can successfully achieve an increased conversion efficiency of sewage sludge or any other biomasses at lower gasification temperature [55]-[60]. Currently, many economic factors are providing a discussion on considering gasification as one of the appropriate options for sewage sludge and other biomasses [61]-[64]. In several circumstances where the price of fossil fuels is higher or where supplies are not reliable, gasification can deliver an economically and sustainable solution for biomass or sewage sludge conversion to clean energy provided that the suitable feedstock is easily available [64]. Looking at the characteristics of gasification, as well as the most important technologies, it can be concluded that sewage sludge gasification can play a key role in meeting the future needs of growing energy production. Gasifying sewage sludge or any biomass for clean energy production can provide sustainability a balanced reduction of greenhouse gas emissions and a steady energy supply [63], [64]. Consequently, sewage sludge and other biomass gasification deserve much attention because of the energy output in terms of quality and quantity. Pyrolysis is the thermal degradation of organic material in the absence of oxygen and can be an interesting option to convert material with low energy density into high energy fuels [65]. In these thermochemical processes the sludge should be subjected to a drying process before entering the reactor. The drying process is time and energy consuming and consequently it is representing an added cost. This implies that the sludge moisture content is required to be at the lowest level. A disintegration of more than 80% of the organic matter is reported to take place during thermochemical processes, this is achieved at a controlled and fast rate. Also, organic matter being partially oxidized provides to the thermal processes a major advantage compared to anaerobic digestion [65], [66]. Although thermochemical technologies costs are still considerably higher, there is a process named incineration which is another prominent process. It is currently in use for sewage sludge management, the traditional practice was not intended for energy recovery but for waste volume reduction and harmful elements destruction [65], [66]. The traditional incinerator can work as a classic combustion system to harness heat from the flue gas derived after the complete oxidation of organic matter at high temperatures ranging from 800 to 1150 ^oC [66], [67]. The heat extracted is used for heating water to produce steam for a turbine that assists in generating electricity. Compared to combustion, pyrolysis occurs in completely inert atmosphere without a single presence of oxygen, at moderate to high temperature ranging from 300 to 900^oC. Consequently, pyrolytic oil, biochar, non-condensable gases such as CO, H_2, CO_2, CH_4 and light hydrocarbons can be generated [67], [68]. The operating conditions including temperature, heating rate and residence time have significantly impacted on the energy content of pyrolytic products. Bio-oil can be upgraded and used as liquid fuel or reformed to synthesis gases such as CO and H_2. Finally, gasification deals with the thermochemical conversion of organic matter contained in the sewage sludge via partial oxidation at high temperatures from 650 to 1000 ^oC. It aims to maximising gaseous products such as CO, H_2, CO_2 and light hydrocarbons [67]-[69]. The energy content of the gas varies from 4–28 MJ/Nm depending on the gasifying agent and temperature [68], [69]. The biogas produced in this case can be used for direct combustion, for heat and electricity generation using a combined cycle gas turbine.

VII. Biogas Production and Heat Requirements

One m^3 biogas is generated per day when the digestion temperature is at least 5 ^0C [69]. Each m^3 of biogas represents about 6 kWh of heating energy, whenever there is conversion of biogas to electricity in a biogas powered electrical generator, about 2 kWh of usable electricity can be generated and remaining biogas is converted into heat which can then be used for heating applications.

VIII. Conversion of Sludge Sewage into Hydrogen

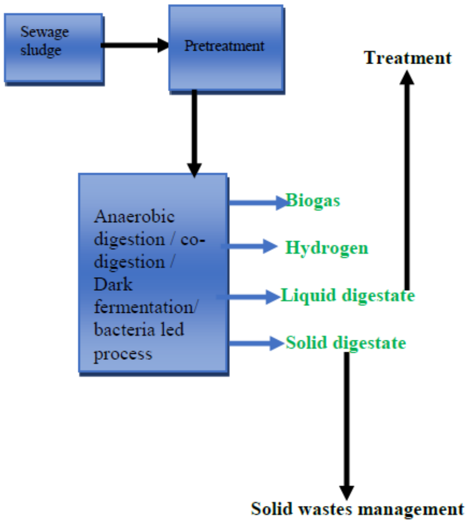

Fig. 2. Process overview from sewage sludge to biogas and biohydrogen.

There is a significant increase of sewage sludge in many countries due the rapid urbanization, lifestyle and the promotion of municipal wastewater treatment. Solid wastes generated from wastewater treatment plants can be a reliable source of clean energy depending on their biodegradability. Therefore, hydrogen as a source of energy can be generated from sewage sludge and it has a reputation of being a clean fuel. Considering the emerging global energy crisis and the growing demand for environmental protection, hydrogen can stand as one of the best options in this situation. Producing hydrogen from sewage sludge through anaerobic digestion (AD) is perceived as an economical and environmentally sustainable technology due to the low costs and effectiveness of AD. Many current studies focus on effective production technologies, sludge pretreatment options, key factors affecting hydrogen production and costs of production. The main challenge related to hydrogen production from various sources is that yields are not significant and the production is generally completed in batches. Hydrogen production from anaerobic co-digestion is also another option to be undertaken for sewage sludge [66]-[69]. In this process, it is reported that the relationship between the concentrations of carbohydrates and proteins may possibly increase the potential production of hydrogen due to the presence of enriched proteins found in sewage sludge [66]-[69]. Furthermore, the specific hydrogen production rate of hydrogen during co-digestion can also be increased and metabolic data has indicated that hydrogen production can be accompanied by n-butyrate production [66]-[69]. Another option is focusing on inhibiting hydrogen-consuming bacteria, culturing, and screening high-efficiency bacteria in order to effectively produce hydrogen from sewage sludge. This is possible by changing the effect of varying pH (4.5−7.5) and substrate concentration. Hydrogen-consuming methanogens are inhibited using the heat, this allows the enrichment of hydrogen-producing acidogens [68]. Prior to the production of hydrogen, a pre-treatment process of the inoculum allowing the selection of the group of acidogenic bacteria (AB) and thereby inhibiting the methanogenic bacteria (MB) in mixed culture should be undertaken. The aim of the process is to improve the effectiveness of the AD or any bacteria led process. There are four major types of pre-treatment processes which include physical, mechanical, chemical and biological [67], [69] The pre-treatment of inoculum can assist in the selection of microorganisms with the biochemical function towards acidogenesis. Pre-treatment of inoculum helps to reduce the substrate degradation which is attributed to the inhibition of hydrogen consuming bacteria [67], [69]. Fig. 2 shows the position of pre-treatment in the AD of sewage sludge for biogas and biohydrogen production.

Dark fermentation can also be used as a process for hydrogen production from sewage sludge. The process is a fermentative conversion of organic substrates to bio-hydrogen. It is also a complex process established by diverse groups of bacteria, involving a series of biochemical reactions using three steps similar to anaerobic conversion [68], [69]. Various techniques and methods are used to evaluate the microbial community and enhancement of hydrogen production by dark fermentation [69]. Dark fermentation differs from photofermentation in that it proceeds without the presence of light. In fact, dark fermentation (DF) is made by the first two phases of anaerobic digestion (AD) (hydrolysis and acidogenesis). In dark fermentation (DF) the aim is to produce hydrogen while in anaerobic digestion (AD) the main objective is to produce biogas which can be further upgraded to bio-methane [68], [69]. The differences are in the operating conditions. In DF there is inhibition of methanogens growth which consumes hydrogen and to do so, there are some strategies to be applied including inoculum pre-treatment, operating at low hydraulic retention time (HRT) and operating at pH lower than 7. In anaerobic digestion, HRT is usually high and the pH is near 7 [69]. Usually DF is followed by AD to achieve maximum energy production and COD removal. When considering the process, it is crucial to look at the conditions, the microorganisms, carbohydrates and proteins that may be responsible for hydrogen production. In the process, anaerobes act on them to produce hydrogen. Again, organisms that form spores are responsible for breaking down the carbohydrates [68], [69]. The species of *enterobactericeae* have the ability to metabolize glucose. Substrates that are decomposed in the process is another important element in the production of hydrogen. Simple sugars are mainly broken down into the organic wastes. Glucose is broken down to produce hydrogen. Starch containing wastes can also be used as the substrates for the process of dark fermentation [68], [69]. Most of domestic wastes contain starch and when they are broken down, they produce different gases including hydrogen. Starch containing materials are many in nature and they can be used as great carbohydrates for the production of hydrogen from domestic sewage sludge. Cellulose containing wastes constitutes another substrate that can be used in the production of hydrogen. Another type of substrates used for hydrogen production are biodegradable wastes from the food industry. The other process to be used for the production of hydrogen from sewage sludge is photo-fermentation. When using this process, there is a need to consider the fact that there are some photo-heterophic bacteria with the ability to convert organic acids that might be present in domestic sewage sludge conversion to hydrogen and carbon dioxide. The process is only possible under anaerobic conditions in the presence of light. The bacteria used for hydrogen production can act only when there is sunlight in the anaerobic decomposition. In this process, different substrates can also be used.

IX. Assessment and Comparison of Various Methods of Sewage Sludge Conversion

Tables III to VI summarize various aspects related to anaerobic digestion, gasification, combustion and pyrolysis of sewage sludge. They focus on the aspects related to technology, social and environment, economics, and present some areas where more studies can be undertaken.

TABLE III: Summary of the Assessment for Anaerobic Digestion of Sewage Sludge for Biogas/Hydrogen Production

ANAEROBIC DIGESTION

Technology	Social and environment	Economics	Future research focus
Advantages	*Advantages*	*Advantages*	Innovative ways to increase biogas yield and quality
Suitable for sludge with high moisture content	Low carbon emissions	No transportation and disposal costs	Analyzing the ways of Reducing reaction time
High energy content from biogas	Possibility of employment creation for unskilled and skilled labors	Profit can be made with the sale of fertilizers , digestate and biogas	Innovative ways to reduce operating
Potential for combined heat and power plant	Residuals products to be used as fertilizers		
Disadvantages	*Disadvantages*	*Disadvantages*	
Long reaction time	Generating a bad smell or odor	High capital and operating costs	
Presence of high organic pollutants	Need of appropriate treatment to prevent public and environmental hazards		
Low conversion efficiency			

TABLE IV: Summary of the Assessment for Gasification of Sewage Sludge for Biogas/Hydrogen Production

GASIFICATION

Technology	Social and environment	Economics	Future research focus
Advantages	*Advantages*	*Advantages*	Further studies on optimization in terms of quality and quantity of the gas are needed
The technology is very efficient in terms of providing high amount of energy	Low amount of wastes generated	Large scale plants can be economically viable	Studies on effective removal and minimization of tar should be very useful
It is also a self-sustaining technology	Low carbon emissions and heavy metals release.	Low carbon economy potential for energy industry	Ash and corrosion issues are frequent, therefore, remedial measures are needed to improve the effectiveness of the technology
Disadvantages	*Disadvantages*	*Disadvantages*	Studies should be undertaken on the economics and energy efficiency aspects regarding the pre-processing of sludge which focuses more on drying.
If the sludge has more than 30% moisture the drying will be required	Expensive technology with costs in terms capital and operating costs	High capital and operating costs	Minimization of carbon emissions are required to reduce the technological impact in the environment
The technology has not yet reached the maturity level though it can be used at large scales.		Release of heavy metals in the emissions	
The process involves the occurrence of complex reaction		Formation of toxic pollutants that can cause health hazards.	

TABLE V: Summary of the Assessment for Combustion of Sewage Sludge for Biogas/ Bio-hydrogen Production

COMBUSTION

Technology	Social and environment	Economics	Future research focus
Advantages	*Advantages*	*Advantages*	
The technology is matured and well-known	Possibility of co-utilization with other solid fuels to reduce greenhouse gas emissions	Use of existing infrastructures	Ash slagging and corrosion to be investigated in order to remediate to these issues
Good possibility of producing heat and electricity	Easy integration of pollutant capture technologies	Cost savings because when using co-firing with other solid fuels	Further studies to be undertaken regarding ash reuse
Lower production of organic pollutants from flue gas		Potential for energy saving regarding sludge treatment plants	Heavy metals emissions studies are needed to provide more innovative ways of dealing with this problem.
Disadvantages	*Disadvantages*	*Disadvantages*	Drying is an added cost , therefore , it will be necessary to look into the economic and energy aspects related to pre-processing drying technology
Sludge with high moisture content is not appropriate , therefore , there is necessity for sludge drying	Generating greenhouse gases	High costs of flue gas cleaning technology	
Waste ash will require to look for disposal and sustainable reuse options	The public acceptance is still a challenge	High costs for ash disposal	
		Requires a strict pollutants monitoring	

TABLE VI: SUMMARY OF THE ASSESSMENT FOR PYROLYSIS OF SEWAGE SLUDGE FOR BIOGAS/ BIO-HYDROGEN PRODUCTION

PYROLYSIS			
Technology	**Social and environment**	**Economics**	**Future research focus**
Advantages	***Advantages***	***Advantages***	
The technology is a zero waste process	The technology can generate very low amount of wastes	Only large scale plants can be effective and economically viable to a certain extent.	Further studies on the improvement of the quality and quantity of biogas/biohydrogen by undertaking the optimization studies
Potential for liquid fuels and chemicals production	The technology can generate low carbon emissions and releases very small amount of heavy metals	Low carbon potential economy potential for the energy industry	Further investigations on environmental impacts from generated char
Disadvantages	***Disadvantages***	***Disadvantages***	Study on the economy and energy efficient drying processing which is used as a pre-treatment process
High moisture sludge can be handled , there should be a drying process used as a pre-treatment step	The use of char as heavy metal reservoir requires expensive treatment for disposal	High capital and operating costs	
Technology involves a complex reaction		Many uncertainties in terms of economic viability	
Technology has not reached the maturity level			

X. COSTS IMPLICATIONS AND PROFITABILITY: OVERVIEW

The cost-effectiveness analysis of biogas/bio-hydrogen includes cost savings resulting from decreasing the expenditures connected with biogas/bio-hydrogen production, transportation of sewage sludge and the income from selling the final product of bioconversion as well as the costs of energy spent in sludge generation. The analysis is based on the assumption that the final product will be contracted by a major industrial electricity and/or heat generation plant [69]. Because major biogas producer can have as strong financial capacity to handle a large amount of sewage sludge on viable commercial plants. The form of the final product should allow long distance transportation; however, it has an impact on the price. Also, smaller producers of biogas can be able to handle a biogas unit provided that they operate at low operating costs with small units. The profitability will be based on the following factors: transportation savings, income from the sale of bioconversion and operational costs.

XI. CONCLUSION

Sustainable and renewable energy sources are currently considered as the best substitutes for energy and conventional fuel sources. Achieving environmental sustainability would only be possible when there is a move from the use of non-renewable energy sources to renewable ones. Biogas and hydrogen are one of the options to be explored in order to reduce the gap between the supply and demand for renewable energy sources. They may constitute an important energy source that is obtained from domestic sewage sludge. The production of biogas from domestic sewage sludge is an acceptable way through which energy is produced sustainably from a biodegradable raw material that is available from wastewater treatment plants. The sewage sludge is available on a daily basis on an increasing trend, it is generated from wastewater treatment plants, the lifestyle, the industrialization and fast rate of population increase in many countries around the world are the factors that affect the production of sewage sludge. Anaerobic digestion, gasification, combustion, pyrolysis and dark fermentation are reported to be effective for biogas and hydrogen production, they are showing promising future despite some challenges that may require optimization and more studies on improvement of production yield rates to be sustainable and costs competitive.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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