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Sustainability Consideration in the Production of Hydrogen from Biogas and its Use as a Future Automotive Fuel

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Abstract:
Through the search for alternative, renewable fuels and fuel carriers that significantly reduce CO_2 emissions and the dependence on fossil fuels, hydrogen appears to be promising automotive fuel. However, virtually all of the world's hydrogen is currently produced from fossil fuels. Hydrogen can be produced from renewable feedstock such as biogas, which is produced by fermentation of organic material such as manure, municipal solid waste (MSW), wastewater sludge, or any other biodegradable feedstock, under anaerobic conditions. The goal of this study is to evaluate the advantages of hydrogen production in a small scale unit and its use and compare it with use of biogas as a direct source of fuel. Criteria used in this selection are thermal efficiency, CO_2 emissions, by-products and cost per kg of hydrogen followed by sustainability discussions. In order to justify hydrogen production from biogas, a significant focus must be made regarding the sustainability of not only the design, but of the end use of products. The sustainability considerations thus become complex layers that take into account the three pillars of sustainability, i.e., economy, environment and society.

Keywords: hydrogen; biogas; sustainability; environment; fuel.

1. Introduction

The harsh effects of global warming, which are being realized more and more each day, are thought to be directly linked to the amount of CO2 emitted from anthropogenic sources. Specifically, the largest source for CO2 comes from the burning of fossil fuels such as oil, coal, and natural gas. Therefore, it is both appropriate and necessary that mankind starts searching for alternative, renewable fuels that significantly reduce CO2 emissions [1].Biogas

Of the numerous options for renewable energy sources and energy carriers, hydrogen appears to be one of the most promising for a sustainable future. Going further along the path towards sustainability, there are several options to produce hydrogen from renewable feedstock [2],

one of which is biogas. Biogas is a bio-fuel which is used all over the world as a valuable fuel source. Europe, especially Sweden, uses biogas as fuel in vehicles and for electricity generation in gas engines.

Scholarly articles that discuss the future of planet Earth agree that there are three major challenges approaching on the horizon. First, the population is rapidly approaching devastating levels. Second, there is a finite amount of fossil fuels in the earth and they are being extracted at non-renewable rates. Finally, our precious high energy sources are being degraded into hazardous waste beyond economical reuse [3].

Although the population increase is imminent and cannot be directly solved by the use of renewable energy sources, the second two global challenges mentioned apply. It is becoming increasingly important when considering new technologies and energy generation methods that the aforementioned three challenges are taken into consideration. Current study is focused on advantages of hydrogen production in comparison with Biogas as a direct source of fuel in global sustainability context.

2. Biogas

Anaerobic fermentation of biomass produces methane known as biogas or in fact any other biodegradable feedstock, under anaerobic conditions. A more recently developed technology is collection of biogas from landfills. In the landfill, the amount of biogas generated has some link with the moistened content of feed stack. In this study, the focus is placed on the biogas generated from wastewater treatment plants.

2.1 Applications

Biogas can be used for electricity production, space heating, water heating and process heating. If compressed, it can replace compressed natural gas for use in vehicles where it can fuel an internal combustion engine or fuel cells [4].

It is worth mentioning that Biogas as vehicle fuel in Sweden has reached a major break-through due to a surplus of gas produced from biogas plants, mostly from sewage treatment plants. The Swedish government regulations have specific requirements regarding the purity of biogas in the transportation industry. The Swedish national specifications are referred to as SS 12 54 38 and state that biogas must contain a minimum of 97% methane [5].

2.2 Composition

Digesters produce two products: biogas and digestate. Biogas can vary in composition from 50 to 80 percent methane, and the rest being carbon dioxide, water, and hydrogen sulfide. It must be noted that the general composition cited in literature is usually 60 to 65 percent methane, and the rest being carbon dioxide with negligible amounts of water and hydrogen sulfide [6-9]. Digestate usually contains cellulose fibers, lignin, and remnants of the anaerobic microorganisms and can be used for soil amendment.

2.3 Comparison with Natural Gas

If biogas is cleaned up sufficiently up to pipeline quality, biogas can be used in every application that natural gas is used for and it would have the same characteristics as natural gas.

3. Hydrogen

Fossil fuels, such as coal, and petroleum has a significant value for the continuance of people's daily activities. However, the supply is depleting in a concerning rate, and the emissions produced have a considerable impact on the environment. New energy solutions are needed to address the global energy security, social equity, air pollution and economic growth issues [10].

The hydrogen economy is a hypothetical economy in the future in which the primary stored energy for mobile applications and load balancing is hydrogen. It has cutting edge over the others being renewable, clean (emits water as emission), non-toxic, high energy conversion efficiency and has a higher quality of energy content per mass compared to conventional fuel oil. Hydrogen has unique application to produce electricity by turning alternator using internal combustion (IC) engines. The reaction occurring in the fuel cell is as follows [11]:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

$$(\text{LHV } -242 \text{ kJ/mol } H_2,\ \text{HHV } -286 \text{ kJ/mol } H_2)$$

The water cycle is an important feature of the hydrogen energy system; considering that water is the feedstock for producing hydrogen and water is also the product of hydrogen use. This characteristic is the fundamental in understanding the sustainability aspect of hydrogen as an energy carrier.

From an environmental aspect, hydrogen possesses better environmental performance; because unlike conventional fossil fuel combustion, it does not produce carbon dioxide which causes global warming. It also does not produce carbon monoxide which is poisonous to human beings and no generation of NO_x and SO_x emissions which contribute to acid rain and react with sunlight to create ground level smog. Until today, 99% of the hydrogen produced is from fossil fuel [12]. This fact would contradict with the sustainability aspect for having hydrogen as an energy carrier, because fossil fuel as has been stated before is nonrenewable and depleting. The challenge right now is to produce hydrogen from renewable resources in an efficient, economic and environmentally sound way. Biogas has been recognized as one of the potential feed stocks to produce hydrogen.

3.1 Applications

Most hydrogen is now produced locally and consumed immediately, by the same company that produces it. This practice is done due to the high cost in storage and transportation. The total amount of hydrogen produced globally in 2004 is 50 million metric tons [11]. About half of the total hydrogen production is consumed in fertilizer plants to produce ammonia. The other half is used to convert heavy oil petroleum sources into lighter compounds for use as fuel.

Due to precarious and high storage cost only a small portion of the produced hydrogen is used for fuel cells in transportation systems. Research frontiers are striving for viable solutions within this context.

3.2 Hydrogen Infrastructure

While exploring the technological, economical, and environmental aspects of the process to convert biogas into hydrogen, one must consider the general infrastructure surrounding the suggested technology. Precisely specifically, since this study uses biogas from a wastewater treatment plant, the necessary changes in the infrastructure of the wastewater plant to accommodate the production of hydrogen will be considered.

Actually, as it has been seen from an example in Gothenburg, Sweden, the current infrastructure of many wastewater plants that already collect and store the biogas does not require significant change for hydrogen production. In the provided example, one can see that the biogas is utilized in three ways; heat and electricity production, city gas network, and refueling stations. However, the considered hydrogen process in this study is to use the product (hydrogen) exclusively for fuel cells. Furthermore, this design calls for an integrated decentralized process within the plant. This plan would then make the electricity and gas, city gas network, and biogas refueling stations irrelevant, and use the entire hydrogen product within the wastewater plant. The biogas from this wastewater plant would then be used in an entirely different application; however, as discussed in this study, it will be used in a much more efficient manner.

It becomes important at the same time to consider the overall hydrogen economy infrastructure, which this paper suggests. Although the specific application of this study is relatively small scale, some background information on the hydrogen situation of today should be mentioned. Currently there are several communities in the world that are testing the viability of a 'hydrogen economy'. For example, Iceland has joined with Shell Hydrogen, DaimlerChrysler, and Norsk Hydro to convert a majority of the cars, busses and boats in the city of Reykjavik into hydrogen fuel cell driven sustainable transportation (Dunn, 2002). However, in other countries, a hydrogen economy is far from being realized at this time. One of the main concerns is the resistance from both the automakers and the refueling station companies. The International Journal of Hydrogen Energy states,

"Automakers are loathe to mass produce direct hydrogen fuel cell vehicles if they cannot be guaranteed that there will be an adequate number of hydrogen refueling stations in place to supply their customers" [12]. Furthermore, it is suggested that in order to overcome this hurdle in the United States, for example, around 10,000 hydrogen capable refueling stations (roughly 10-15% of the total number in the US) would suffice in convincing auto manufacturers to produce fuel cell vehicles [12]. It has been calculated that the initial investment for this aforementioned number of refueling stations would cost upwards of 3 to 15 billion US$. However, these calculations are relevant for a large scale change into hydrogen while the process scale in consideration in this study is relatively small. The hydrogen produced from the process described in this paper will be used for fuel cells in such areas as public transportation.

4. Sustainability Discussion

In order to justify hydrogen production from biogas as discussed in this study, a significant focus must be made regarding the sustainability of not only the design, but of the end use of the products. The sustainability considerations thus become complex layers that take into account the three pillars of sustainability, economy, environment, and society. Through these three categories, a process design and associated product can be assessed methodically according to theories that promote the fundamental concepts of sustainability. This section of the study will be dedicated to the consideration of the fundamental concepts of sustainability in context with the proposed design for hydrogen production from biogas.

The purpose of this study was to provide an alternative use for a relatively small amount of a byproduct from an industrial source. The byproduct was biogas, and the industrial source was a municipal wastewater treatment facility. More specifically, the overall goal of this study was to show the benefits of upgrading biogas to a hydrogen product as opposed to just the biogas product. Therefore, the sustainability discussion must focus on the comparison between hydrogen and biogas and their respective applications.

There are many problems that exist in today's energy consumption and production. These problems have provided a driving force for the ongoing research for alternative fuels. The six major qualities that must exist in a sustainable fuel source are that the fuel must be transportable, easily obtainable, renewable, safe, affordable, and environmentally compatible. Fossil fuels lack the qualities of renewability and environmental compatibility. Both Biogas-hydrogen have the potential to meet these six qualities. The current study will look into each fuel to determine relevant qualities [4].

4.1Environmental Criteria

One of the primary environmental advantages of hydrogen fuel cells as opposed to biogas combustion is the fact that they would replace combustion reactions. Combustion reactions have a tendency to produce significant amounts of NO_x, which is harmful to the environment in a number of ways [13]. One effect of NO_x production is the formation of N_2O, which is a greenhouse gas. Greenhouse gases contribute to global warming, which is a massive problem currently occurring globally. In the case of this study, however, the feedstock is CO_2 neutral and does not contribute to this effect. Evidence of this global warming has been provided by studies from NASA and is seen in the figure 1 below [14].

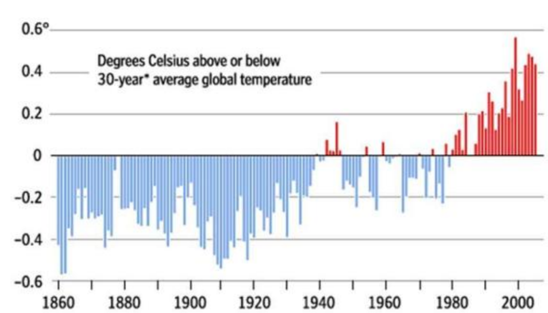

Figure1. Global land-sea temperature difference over the years

One additional environmental impact would be that of noise pollution. If more fuel cells were used than internal combustion engines, there would be a significant reduction in noise pollution. This effect applies most to automotive applications but would also make a difference in industrial applications too [15].

Considering the whole life cycle of production of hydrogen, since its origin is organic waste which is fermented produce biogas, it eventually results in reducing COD content of the wastewater, and improving living conditions for aquatic life which otherwise will result in increasing COD content of wastewater.

4.2 Process Emissions

The countries which have ratified the Kyoto protocol are mainly concerned about CO_2 emissions produced from different sources and are looking for processes and resources which can enable them to reduce overall CO_2 emissions [16]. This is one of the advantages of using hydrogen as an energy carrier and its production from biogas. It is a CO_2 free energy carrier and its use in fuel cells only releases water. The biogas production from the plant is 10,000 tons per year. This means that the annual production of emissions, consisting of H_2S, CO_2, and CO that comes from an upgrading station capable of handling the whole biogas from this plant is about 857.14 tons per year. Of this amount, there are 837.44 tons of CO_2, 7.39 tones of CO, and 12.32 tons of hydrogen sulfide. If it is assumed that nearly the entire biogas product is combusted and considering the purity upgrading step, then there is an annual CO_2 production of nearly 15,000 tons [17].

Next, these emissions must be compared with the emissions from hydrogen production. The main difference between the two options is that after hydrogen is produced, there are no more emissions. It means that if a majority of the cars in a large crowded city were run on hydrogen fuel cells, then the local air quality would be significantly improved. Regardless of the fact that biogas is CO_2 neutral, it still produces CO_2 as well as other combustion byproducts, and many cars in a congested area can have a very negative effect on the local air quality [18].

4.3 Economic Considerations

The use of hydrogen has many notable qualities that promote sustainable development, but perhaps one of the most important characteristics is the fact that it has the potential to reduce the consumption of non-renewable fossil fuels. The European Union Commission for Research and Energy states this important quality in the Hydrogen Energy and Fuel Cells special report (2003) [19],

"Today's society depends crucially on the uninterrupted availability of affordable fossil fuels which, in future, will be increasingly concentrated in a smaller number of countries – creating the potential for geographical and price instability. Hydrogen opens access to a broad range of primary energy sources, including fossil fuels, nuclear energy and, increasingly, renewable energy sources (e.g. wind, solar, ocean, and biomass), as they become more widely available. Thus, the availability and price of hydrogen as a carrier should be more stable than any single energy source"

Hydrogen certainly has the potential to be produced from a number of primary sources, which makes it essentially 'more stable' because there are less production limitations such as in the case of fossil fuels. In fact, such limitations are slowly being realized in Europe due to the fact that 25% of the consumed oil comes from the North Sea region, which is estimated to reach its peak production by the year 2020 [20]. At this time, if current estimates are correct, only 10% of total consumption will come from the North Sea and the remainder will come from the 'Middle East' making Europe more dependent on other countries.

Most industries, since the 1970's, do not demonstrate a linear relationship between economic growth and energy demand growth. Yet, as the transportation industry expands, it consumes more and more energy. Fortunately it seems that many major companies in this area are beginning to notice this effect. In Japan and the US, the investments continue to grow for research on hydrogen technology such as fuel cells. Large international car companies such as Daimler Chrysler, Opel, Ford, and BMW have been active in research to develop hydrogen production vehicles [21]. Through the application of hydrogen fuel cells, other significant economic benefits also exist. For example, hydrogen fuel cells can easily be made compliment decentralized power. A fuel cell can be smaller and local allowing flexibility, and the ability to meet the customers' specific needs [22].

Hydrogen has higher energy content per mass compared to biogas and also the efficiency of the fuel cell is higher than that of a conventional CHP (Combined Heat & Power) unit or an internal combustion engine. In this section, the comparison between a biogas-fed CHP (Combined Heat & Power) plant and hydrogen fuel cell is discussed based on the value of energy (electricity and heat) each of them produce [23].

4.4 Economic value of the energy produced by conventional CHP and hydrogen fuel cell

Table 1. Comparison of the values of electricity and heat produced by conventional CHP and hydrogen fuel cell based on the biogas produced by Wastewater Treatment Plant, Gothenburg, Sweden

	Electricity (w/ tax)	Heat (w/ tax)
Price + tax (Swedish Krones)	1.02 per kWh	January-April : 0.79/kWh May-October : 0.35/kWh Nov-December: 0.79/kWh Average : 0.57 per kWh
Efficiency - Conventional biogas-fed	35% 60%	50% 25%
Calculated energy output (annually) - Conventional biogas-fed	17,185 24,550	24,550 10,229
Value of energy (annually) - Conventional biogas-fed CHP	17,594,003 25,134,290	13,968,415 5,820,173,00
Total energy value (electricity+heat) - Conventional biogas-fed CHP (SEK/year) - Fuel cell (SEK/year)	31.56 million 30.95 million	

The Table 1 shows that the value of energy (electricity and heat) produced by conventional Combined Heat and Power (CHP), is a bit higher than of the hydrogen fuel cell. It must be mentioned that the prices used in table1 are taken from the respective websites of "plus energy" and Gothenburg energy [17, 24]. From this comparison, the conventional biogas-fed CHP plant which is already running is more economical than the proposed hydrogen production plant. However, this condition applies only in Sweden and other European countries which have extreme weather conditions during winter. If the technology is applied in tropical countries, where they have practically no need for heating systems in housing, a hydrogen production plant based on wastewater treatment plant's biogas can be an interesting option

Considering the option of selling raw biogas or hydrogen bring an interesting comparison between both fuels. The price of biogas in Sweden per gallon of gasoline equivalent is US $3.5. Gasoline gallon equivalent is the amount of fuel which is required to produce the same amount of energy as of one liquid gallon of gasoline. In this study, current price of hydrogen in the US is taken as reference which is around 6 US $. It is estimated that the value of money earned by selling biogas for use in internal combustion engines is US $ 5,093,550 less than that earned by selling hydrogen on a yearly basis [17].

In other words while considering the use of hydrogen for fuel cells for automobiles in Gothenburg city, it has potential to replace (168x24x366) 1475712 gallons of gasoline. On the other hand using biogas in automobiles, it has the potential of replacing (2502x366) 915732 gallons of gasoline [19]. Thus hydrogen has much more potential to replace fossil fuels than biogas making it more sustainable and economically feasible.

In addition, investments in hydrogen infrastructure are not only investments in a technology, but also investments in the future. By investing in an ultimately sustainable energy carrier such as hydrogen, a country can attempt to avoid a so-called 'lock in' where the population's energy consumption can no longer be supported on an energy source.

4.5 Social Aspects

Society, existing as one of the pillars of sustainability, also benefits from the use of hydrogen fuel cells. First, and most importantly, hydrogen fuel cells produce only water and no emissions. Thus, there are no health risks such as particulate matter inhalation, ground level ozone formation, troposphere ozone depletion that allow UV rays to the earth's surface, acid rain, smog, etc., that could be associated with combustion of biogas. Since the current global trend favors the urban areas rather than the rural areas, energy sources without emissions will benefit local atmospheres significantly. A mass of fossil fuel burning cars in a small, congested area will produce unsafe air quality for all of those living in close proximity. Thus, hydrogen fuel cells can improve the local air quality [25]. Society would be benefited in the case of implementation of hydrogen fuel cells due to the creation of numerous jobs. From operators in fuel cell plants to research and development scientists, there are many types of specific jobs needed.

5. Conclusions

Global warming is receiving increased apprehension and CO_2 emissions are considered the chief contributor to the quandary. Independence from fossil fuels is recognized as a viable solution; therefore, it is necessary for humankind to develop new alternative energy resources to reduce CO_2 emissions.

The hydrogen economy is a hypothetical economy in the future, which is considered as one of the possible solutions for global warming and sustainability issues. The fact that biogas is an energy source and hydrogen is an energy carrier makes it difficult to make a substantial comparison between them. However, the comparison of biogas and hydrogen as fuel for harnessing energy was carried out by utilizing the heating value of both fuels. The comparison of total energy produced was carried out between the conventional biogas-fed CHP and hydrogen fuel cell CHP to distinguish the more economically feasible fuel. Comparisons were also done between the energy produced in internal combustion engine and a hydrogen fuel cell; and between the direct selling of the biogas and hydrogen. For CHP operation, the value of energy (electricity and heat) produced by hydrogen fuel cell is slightly lower than the value of biogas energy, although the electricity produced by hydrogen fuel cell is 40% larger than the biogas fed CHP. Comparison between a fuel cell and internal combustion engine showed more favorable results for hydrogen use. In addition, the direct sale of hydrogen and biogas was compared and it was found that hydrogen was economically more profitable.

The thermal efficiency for the whole plant was calculated to be 46%, which was slightly higher than the value expected in the literature. The increase is possibly due to the heat integration and optimization of the plant. Based on the environmental performance, the conversion of biogas to hydrogen is considered more environmentally friendly because biogas combustion results in NO_x whereas a hydrogen fuel cell does not. The better condition of the environment will eventually benefit society due to the healthier air quality like wastewater treatment plant landfill potential opportunities and should be lapped at Bio alternate energy resource. However, if biogas is not considered free the payback period will be extended to 12 years, which by industry standards translates to the hydrogen production plant not being currently feasible.

6. Recommendations

Based on the study, the hydrogen produced from sewage treatment biogas can be utilized in a hydrogen fuel cell cogeneration (CHP) plant, for automobile fuel cells and it can be directly sold to interested parties. For the CHP plant, the use of hydrogen fuel cell will give higher efficiency to electricity compared to heat production. The option is feasible if electricity is the main product that is needed by customers. This condition can only be applied in tropical countries, which do not have extreme cold weather condition, and do not need district heating. The time limitation and the scope of study have constrained the analysis of hydrogen use in different applications such as automobiles, direct selling to customers in the form of liquid hydrogen. Based on the market price of hydrogen and biogas, the hydrogen production from sewage plant biogas has higher value than the biogas itself. Nevertheless, further study could be used to increase the depth and precision of the analysis and refine the conclusions. Also, a Life Cycle Assessment (LCA) can be carried out in further study to supplement the sustainability study of the proposed plant design.

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