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LOCAL ALTERNATIVE SOURCES FOR COGENERATION COMBINED HEAT
AND POWER SYSTEM

by

ABDULHAKIM AMER AGLL

A DISSERTATION

Presented to the Faculty of the Graduate School of the
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

in

MECHANICAL ENGINEERING

2015

Approved
Ashok Midha, Advisor
John W. Sheffield, Co-advisor
Robert Landers
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V.A.Samaranayake

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PUBLICATION DISSERTATION OPTION

This dissertation has been prepared in the format of the publication option. Three journal articles are presented.

- 1) Pages 9 to 24 “*Study of a molten carbonate fuel cell combined heat, hydrogen and power system: Energy analysis*” is in the style required by Applied Thermal Engineering. It has been accepted and published. The citation is:

Agll, A.A., Hamad, Y., Hamad,T., Thomas, M., Martin, K.B., Sheffield, J.W., (2013). Study of a molten carbonate fuel cell combined heat, hydrogen and power system: Energy analysis. *Applied Thermal Engineering* 59 (2013) 634-638.

- 2) Pages 25 to 42 “*Study of energy recovery and power generation from alternative energy source*” is in the style required by Case Studies in Thermal Engineering. It has been accepted and published. The citation is:

Agll, A.A., Hamad, Y., Hamad,T., Sheffield, J.W., (2014). Study of energy recovery and power generation from alternative energy source. *Case Studies in Thermal Engineering* 4(2014)92–98.

- 3) Pages 43 to 70 “*Development of design a drop-in hydrogen fueling station*” is in the style required by International Journal for Hydrogen Energy. It has been submitted/is under review.

The Introduction, and Conclusions, sections have been added for purposes normal to dissertation writing.

ABSTRACT

Global demand for energy continues to grow while countries around the globe race to reduce their reliance on fossil fuels and greenhouse gas emissions by implementing policy measures and advancing technology. Sustainability has become an important issue in transportation and infrastructure development projects. While several agencies are trying to incorporate a range of sustainability measures in their goals and missions, only a few planning agencies have been able to implement these policies and they are far from perfect. The low rate of success in implementing sustainable policies is primarily due to incomplete understanding of the system and the interaction between various elements of the system. The conventional planning efforts focuses mainly on performance measures pertaining to the system and its impact on the environment but seldom on the social and economic impacts.

The objective of this study is to use clean and alternative energy can be produced from many sources, and even use existing materials for energy generation. One such pathway is using wastewater, animal and organic waste, or landfills to create biogas for energy production. There are three tasks for this study. In topic one evaluated the energy saving that produced from combined hydrogen, heat, and power and mitigate greenhouse gas emissions by using local sustainable energy at the Missouri S&T campus to reduce energy consumption and fossil fuel usage. Second topic aimed to estimate energy recovery and power generation from alternative energy source by using Rankin steam cycle from municipal solid waste at Benghazi- Libya. And the last task is in progress. The results for topics one and two have been presented.

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I would like to express my gratitude to the people, without the decisive contribution of whom the completion of this dissertation would not be possible, throughout my stay here at Missouri University of Science and Technology. I would like to express my deepest gratitude to my co-advisor Dr. John W. Sheffield, who gave me an opportunity to participate in the hydrogen student design contests and conduct research under his supervision. Dr. Sheffield has continuously conveyed a passion for research work and excitement for teaching.

I owe my deep appreciation to my advisor, Dr. Ashok Midha, for his profound insight and guidance. Dr. Midha's vision and enthusiasm has not only been as a researcher in the success of this work but also for the very existence of the field of compliant mechanisms, and also for his knowledge and helpfulness particularly during Dr. Sheffield's absence.

I owe thanks and deep appreciation also to Dr. Robert Landers, Dr. K. Chandrashekhara and Dr. V.A. Samaranayake for their time and service on the Advisory Committee.

Next, I would like to acknowledge my gratitude to the Hydrogen Education Foundation for their support of the annual Hydrogen Student Design Contest.

I would like to show my gratitude to family here and my parents and siblings in my home country, for that has guided and supported me in all aspects of my life. It was under their supervision that I gained the ability to tackle challenges and issues. A special thanks to my brothers and all my dear friends who have been supporting me throughout my life with their love, and encouragement.

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SECTION

1. INTRODUCTION

1.1. BACKGROUND

Over the last three decades, people have become more and more dependent on energy that they dig out of the ground. In the 1700's, almost all the energy source came from wind, water, firewood, or muscle power. The wind powered by windmills and sailing ships, water powered the water wheels, and firewood did the cooking and heated the homes. Muscle power did just about everything else. All these energy sources came from the sun, since solar energy drove wind and rain, grew trees, and grew crops to nourish the animals and ourselves. So, the energy sources were renewable, since wind kept flowing, and trees and crops kept growing [1]. About 1800, the people began to get much of energy from coal dug out of the ground. Furthermore, in 1900 the human start to search and drill for petroleum. By 1950 these "fossil fuels" needed primarily expatriate the initial energy sources excluding the water power generation [2]. However, the fossil fuels come from the decayed remains of old plants and animals. So, the energy comes originally from the sun. In around the world there are some of places fossil fuels are being formed even at present. Anyway, using fossil fuels is a far greater quantity than being created, by consumed of up energy stored over hundreds of millions of years in a few hundred years.

Later in 1950's, the advanced world started work on nuclear energy from uranium. This type of energy does not come from the sun. It is similar to fossil fuels, non-renewable it is vanish once it's used up. Since, in the 1980's the world turned again to use the first renewable energy sources have greater than before [3]. The worldwide have recognized

that fossil and atomic fuels will not last forever, and that their usage effect on greenhouse gas emission. Sustainable energy which mainly came from the sun as a new provides opportunity for an unlimited alternative energy supply with low environmental impact.

Biomass as a fuel is made of organic substance such as industrial waste, agricultural waste, wood, and bark. Biomass can be burned directly in specially designed power plants, or used to replace up to 15% of coal as a fuel in regular power plants. Biomass burns cleaner than coal because it has less sulfur, which means less sulfur dioxide will be released into the atmosphere [4]. Biomass can also be used indirectly, since it produces methane gas as it degenerates or through a gasification process. Methane can generate power by boiling water to create super-heated vapor to excite steam turbines to turn around or through internal combustion in gas turbines and reciprocating engines. Furniture plants, sawmills, and paper mills usually burn their wood waste to produce heat and electricity. Many homeowners use firewood or pellets for winter heat [5].

Sustainability and sustainable improvement concepts become an important issue in transportation and power generation development projects. While several organizations are trying to combine a variety of sustainability measures in their goals and missions, only a few organization agencies have been able to implement these policies, and they are far from being perfect. The low rate of success in implementing sustainable policies is primarily due to incomplete understanding of the system and the interaction between various elements of the system. Conventional planning efforts emphasis mostly on performance measures pertaining to the system and its impact on the environment but rarely on the social and economic impacts (Jeon & Amekudzi, 2005; Deakin, 2003). Global energy consumption is going up. According to the International Energy Outlook 2014 by

the U.S. Energy Information Administration (EIA), the total world energy consumption is estimated to rise from 559 quadrillion British thermal units (Btu) in 2014 to 620 quadrillion Btu in 2020 and 777 quadrillion (Btu) in 2035 [6].

Renewable and alternative energy technologies can aid to reduce of fossil fuels usage and can mitigate greenhouse gas emissions. Renewable energy is the world's rapidly growing procedure of energy [6] and can deliver energy required and can keep the nation from the variations of oil price and other fossil fuels. By applying energy strategies to implement more renewable and alternative energy technologies, the United States can achieve greater energy security.

Despite the fact at hand are numerous alternative energy technologies at this time accessible in their elementary stage and have not been widely organized for actual use. Sustainable sources like geothermal, solar and wind energy are highly spot specific at through investigation of these resources at the site must be performed before used them. This study starts at distribute of the sustainable technologies for actual applications. It considers the steps needed for the deployment of alternative energy technologies, its achievability, and the programs accomplished from different assignments. In fact, the study illustrates the use of renewable energy technologies for example waste to energy conversion, biogas production and hydrogen fuel cells.

Previous works clarifies the obligatory and advantage for the use of renewable and alternative energy technologies. Lund [7] illustrated that 40% of all the global electricity needs can deliver by wind and solar power if they have excellent investment plan. Morrison [8] showed that the world's power generating rate must to add renewable energy sources when coal is used as fuel. Wisner and Bolinger [9] suggested that can minimize the threat

of high natural gas prices in the future if rising up investments in renewable energy. Klass [10] described the commercial energy combination in the United States will “include major contributions to energy demand by renewable energy resources” for renewable energy usage and predicts. Bristow [11] explained the effects of increase in energy costs to mitigate the “building-scale alternative energy”. Graus et al. [12], discussed that can be achieved energy efficiency in energy generation, transmission and distribution as per “a total potential for energy efficiency improvement of 55% in 2050”.

Fuel cells technologies are affecting on a most important part in the alternative energy technology as sustainability. Solar and wind energy are fluctuating energy sources and cannot produce constant power. In addition, solar and wind as fluctuated energy can be used to produce hydrogen through electrolysis of water. The hydrogen produced is energy carrier and can be used to produce electricity by a fuel cell. Zerta et al. [13] showed that hydrogen lead to change the universal energy green. Bartels et al. [14] evaluated the best sources of hydrogen from biomass are coal and natural gas. Moreover, hydrogen production from alternative fuel sources possibly will developed commercial in the future as a result of the growing feedstock expenses of traditional fossil power plants, equipment improvements, and reduction in the cost of alternative energy technologies [14]. Ali and Salman [15] performed full evaluation of the fuel cells technology and hydrogen low-cost. Becker et al. [16] evaluated the solid oxide fuel cell and the combined heat, hydrogen, and power systems are capable of electrical efficiency of 48.4% and an overall efficiency of 85.2%. This is enhancement over the existing technology for the value of power produced has greater energy efficiency and lesser emissions. Han et al. [17] worked on phosphoric acid fuel cell and molten carbonate fuel cell as a combined hydrogen, heat and power

systems to improve energy production and mitigate greenhouse gas emission. Williams and Kurani [18] showed “Mobile Electricity” technologies and opportunities the commercialization of vehicles with plug-in/plug-out ability limited-duty hydrogen-fuel-cell, and driver towards marketing of alternative energy vehicle technologies. Alternative energy technology utilizations combined with other renewable technology is the best couple to the hydrogen technologies.

Del Rio and Burguillo [19] discussed a rough idea for the investigation of the influence of alternative energy sources on local viability, concentrating on the public and commercial scopes. Amer and Daim [20] presented the application of technology roadmaps for renewable energy sector to aid strategy planning and aligning it with overall business plan. Grossmann et al. [21] demonstrated that changed signs to estimate the specific development for the greatest alternative energy technologies. All of these structure and applications drive and aid to optimize which the renewable energy technology is the best for arrangement at a certain location.

Biogas is produced by anaerobic digestion of wastewater, organic waste, agricultural waste, and industrial waste are a potential source of renewable energy. Treated biogas can be used to generate Combined Heat, Hydrogen and Power (CHHP) using a molten carbonate fuel cell. The power generated by the CHHP system is used at various locations to reduce the overall electric power consumption and minimize air pollution to benefit community health [22-24]. In addition, CHHP systems have higher efficiency than other distributed generation plants of similar capacity [25, 26]. An energy flow and resource availability study was performed to identify the type and source of feedstock required to continuously run the CHHP system to produce maximum capacity of electricity,

heat recovery and hydrogen [27]. MSW (Municipal solid waste) contains methane is considered a potential source of clean renewable energy. Studies of energy and waste management is, deserve special attention, due to the constraints arising from limited availability of land, resources and pollution [28, 29].

Today, the world's population generates enormous amount of waste. Whether we live in industrialized countries or developing countries, in big or in small cities, or whether people are rich or poor, all produce waste, for decades, industrial countries (ICs) have lived beyond these resources. Yesterday's belief that all resources were eternal has now changed. Waste minimization is a key concept in ICs. The amount of waste produced is dependent on the country, type of urban district, population, city size, culture, style of life and of course income. Selective sorting from MSW (municipal solid waste) or recycling and recovering materials is generally a difficult task in small isolated systems. Moreover, the alternative energy sources and the price of primary energy transportation are very expensive due to limited markets there. Consequently, the policies are recommended to use of local energy sources, to be exact incineration of MSW with energy recovery and carbon dioxide emission mitigation [30]. In addition, thermal technology has been applied for a long time to reduce the volume of MSW through recovery the incineration of energy, to generate heat and/or electricity [31]. The main objective of an incineration plant is decreasing of MSW landfill. The energy recovery is working out for sustainability of energy with the optimum costs as fundamentals on it. Therefore, it should not compare with the energy generation from fossil fuels.

The air pollution is one of the significant sides to the MSW incineration project. In fact, as a result of using energy recovery lead to reduce the methane emission from landfills

and fossil fuels [32]. The amount of energy recovery was achieved depended on MSW ratio of biogenic to fossil carbon and on the energy transformation efficiency. The MSW has relationship with a human activity and renewable resources, it is a potential source of significant materials and energy [33]. As an importance, the waste characteristics for generation rate and composition have been researched to assist the decision maker's design environmental model for waste policies to give more appropriate solutions [34].

The following Section of the dissertation consists of three papers. The first paper discussed is the "Study of a molten carbonate fuel cell combined heat, hydrogen and power system: energy analysis". In this topic, discusses the design of a CHHP system for the Missouri University of Science and Technology (Missouri S&T) campus using local resources. The CHHP system provides electricity to power the campus, thermal energy for heating the anaerobic digester, and hydrogen for transportation, back-up power and other needs. Energy savings and environmental analysis was also conducted to evaluate the effect of the CHHP system on energy consumption and the environment. The CHHP system is expected to reduce energy consumption, fossil fuel usage, and GHG emissions at the Missouri S&T campus.

The second paper investigates energy recovery and power generation from alternative energy source. Due to that the government spent a lot of money to transfer water from south to north of Libya. This makes the power plants the largest energy users in the country. Furthermore, the MSW management should have a well-organized collection process, the system is limited by the high quantity of waste generated per capita. The primary purpose of this study is to discuss the design of the Rankin steam cycle for the power generation (PG) and combined heat power (CHP).

The third paper is development of a drop-in hydrogen fueling Station. To design a hydrogen fueling module that fulfills the requirements of low-cost, easy permitting, low-maintenance, mass-production, and transportability in order to create a model for a reliable, convenient and reasonably priced refueling experience for all hydrogen fuel cell vehicle customers. The effect of the location and availability of utilities, the closeness to residential area, unintended safety concerns, people outlook towards hydrogen, etc. The proposed design of a drop-in station mainly considers only off-the-shelf items. The modular design approach, with the off-the-shelf items allows for a design with the capability of mass production, and ease in transport and integration. The design provides necessary sensors, isolation valves and redundancies, in line with the present day standards and regulations.

PAPER

I. Study of a molten carbonate fuel cell combined heat, hydrogen and power system: Energy analysis

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ABSTRACT

Countries around the world are trying to use alternative fuels and renewable energy to reduce the energy consumption and greenhouse gas emissions. Biogas contains Methane is considered a potential source of clean renewable energy. This paper discusses the design of a combined heat, hydrogen and power system, which generated by Methane with use of fuel cell, for the campus of Missouri University of Science and Technology located in Rolla, Missouri, USA. An energy flow and resource availability study was performed to identify sustainable type and source of feedstock needed to run the fuel cell at its maximum capacity. FuelCell Energy's DFC1500 unit (a molten carbonate fuel cell) was selected as the fuel cell for the tri-generation (heat, hydrogen and electric power) system. This tri-generation system provides electric power to the campus, thermal energy for heating the anaerobic digester, and hydrogen for transportation, back-up power and other applications on the campus. In conclusion, the combined heat, hydrogen and power system reduce fossil fuel usage, and greenhouse gas emissions at the university campus.

Keywords: Hydrogen garage; a molten carbonate; Renewable energy; Fuel cell systems; Tri-generation; Biogas; Energy saving;

1. Introduction

Biogas contains Methane is considered a potential source of clean renewable energy. Treated biogas can be used to generate Combined Heat, Hydrogen and Power (CHHP) using a molten carbonate fuel cell. The biogas is produced by anaerobic digestion of waste water, organic, agricultural, and industrial. The paper investigates the use of a CHHP system at Missouri University of Science and Technology (Missouri S&T) campus in Rolla, Missouri USA. The power generated by the CHHP system is used at various locations on the campus to reduce the overall electric power consumption and minimize air pollution to benefit community health [1-3].

In addition, CHHP system has higher efficiency than other distributed generation plants of similar capacity [4-5]. The hydrogen generated is used to power different applications on the university campus including personal transportation, backup power, portable power, and mobility/utility applications. Locally available feedstocks near the Missouri S&T campus that can be used for biogas production were identified [6-9]. An energy flow and resource availability study was performed to identify the type and source of feedstock required to continuously run the CHHP system to produce maximum capacity of electricity, heat recovery and hydrogen [10].

2. Case study background

The Missouri S&T campus is a relatively small campus with 284 acres (1.15 km²) and approximately 6,500 students on campus. It is located in the small rural city of Rolla,

Missouri with a population of 19,500 midway between the larger cities of St. Louis and Springfield, Missouri along Interstate-44. The university is one of the City of Rolla's largest electric power consumers with a peak demand of 6.36 MWe and annual electric energy consumption of 2.55×10^6 kWh/yr. Currently, electrical power for the university campus is purchased from Rolla Municipal Utilities (RMU) and distributed from the substation and switchgear located at the campus power plant. In addition, the university thermal power plant generates electricity with a back pressure steam turbine, accounting for an additional 10% of electricity. The power plant, built in 1945, is fueled by coal and wood chips and provides steam to the university campus for space heating, chilled water via absorption chillers and back pressure steam turbines. The research presented in this paper was performed as part of the 2012 Hydrogen Student Design Contest. The contest rules specified the use of a FuelCell Energy fuel cell and biogas with 60% methane and 40% carbon dioxide concentration [11].

3. Analysis procedure

3.1. Feedstock source for energy conversions

Feedstock, except waste water, will be stored on campus at the feedstock storage facility (Facility A) and will undergo anaerobic digestion at this location; Figure 1 shows the type and amount of feedstock that is available daily at Facility A. The estimated methane production from the feedstock at Facility A is illustrated in Figure 2. Facility B receives $14,320 \text{ m}^3$ of waste water per day and the estimated methane production from it is $20.5 \text{ m}^3/\text{h}$. It is assumed that the biogas produced from the digester will contain a minimum of 60% methane and the PSA unit has a 90% methane recovery rate [12-14].

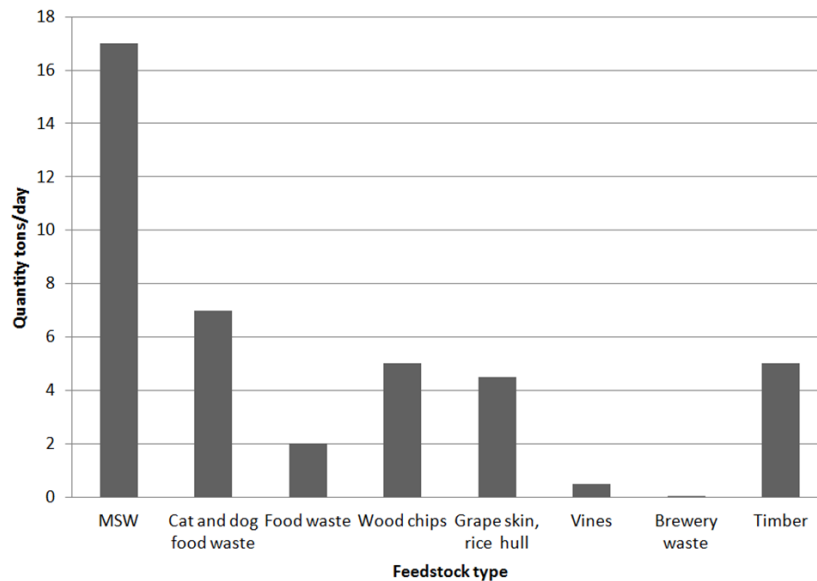


Fig. 1. Daily quantity of locally available feedstock for Facility A.

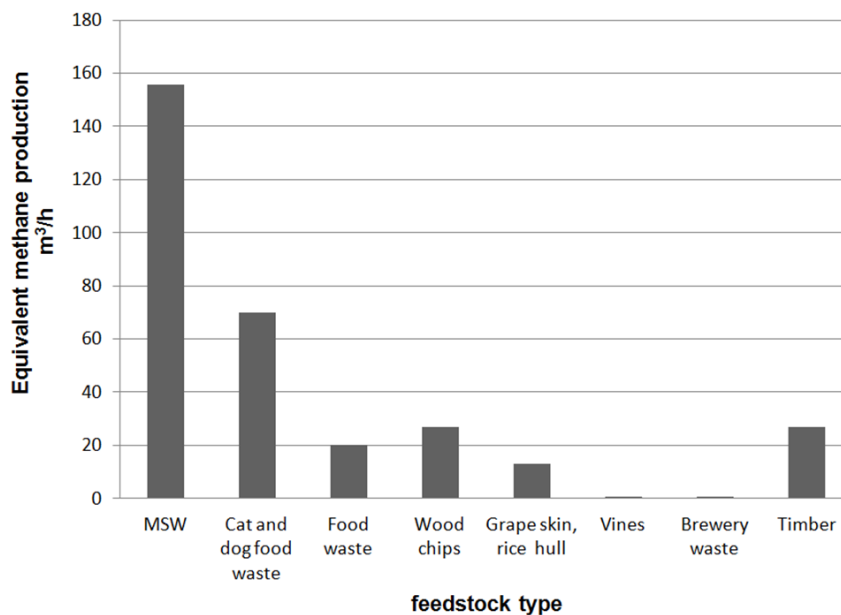


Fig. 2. Estimated methane production from Facility A.

The fuel requirement of the DFC1500TM unit is 307 m³/h of methane with a heat content of 156 MJ/m³. The strategy is to provide at least 80% renewable fuel to the CHHP

plants. The equivalent methane production from feedstock at Facility A is estimated to be 314 m³/h after biogas treatment. However, wood chips and timber were not selected as feedstock due to its slow digestion rate. Hence, the anticipated methane production after biogas treatment at Facility A is 260 m³/h with a heat content of 156 MJ/m³. Consequently, a DFC1500TM unit was selected for the CHHP system for which local resources can provide 91% of the fuel requirements. The daily unmet fuel need will be supplied by natural gas purchased from the local utility company. Since the methane production at Facility B is low, no CHHP plant will be installed at this facility. Figure 3 describes the feedstock to energy conversion process. The heat energy available for recovery from the DFC1500TM unit working in the CHHP mode is relatively lower than the DFC1500TM unit working in the CHP mode due to the losses associated with the hydrogen recovery [15]. Heat is recovered from the fuel cell exhaust gas using an air to water heat exchanger and will be transported to various locations as hot water. The electric power generated by the fuel cells will be the primarily power source for the future green hotel and will also be distributed to the university campus.

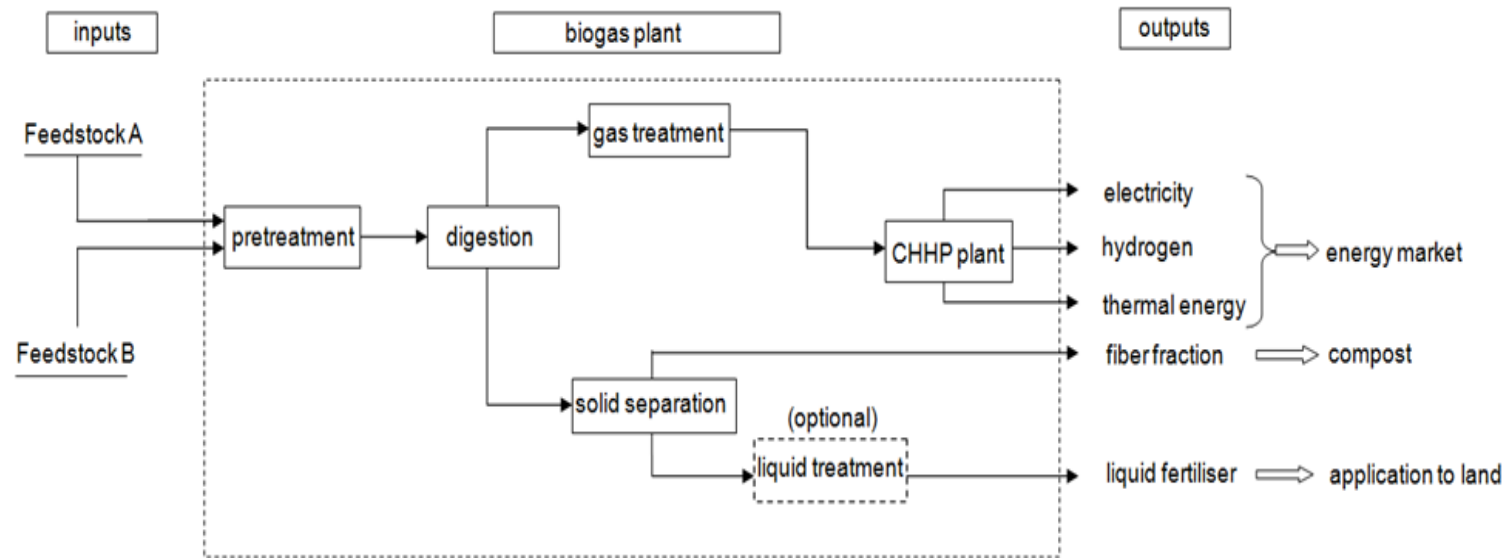


Fig. 3. Simplified flow diagram of a generic anaerobic digestion plant based of organic feedstocks.

3.2. Energy end-uses on the university campus from CHHP system

Different uses for the electric, thermal and hydrogen energy from the DFC1500TM Fuel cell were identified. A 65% fuel utilization rate for electricity production and 35% for hydrogen production was used while making the calculations for electric, thermal, and hydrogen output from the CHHP system.

Electricity power output of the DFC1500TM unit operating in the simple cycle CHP mode is 1.4 MWe [16]. This corresponds to the net power after providing the parasitic loads for its Mechanical Balance of the Plant (MBOP) and energy loss in the Electrical Balance of the Plant (E-BOP). Based on the power requirements of these components, the net power output from the CHHP system was estimated to be 1.1 MWe. The total electric power requirement of different equipment used in the design is estimated to be approximately 280 kWe. Figure 4 illustrate the percentage daily energy consumption for equipment. The total net energy production from the CHHP system is 26.4×10^3 kWh per day and the energy demand for on-site use is 4,548 kWh per day. Hence, the CHHP system will be able to provide 22×10^3 kWh per day to the university campus. This corresponds to 27% of the whole campus electricity requirement.

The thermal energy available for heat recovery was calculated based on the cathode exhaust gas composition in equation (1). The temperature difference of the input and output temperature of the heat recovery system is approximately 320 K.

$$Q = m \times CP (\Delta T) \quad (1)$$

Where: m, CP and ΔT are the mass flow rate of the gas (kg/h), the specific heat of the gas kJ/kgK) and the change in temperature of the gas (K), respectively. (The thermal energy flow rate (MJ/h) for H₂, CO₂, O₂, N₂ and total are 13.1, 53.4, 45.2, 732.8 and 844.5,

respectively. In addition, the total thermal load of the system is 1,719 MJ/h, hygienization unit is 129.4 MJ/h and anaerobic digester is 1,589 MJ/h. The mass of the feedstock and digester sludge that need to be heated are 27×10^3 kg/day and 9×10^6 kg/day, respectively.

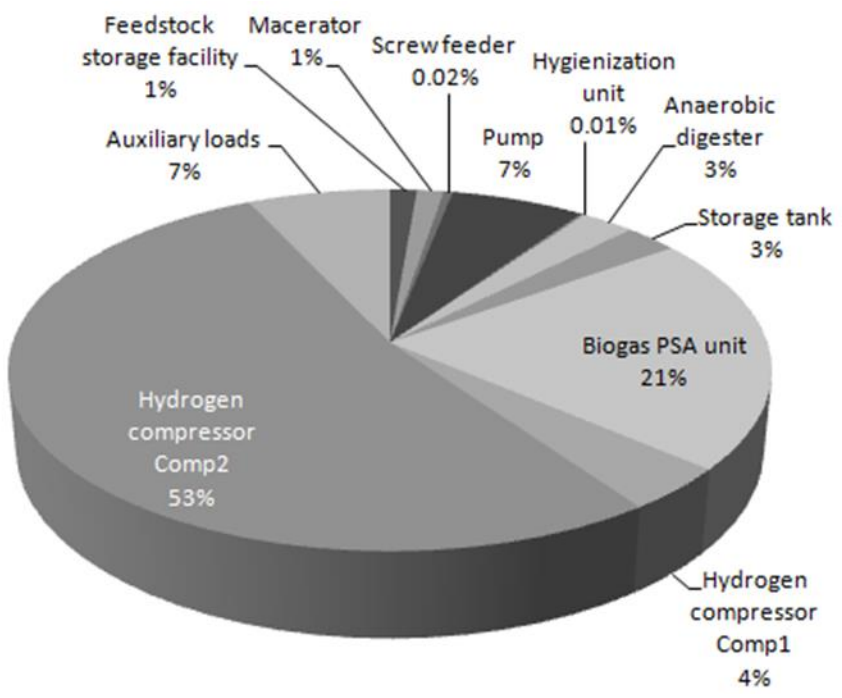


Fig. 4. Percentage daily range energy consumption for equipment.

The temperature of feedstock was assumed to be 20°C. The digester is heated to 40°C during its initial fill and is assumed to lose 1°C on average every hour due to environmental losses. The different applications usage per day in personal transportation, Mobility applications, Backup power, Portable power and other are 56, 16, 29, 17, 5 and 123 kg/day as a total, respectively.

3.3. Energy saving and environmental analysis

The analysis highlights the energy savings following the use of local organic feedstock. The formulas used in this section are from ‘Energy Savings and Environmental Analysis Guidelines’ [17].

The total energy savings can be estimated by the following equation

$$FS = FT + FG + FH - FCHHP - FF \quad (2)$$

Where, FS, FT, FG, FH, FCHHP and FF represent the total fuel savings, fuel use from avoided onsite thermal production, fuel use from avoided purchased grid electricity, fuel use from avoided energy services provided by hydrogen, fuel use by the CHHP system, and fuel use by the feedstock transportation systems, respectively.

The DFC1500TM unit requires 285.8 m³/h at 156 MJ/m³. The feedstock can supply a total of 260 m³/h of methane at 156 MJ/m³ (extracted from the biogas), 90.7% of the total demand of the system. The remaining 9.3% 26.6 m³/h at 155,867 kJ/m³ will be supplied through natural gas. The input fuel energy content for this architecture can be calculated

$$(V_B \times v_B \times E_B + V_N \times v_N \times E_N) / 106 = 8.8 \times 10^6 \text{ kJ/h} \quad (3)$$

Where, V, v, and E represent the volume fraction, volumetric flow rate in standard cubic meter per hour (m³/h), and the energy content in kJ/m³, respectively. The subscripts B and N identify biogas and natural gas, respectively. The entire system output will be used by the university that has a minimum demand of 25 MWe. Therefore,

$$FLOE = TAOS / CS_{max} = 8,760 \text{ h/yr} \quad (4)$$

Thus, the CHHP system fuel consumption can be estimated as,

$$FCHHP = FIR \times FLOE = 77.6 \times 10^{12} \text{ kJ/yr} \quad (5)$$

Where, FLOE, TAOS, CS_{max} and FIR represent the Equivalent full load operating hrs,

Total annual output by the system, Maximum capacity of the system and Fuel Input Rate, respectively.

3.4 Fuel consumption in transporting feedstocks

A majority of the feedstock requires transport and therefore will consume a significant amount of conventional fuel. Since the food waste will not require any type of additional transport to the university campus facility, it is not included in total fuel used for transporting feedstock, where the total is 18.42 m³ motor gasoline/year. The quantity of fuel requires is estimated upon the location of resource and the frequency of pick-ups. Considering the energy content of motor gasoline as 29.6 GJ/L, the fuel used for transporting feed stock will be,

$$FF = 670 \times 10^9 \text{ kJ/yr.}$$

From the Section 3.1, the DFC1500TM generates 1.4 MWe and the total parasitic loads in the system are approximately 580 kWe including the losses from the CHHP system. Therefore, the net electrical output per year can be given as,

$$E_{\text{Onet}} (\text{kWh}) \times E_{\text{OG}} (\text{kWh}) - \sum PL (\text{kWh}) = 7.18 \times 10^6 \text{ kWh} \quad (6)$$

Where, E_{Onet} , E_{OG} and PL are the Net Electrical Output, Gross Electrical Output, and Parasitic Loads respectively.

The total demand of the university campus is 35×10^6 kWh per year. Hence the CHHP system will supply 27% of electrical consumption. Considering the eastern grid transmission losses,

$$ACSE = E_{\text{OOnet}} / (1 - T\&DLF) = 10.49 \times 10^6 \text{ kWh} \quad (7)$$

Where, $ACSE$, E_{OOnet} and $T\&DLF$ are the Avoided Central Station Electricity, Net

Electricity Output onsite, and T&D Loss factor respectively. Considering the Southeastern Electric Reliability Council (SERC) Midwest sub region, the fuel avoided due to the savings of central station electricity can be estimated as,

$$AFCS = (ACSE \times AFHR) / 10^6 = 116 \times 10^9 \text{ kJ/yr} \quad (8)$$

Where, AFCS and AFHR are the Avoided Fuel Central Station and Average Fossil Heat Rate. The thermal energy recovered from the DFC1500TM will be used within the facility itself as in Section 3.2 Hence,

$$AFTH = 7.4 \times 10^{12} \text{ kJ/yr} \quad (9)$$

Where, AFTH is Avoided Fuel Thermal. As mentioned in Section 3.2, a total of 123 kg of hydrogen will be used per day to displace conventional fuel. The fuel type displaced, amount of energy, and amount of fuel displaced by hydrogen is identified and tabulated in Table 1. For the application that involves a savings in the electricity, the fuel avoided at the central station is estimated, for others, the conventional fuel avoided for each application, due to the hydrogen used, can be calculated by following equation:

$$AFH = CHHPH C \times HCR \times HCOCF / DCFCR \quad (10)$$

Where, AFH, CHHPH C, HCR, HCOCF and DCFCR are the Avoided Fuel Hydrogen, CHHP Hydrogen Consumption, Hydrogen Consumption Rate, Heat Content of Conventional Fuel and Displaced Conventional Fuel Consumption Rate, respectively.

Therefore, the avoided fuel due to hydrogen usage,

$$AFH = 1.72 \times 10^{12} \text{ kJ/yr} \quad (11)$$

By using equation (2) the total energy savings is 1.71×10^{12} kJ/yr, and by substituting in equation (3) the input fuel energy content for this architecture can be calculated as 8.8×10^6 kJ/h.

Table 1
Avoided conventional fuel details.

| No. | Application | Fuel displaced | Energy services provided by utilizing hydrogen (per year) | Amount of conventional fuel avoided (TJ/yr) |
|-----|---|-----------------------------|---|---|
| 1 | Fuel cell forklifts | diesel | 630 MWh | 73.6 |
| 2 | Backup power UPS | diesel | 210 MWh | 588 |
| 3 | H ₂ blended diesel generator | diesel | - | 563 |
| 4 | Handheld fuel cell charger | central station electricity | 331 MWh | 3.80 |
| 5 | Portable power | central station electricity | | |
| 6 | APU for AC unit in electric bus | diesel | 548 MWh | 94.0 |
| 7 | Fuel cell three-wheeler | gasoline | 7343 km | 270 |
| 8 | Fuel cell scooter | gasoline | 29,371 km | 85.5 |
| 9 | Retrofitted electric bike | none | 5.50 MWh | 0.00 |
| 10 | Retrofitted Segway | central station electricity | 408 MWh | 4.70 |
| 11 | Fuel cell utility vehicle | gasoline | 841 MWh | 25.0 |
| 12 | Fuel cell lawn mower | gasoline | 383 MWh | 12.0 |

The environmental impact of the proposed design is investigated through the reduction of the carbon dioxide emissions, which can be estimated by the following relationship:

$$ORCO_2 = (\sum k) \times (AFH) \times (ER_{netCO_2}) \quad (12)$$

Where, $ORCO_2$ and ER_{netCO_2} are the Overall CO₂ Reduction and Net CO₂ Emissions Rate. Also, $k = -1$ for fuel consumed and 1 for fuel avoided, which includes the CHHP fuel

consumption, fuel consumption for feed stock transport, avoided central station fuel, avoided thermal fuel, and avoided fuel due to hydrogen. Thus, overall CO₂ reduction, be 88,426 tons/yr.

In addition to the mitigation in the CO₂ emissions, the land required to store the organic wastes if not used otherwise, will be an added advantage. This can be estimated through the amount of solid waste digested. As mentioned in the technical design section, the digester will have a 50% solid reduction, alleviating 5,475 tons/yr of solid waste disposal.

4. Conclusion

This article discusses the design of a CHHP system for the Missouri S&T campus using local resources. The CHHP system provides electricity to power the university campus, thermal energy for heating the anaerobic digester, and hydrogen for transportation, back-up power and other needs. Energy savings and environmental analysis was conducted to evaluate the effect of the CHHP system on energy consumption and the environment. The CHHP system will be able to provide approximately 22,000 kWh which is 27% of the university campus' electricity need. In addition, 650 kg/day of hydrogen will be produced. The design will have an overall carbon dioxide reduction of 88,426 tons/yr if it is implemented. In conclusion, the CHHP system will reduce energy consumption, fossil fuel usage, and GHG emissions at the Missouri S&T campus.

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II. Study of energy recovery and power generation from alternative energy source

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ABSTRACT

The Energy requirement pattern of world is growing up and developing technology. The available sources, while exhausting and not friendly to the environment, it is highly used. Looking at partial supply and different option of environment problems associated with usage, renewable energy sources are getting attention. MSW (Municipal solid waste) composition data had been collected from 1997 to 2009, in Benghazi Libya, to evaluate the waste enthalpy. An incinerator with capacity of 43,761 kg/h was confirmed to burn all the quantity of waste generated by the city through the next 15 years. Initial study was performed to investigate energy flow and resource availability to insure sustainable MSW required by the incinerator to work at its maximum capacity during the designated period. The primary purpose of the paper is to discuss the design of Rankin steam cycle for the generation of both power (PG) and combined heat power (CHP). In the power generation case, the system was found to be able to generate electrical power of 14.33 MW. Including the combined heat power case, the results showed that the system was able to produce 6.8 million m³/year of desalinated water and generate 11.33 MW of electricity. In conclusion, the CHP designed system has the greatest potential to maximize energy saving, due to the optimal combination of heat production and electricity generation.

Keywords: Renewable energy; CHP plant; Co-generation; Alternative energy source; Energy saving.

1. Introduction

MSW (Municipal solid waste) contains methane is considered a potential source of clean renewable energy. Studies of energy and waste management is, deserve special attention, due to the constraints arising from limited availability of land, resources and pollution [1, 2].

Today, the world's population generates enormous amount of waste. Whether living in industrialized countries or developing countries, in big or in small cities, or whether being rich or poor, all people produce waste, for decades, industrial countries (ICs) have lived beyond these resources. Yesterday's belief that all resources were eternal has now changed. Waste minimization is a key concept in ICs. The amount of waste produced is dependent on the country, type of urban district, population, city size, culture, style of life and of course income. Selective sorting from MSW (municipal solid waste) or recycling and recovering materials is generally a difficult task in small isolated systems. Moreover, the alternative energy sources and the price of primary energy transportation are very expensive due to limited markets there. Consequently, the policies are recommended to use of local energy sources, to be exact incineration of MSW with energy recovery and carbon dioxide emission mitigation [3].

Thermal technology has been applied for a long time to shrink the volume of MSW. In addition, to recovery the incineration of energy, to generate heat and/or electricity as a main objective of an incineration plant is decreasing of MSW landfill area [4]. The energy recovery is working out for sustainability of energy with the optimum costs as fundamentals on it. Therefore, it should not compare with the energy generation from fossil fuels. The air pollution is one of the significant sides to the MSW incineration project. In

fact, the world can reduce the methane emission from landfills and fossil fuels as a result of using energy recovery [5]. The amount of energy recovery as achieved depended on MSW ratio of biogenic to fossil carbon and on the energy transformation efficiency. The MSW has relationship with a human activity and renewable resource, it is a potential source of significant materials and energy [6]. As an importance, the waste characteristics for generation rate and composition have been researched to assist the decision maker's design environmental model for waste policies for more appropriate technological solutions [7].

This study aimed to discuss the benefits of MSW incineration with energy recovery possibly will bring to big city, Benghazi, Libya. This study determines the MSW incineration as an alternative source of energy for power generation. First of all, the waste components were estimated and its low heat value determined, to evaluate the total heat potential. Second, the analysis of the incineration process was carried out, to appraise the potential of the energy recovered for thermal water treatment and electricity generation. Technologies to convert biomass to energy come under two categories [7]:

1. Biological process:

[a] Anaerobic digestion

[b] Fermentation

2. Thermochemical process:

[a] Combustion

[b] Pyrolysis

[c] Gasification

[d] Liquefaction.

2. Case study background

The MSW is management problems that are made worse by its specific distinctiveness. In contrast, those same extreme characteristics put together Benghazi for the most part interesting case study. In nature, Benghazi is located in the north-eastern of Libya at coordinates (32°07'N 20°04'E) with an area of 314 km², it is on the Mediterranean Sea at Gulf of Sidra in the north of Africa. Benghazi is the second largest city in Libya, dominating the eastern Cyrenaica region, and is the capital of the district of Benghazi. (See Figure 1(a)& (b). Mild winters (5-18°C) and dry, hot summers (23-36°C), typical of the Mediterranean climate, define the weather in Benghazi-Libya [8].



Fig. 1. (a) Geographical location of Benghazi Libya [8]. (b) Zone location of Benghazi Libya [9].

Source: Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels.

According to the Libya National Statistics Office 2009 projections, the Benghazi has 622,847 inhabitants, leading to the highest population density in the other Libyan cities, 2,000 inhabitants per square kilometer. Electric energy is generated by two power plants, fueled by imported fossil fuels and natural gas. As a significant, the power plant stations

have a high effect in the global carbon dioxide emissions and in the economy. Economy raise electricity consumption, mainly through the use of air conditioning systems and electrical heating appliances, while there is no central heating system; it is most important key for the grid overload. At this time, the government plans to enhance the renewable sources part of the energy combination, but it is highly restricted by a number of factors. On the other hand, even the off-shore projects face environmental restriction problems. Water supply in Benghazi-Libya is strongly dependent on south of Libya, as rainfall is rather low, approximately 400 mm/year [9]. Due to that the government spent a lot of money to transfer water from south to north of Libya. This makes the power plants the largest energy users in the country. Furthermore, the MSW management should be having a well-organized collection process, the system is limited by the high quantity of waste generated per capita. The average amount of MSW generated in Benghazi was between the ranges 0.95 kg / person /day, which is almost equal to the national average (1.1 kg per person per day) [9]. Indeed, Benghazi has close the same amount of waste collected per capita/day as the some Libyan cities and some of world cities instances; Bani Walid City (Libya), Tripoli City (Libya), Penang State (Malaysia), Tehran (Iran), Santiago de Cuba (Cuba), Beijing & Shenzhen (China), Gümüşhane (Turkey) the amount of waste collected per capita/day for the cities are 0.89, 1, 0.9–1.1, 0.88, 0.86, 1.21, and 1, respectively [10].

There are many cities in other countries produce lower amounts of MSW per capita than Benghazi. The facts up to date Benghazi Libya government projects to make an incineration plant forced this study, based on current MSW data as well as thermodynamic and combustion idea on incineration with energy recovery. Case study demonstrates the combination of water resource management with efficient use of local MSW resources.

3. Analysis procedure

The flow chart shown in Figure 2 illustrates the procedure of MSW generation and management chain of a city waste. Also, the flow chart showed the procedure from the MSW analysis to the energy analysis. It is clear from the scheme that it is necessary to know the average Benghazi-Libya MSW components one by one to distinction the efficiency of waste separation as a group. In addition, those components are required to study the incineration process, for that it is used as an input in the heat recovery calculation.

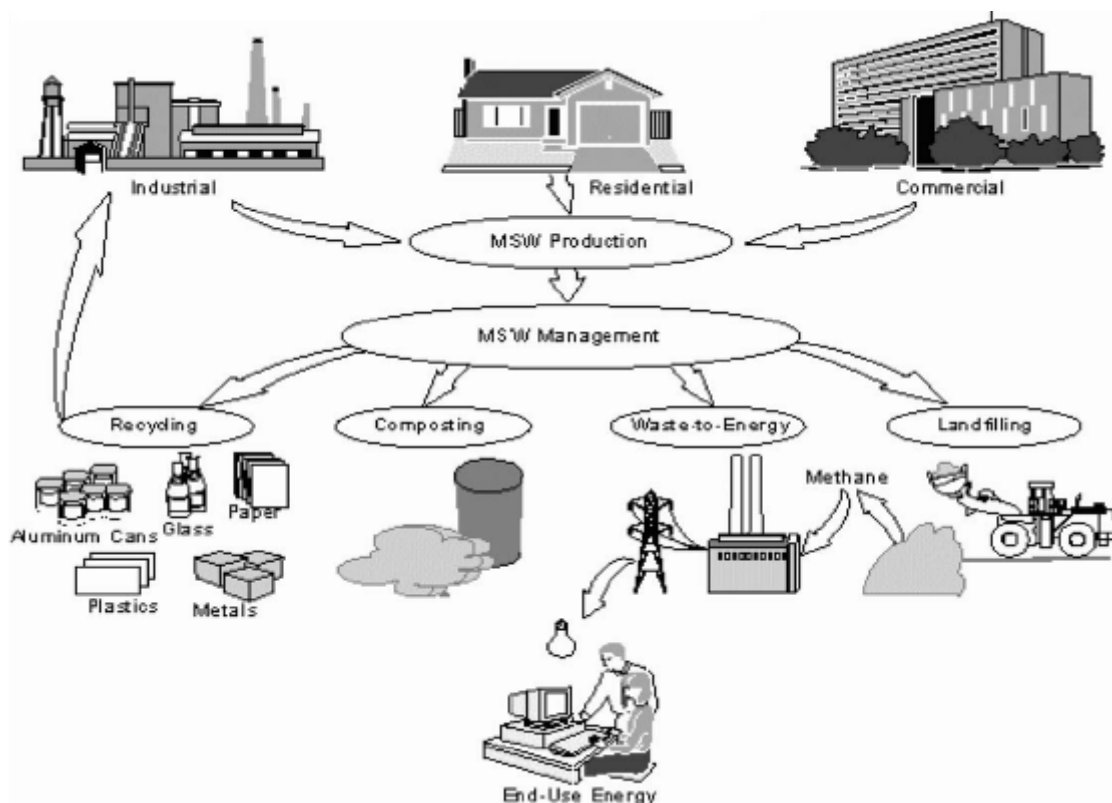


Fig. 2. MSW generation and management chain [7].

3.1 MSW analysis

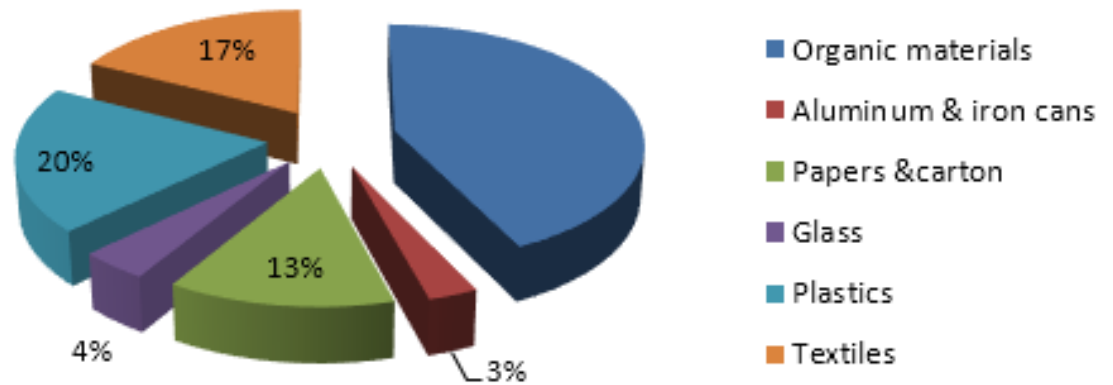
The Benghazi-Libya MSW analysis includes data from household, hotels and restaurants waste, as well as commercial and industrial waste. The data was collected from

Libyan Authority Statistics Office (LASO) 2006 surveys. The waste from the commercial and industrial streams was determined using literature data on the composition of the same streams in similar countries, like Bani Walid City (Libya), Tripoli City (Libya), Penang State (Malaysia), Tehran (Iran), Santiago de Cuba (Cuba), Beijing & Shenzhen (China) and Gumuşhane (Turkey) [10]. Figure 3 (a) illustrates the Benghazi-Libya MSW consists of. Moreover, the final MSW composition determinant about 85% of the total waste generated between 2003 and 2006 from household solid waste [9]. The largest MSW fraction in the survey discovered is organic waste (food) as illustrated in Figure 3 (b) [9].

The forecast of the waste to be generated in future years is important to establish the capacity of any incineration plant. Since, no studies did forecasting to progression of the Benghazi-Libya MSW. In other hand, the quantity of waste generated in 2010 it was 200×10^6 kg. Therefore, the future MSW generation could be predicted by using that data. The yearly operation time of the incinerator based on values supplied by the energy plant agency was projected to be 8000 h. In view of the 2010 MSW data, this leads to a 25,000 kg/h capacity. For an unexpected variety of capacity add 5% from the amount of capacity for safety coverage [11], the amount of MSW burned become 26,250 kg/h. Figure 3 (b) shown the historical MSW data generation between 1997 and 2009.

The last idea was established using the MSW generated to support expectations estimations. These data were taken from the Benghazi-Libya population (growth rate 3.1%) [12], the expected population peak at 1,105,555 inhabitants in 2025. The yearly MSW generation estimated gets to a in the 15 years is 383×10^6 kg, for 8000 h of operation/year. However, we can conclude that the 43,761 kg/h capacity got to use till 2025, that is, a yearly MSW capacity up to 2025 of 383×10^6 kg. This will be next calculations.

a



b

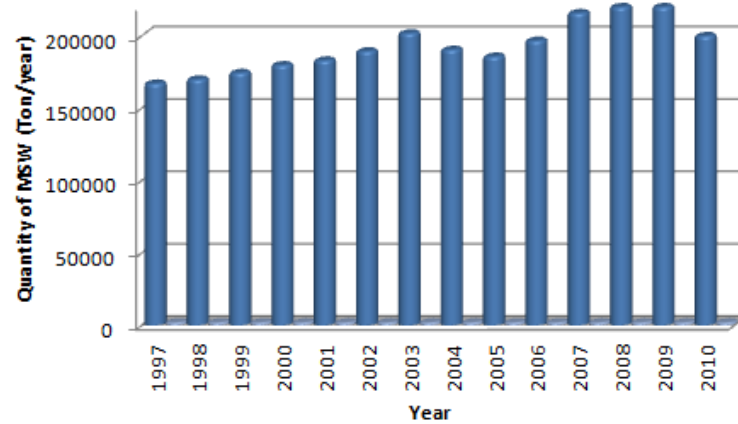


Fig. 3. (a) Physical compositions of MSW collected in Benghazi City. (b) Historical Benghazi-Libya MSW generation [12].

3.2 Incineration and energy saving

This analysis concedes to the incineration process, estimating the chimney gas and the air supplies temperature required to achieve complete burning. All data from the literature and were used on the cumulative burden imposed by the EU Directives. The mass

burn technology was considered, that is the firing technology, useful for the solids till completely burnout. Low level processing of MSW is required for this technology.

The principles of energy and mass conservation applied to the MSW characteristics were utilized to find the output volume of chimney gas generated, the heat generated, and the input air. The MSW incineration analysis considers the complete combustion of the three basic elements - sulfur (S), carbon (C) and hydrogen (H) [13]. Therefore, with elemental compositions and typical physical from the literature [14] the calculations begin by estimating the stoichiometric oxygen that feeds the combustion chamber.

In addition, the European Incineration Directive [15] in subsequent requirements of were measured the temperature of the chimney gas should be retained at the range of (850 – 1050)°C to keep away from dioxins formation at lowest [14] and exceed from highest cause by ash fusion degradation of the refractory material [6, 16] and the oxygen volumetric ratio in the chimney gas $\geq 6\%$ [13]. Now, by using the Equation (1) [13] are easy to evaluate the chimney gas volume (V_{fg} , (m^3)) and excess air (e , (m^3)). The MSW and air is not oxidized the nitrogen as a result released in the molecular form.

$$V_{fg} = V_{CO_2} + V_{H_2O} + V_{SO_2} + V_{N_2,MSW} + [0.79V_{air,theo}(1+e) + 0.21eV_{air,theo}] \quad (1)$$

Where: V_{CO_2} , V_{H_2O} , V_{SO_2} , $V_{N_2,MSW}$, $V_{air,theo}$, and $V_{air,theo}$ are volume of carbon dioxide (m^3), volume of water (m^3), volume of sulfur dioxide (m^3), nitrogen content in the MSW (m^3), and theoretical volume of air (m^3) respectively. By using Dulong suggested a formula for the calculation of the calorific of the fuel from their chemical composition as:

$$CV_{MSW} = 8075(K_C) + 2220(K_S) + 34500(K_H - K_O/8) \quad (2)$$

Where: K_C , K_S , K_H and K_O stand for percentage by mass of Carbon, Sulfur, Hydrogen and Oxygen respectively. Substituting the values of K_C , K_S , K_H and K_O from (Source: P. Chattopadhyay) will give,

$$CV_{MSW} = 8075(0.355) + 2220(0.005) + 34500(0.051 - 0.239/8)$$

$$CV_{MSW} = 3,606.5 \text{ kcal/kg}$$

$$CV_{MSW} = 11,240 \text{ kJ/kg}$$

If take the average annual temperature is 18°C in Benghazi-Libya and an incinerator mass of MSW flow capacity is 43.761×10^3 kg/h, it is doable to calculate the quantity of raw material or information processed of percentage main elements in the combustion process by mass of MSW, Total moisture (H₂O), Total carbon (C), Total hydrogen (H₂), Total oxygen (O₂), Total nitrogen (N₂), Total sulfur (S), and the Ash are %, 35.5, 5.1, 23.9, 2.4, 0.5, and 7.6, respectively.

Table 1 illustrated the oxygen required per kilogram of MSW for complete combustion. Also, estimated the total energy released from the combustion for the enthalpy variant in the calculations that 90%, the 10% left behind is heat losses [6, 16]. Moreover, the excess of theoretical air satisfies all earlier mention criteria, it can be get 52.78% even if still maximize the potential for energy recovery. The heat generated by burning of the MSW must be used in a steam cycle with the option power generation, heat or make both for a combination system. However, to prevent problems with wet steam in power or combined heat and power (CHP) plants usually use the Rankine cycle. Then, by applying second law thermodynamic and the isentropic efficiency for determine the real electrical and thermal power.

Table 1
Oxygen required per kilogram of MSW.

| Constituent | Mass fraction | Oxygen required (kg/kg MSW) |
|--------------------|----------------------|--|
| Carbon (C) | 0.355 | 0.947 |
| Hydrogen (H) | 0.051 | 0.408 |
| Sulfur (S) | 0.005 | 0.005 |
| Oxygen (O) | 0.239 | - 0.239 |
| Nitrogen (N) | 0.024 | |
| Moisture | 0.25 | |
| Ash | 0.190 | |
| Total | | 1.121 |

Furthermore, the pressure drops in the boiler and in the condenser suppose negligible and possibly will be ignored in the computations. The conditions for inlet and outlet are (4.0 MPa; 440°C), (0.01 MPa; 45.8°C), respectively of the steam condensing turbine to determine the potential for power generation. By estimate the steam mass flow rate as the first step; after that, determine the shaft work. The converter efficiency is computed when transfer mechanical energy to electrical and electric consumption power on site by using the developed formulas Zsigraiova [6] and Mastro [13].

4. Results and discussion

The result of steam flow rate, electrical power generation, turbo-alternator efficiency, Electric power consumed in site, Overall plant efficiency, net electrical power, and Mechanical energy are 67.32×10^3 kg/h, 15.72 MW, 95 %, 2.97 MW , 23.47 %, 14.33 MW, and 15.98 MW, respectively. The overall plant efficiency is calculated in order to emphasize the remaining thermal energy that is eliminated in the condenser.

The energy generated by incineration can lead to decrease the quantity of oil consumed in power plants at Benghazi-Libya. On the other hand, the heat recovered could be used for thermal desalinate seawater, by way of multi-effect distillation (MED) and decrease capital cost. MED, lesser electrical consumption and lower operation temperature compare with the multi stage flash (MSF) technology.

The thermal gain output ratio (GOR) calculation has a typical consumed rate of 12 kg of distillate per kilogram of steam was used [18]. This study regard as the minimum steam needed and the resting on GOR rate for the process of the plant, according to the quantity of water is treated if all thermal energy generated was used in a low temperature MED plant. A simple steam condensing cycle operating at 0.035 MPa and 72.68°C was considered, to get the requirements.

In addition, the current RO (reverse osmosis) plant consumed 4.77 kWh/m³ as the actual average energy for each cubic meter of water desalinated and it has become 2 kWh/m³ in this MED plant. Subsequently, the efficiency of the Benghazi electrical power plants (32%), it is achievable to determine this technology decrease oil consumption to roughly 0.75 L/m³ of treated water [19]. Furthermore, by using this system we can save amount of fuel oil as 3.86 barrels per hour, for roughly 6.5 million m³ of water desalinated

per year treated in a thermal plant. On the other hand, the steam is mainly used for power generation by high quality of energy to produce shaft work in the combined system, and the residual thermal energy is useful in heating processes like MED desalination. However, the steam extraction feeds the MED system and the sub-cooled steam remaining in the turbine is condensed, in the case of a condensing turbine. In the earlier case, the estimation of the flow rate of water treated and the electrical power go behind the same procedure refer to earlier than for the steam condensing turbine [6, 13].

The quantity of energy savings supplied by cogeneration was estimated using the so-called primary energy savings (PES) [20]. The fuel energy saved by using a CHP plant compared to the energy required running one by one the heating plant and the power plant with the aim of the cogeneration facility replaces [6]. Tables 2 sum up the design operating conditions results achieved for chimney heat recovery and power generation.

The validation for combination of the water desalination and electricity generation system can save about 22.1 barrels of fuel oil per hour if 6.8 million m³ of water were treated per year by the MED system as an alternative of the RO system. For the condensing turbine with steam extraction, these numbers will be 22.8 barrels/hour and about 4.4 million m³ per year, respectively. The MSW generated in Benghazi-Libya could provide a significant involvement to mitigate with energy problem for three scenarios in this study. To raise the electrical supply or to power the installed RO plants contribute to important principal energy savings use condensing turbine for electrical power generation [21]. Benghazi-Libya consumed approximately 5.8×10^6 m³/year, so if used in a MED plant then about 23% of the total potable water could be generated. Furthermore, this result can express limitation to installed RO system to desalinate seawater.

Table 2
Design operating conditions.

| Parameter | Value | Unit |
|---|----------|---------------------|
| MSW flow rate | 43.76 | ton/h |
| Flue gas temperature at the boiler outlet | 250 | °C |
| Efficiency of heat transfer in the boiler | 90 | % |
| Superheated steam temperature | 440 | °C |
| Superheated steam pressure | 4 | MPa |
| Condensing pressure | 10 | kPa |
| Efficiency for turbine alternator | 95 | % |
| Average annual ambient temperature | 25 | °C |
| Seawater water flow rate | 4,472.7 | m ³ /h |
| Volume of water desalinated | 15,973.8 | m ³ /day |
| Electric power consumed in the plant | 2.97 | MW |
| Electric power produced | 14.3 | MW |
| Net electric power | 11.33 | MW |

Generate electrical power and to desalinate seawater at the same time by CHP plants represent the best model. The potable water created by the thermal method can assist to get together the water demand, without raising the electrical using up, and the plant improve the Benghazi-Libya electrical energy provide.

Moreover, the installation of the condensing turbine with steam extraction is ensuring a higher electrical power production.

5. Conclusions

This article discusses to propose an alternative energy for Benghazi-Libya city by using local resources of MSW. The MSW incineration system will be built in Benghazi-Libya with an electrical power plant, and seawater desalination system. On the other hand, the CHP plant provides the energy necessary to desalinate all the water usage in that year or electricity to power the city. Energy savings analysis was conducted to evaluate the effect of the CHP system on energy consumption. Consequently, the generated of the energy by the MSW burning can be a decrease of the fuel oil energy, even if the fuel oil consumption is too small. The CHP plant is the best method to save fuel. The MED plant can satisfy the increased water demand that occurs in Benghazi-Libya in future. To sum up, the incineration plant give Benghazi-Libya opportunity to save fossil fuel usage, raise the energy provided, and GHG emissions mitigation. CHP with back-pressure steam turbines can desalinate 15,973.8 m³/d of sea water with MED with an additional power production of 11.33 MW, and for the case, potential electric power of 14.33 MW (PG).

Acknowledgments

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III. Development of design a drop-in hydrogen fueling station

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ABSTRACT

This paper provides a design of a drop-in hydrogen fueling station. Drop-in stations are expected to be an important factor in the introduction of hydrogen fueling infrastructure. The stations not only allows a streamlined introduction of hydrogen in the vehicle fueling infrastructure, but also, acts as mini pilot plants that can allow for detailed control studies. The effect of the location and availability of utilities, the closeness to residential area, unintended safety concerns, people outlook towards hydrogen, etc. are some of the factors that can be readily studies with such drop-in stations. The proposed design of a drop-in station mainly considers off-the-shelf items and is conceptualized to be implemented at the Missouri University of Science and Technology. The modular design approach, with the off-the-shelf items allows for a design with the capability of mass production, and ease in transport and integration.

Introduction

According to the International Energy Outlook 2013, released by the U.S. Energy Information Administration (EIA), worldwide energy-related carbon dioxide emissions will rise from about 31 billion metric tons in 2010 to 36 billion metric tons in 2020. The carbon dioxide emissions will further grow to 45 billion metric tons by 2040, resulting in

a total of 46 percent increase [1]. One of the major contributors to the emissions will be in the exhaust gases released from the vehicles. Therefore, it can be said that by employing zero-carbon print vehicle fuel a significant change can be observed in the carbon-dioxide emission levels. Research in the area of alternative fuels, renewable and nonrenewable, has demonstrated its applicability in the vehicle power train section, however, in a laboratory environment. With the available research findings, and considering the need of time, steps have to be taken towards the development of a fueling infrastructure. From the available alternative fuels, hydrogen has shown tremendous potential. Hydrogen not only provides cleaner energy, but also, is easy to transport, allowing centralized production, mimicking a gasoline fueling infrastructure [2]. In order to prove the market potential of hydrogen, and test the business case, mobile drop-in units have been an ideal mode of the introduction of hydrogen fueling infrastructure. This paper provides a design of such a drop-in hydrogen fueling station.

Zerta et al. [3] emphasized the importance of hydrogen in changing the global energy landscape. While, solar and wind power solutions maybe considered as an ideal energy resource, their intermittent nature of availability does not assist in fulfilling the continuous power need. Alternatively, the power obtained from solar and wind energy solutions can be utilized to generate hydrogen, using water, through the process of electrolysis. Hydrogen being an energy carrier can be readily stored and utilized to generate electricity, as and when required. Such a flexibility of hydrogen energy, coupled with the improving fuel cell technologies, has launched hydrogen energy as an important factor in the field of alternative energy technology. Currently, most of the hydrogen is produced using natural gas, with almost all of it used at the production facility itself.

Utilizing natural gas for further production of hydrogen would, therefore, require an increase in the availability of natural gas. As an alternative researchers have been developing technologies that can utilize locally available feedstock for the production of biogas, which can then be used to produce hydrogen, heat and power with a combined heat, hydrogen and power (CHHP) units [4]. Bartels et al. [5] showed that hydrogen production from biomass is a promising option, even though the current most economical sources of hydrogen come from coal and natural gas units. The authors mention that the hydrogen production from alternative fuels, e.g. biomass, may become economically viable in the future due to the increasing feedstock costs of traditional fossil power plants, technology developments and decreasing cost of alternative energy technology. Ali and Salman [6] provide a comprehensive review of the fuel cell technologies and the current state of the art of the hydrogen energy economy. Becker et al. [7] report that the solid oxide fuel cell (SOFC) combined heat, hydrogen and power (CHHP) systems are capable of an electrical efficiency of 48.4%, and an overall efficiency of 85.2%. This is a significant improvement over the existing technology and has higher energy efficiency and lower emissions for the amount of power generated.

Although hydrogen energy has shown such good potential at the research level, its implementation at the customer end has been rather scarce. Williams and Kurani [8] discuss the commercialization of the light duty hydrogen fuel cell vehicles with plug-in/plug-out capability for mobile electricity technologies and opportunities. Even though, currently these may not be economically feasible, it can become a driver towards commercialization of alternative energy vehicle technologies. Hydrogen technologies, coupled with other renewable technologies, are an excellent candidate for alternative

energy technology deployments. More recently Hamad et al. [2] provided a design for the hydrogen energy infrastructure in the Northeastern United States. Investigations are performed on a larger scale and infrastructural timeline is presented to implement the design in the coming decade. The design, however, did not consider the cost and economic impact. In order to determine the business side of the hydrogen energy infrastructure, it is necessary to develop mini pilot plants.

This paper provides a design for a drop-in hydrogen station, which can be utilized to develop the required experience on the technical and business sides of the hydrogen energy infrastructure. The design utilizes available technology, off-the-shelf equipment, and presents a modular setup for a hydrogen fueling station. The station requires a steady supply of methane, water and electricity. These utilities can be either obtained from nearby locations or through the installation of the CHHP system, as described in Hamad et al. [4]. The station design consists of equipment, security and safety interlock details, and the final installation layout. The drop-in station is conceptualized to be utilized at the Missouri University of Science and Technology (Missouri S&T).

Site Plan and Location

The drop-in hydrogen fueling station is conceptualized to be located in the Missouri University of Science and Technology (Missouri S&T) campus. Figure 1 shows the master plan of Missouri S&T, along with the proposed site of the drop-in hydrogen fueling station marked on it. The station will be located west of the Algood-Bailey Stadium, near the tennis courts. The location has sufficient supply of natural gas, water and electricity, required for the operation of the drop-in hydrogen fueling station design presented in this

paper. Figure 2 shows the layout of the proposed design. Each component of the design is explained in the subsequent sections.



Fig. 1- Site location for the proposed drop-in hydrogen fueling station [9].

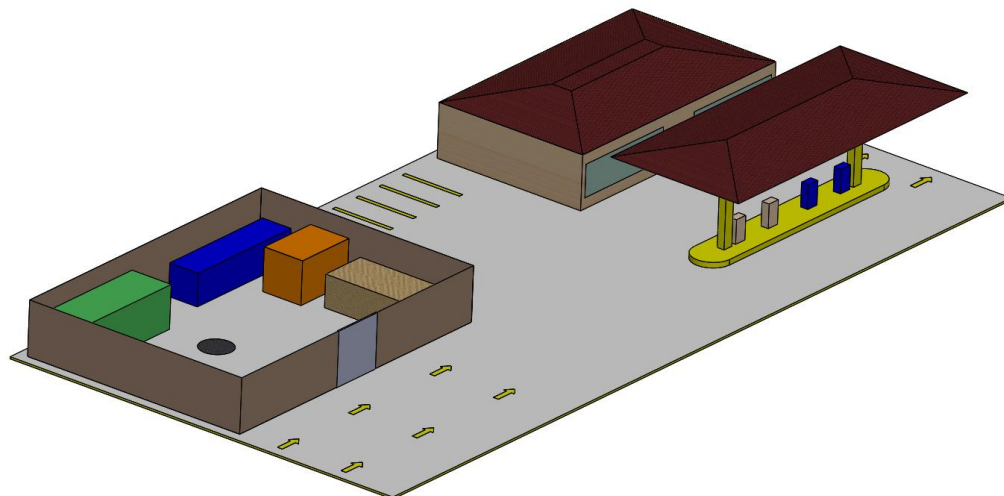


Fig. 2- Proposed drop-in hydrogen fueling station and convenience store.

Drop-in hydrogen fueling station design

Figure 3 provides the schematic of the drop-in hydrogen fuel station design. The station is designed for 100 kg/day. The design utilizes an off-the-shelf hydrogen production unit, which produces hydrogen using the steam-methane reforming technology. An integral part of this unit is a hydrogen compression and storage station. Hydrogen is compressed to 5,000 psig and stored for delivery. In order to take advantage of this feature, the design has a hydrogen dispenser that is capable of dispensing hydrogen at 5,000 psig and at 10,000 psig. A three-way valve is used to direct the hydrogen from the fuel cell to either the dispenser or to the compressor. The positive displacement compressor in the fuel station will compress hydrogen to 10,000 psig. A local control panel near the dispenser will allow an operator to manipulate the three-way valve. The station houses a HVAC unit, which helps in maintaining the surrounding temperature. Hydrogen's density is dependent on the temperature, and therefore, the HVAC unit is a very important part of the design. In addition to these basic components, the station contains adequate safety hardware. Control stations required for major components are supplied with the units itself.

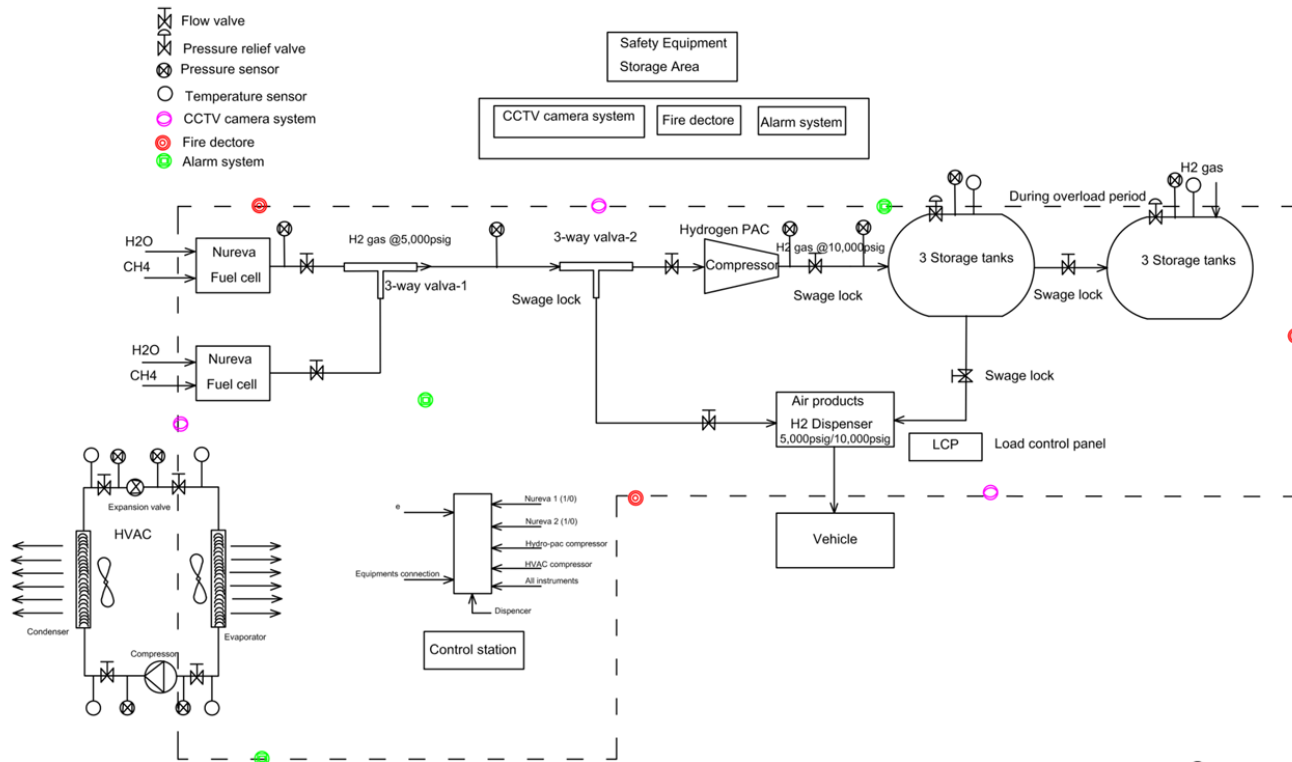


Fig. 3 - A schematic of the drop-in hydrogen fuel station design.

Hydrogen Production Evaluation

Holladay et al. [10], and Bicakova and Straka [11] provided an extensive list of hydrogen production technologies. Although, hydrogen can be produced through many approaches, steam-methane reforming is still the most suitable mode of hydrogen production at the commercial scale. Natural gas required for steam methane reforming is readily available in the US. Additionally, the recent advancements have shown that methane, a key component of natural gas, can be produced on site by performing anaerobic digestion of biomass [4]. Therefore, considering future expansion of the station, and transformation to a renewable feedstock, steam methane reforming has been considered by the authors for hydrogen production.

With this background, the authors performed an extensive search for modular steam-methane reformers (SMRs). The authors have selected Nuvera PowerTap™ for the hydrogen production. In addition to the SMR, this unit also houses preprocessing, compressing, and hydrogen storage stations. The unit requires a supply of natural gas and water to provide 50 kg of hydrogen per day, at 5,000 psig. Figure 4 shows the selected Nuvera PowerTap™ and Table 1 provides its specifications. The unit is easy to install and is supplied on a skid.

Table 1- Specifications for Nuvera PowerTap™ [6].

| Item | Specification |
|------------------------------|---------------------------------|
| Hydrogen Generation Capacity | 50 kg/day |
| Dispensing Pressure | 5,000 psig |
| Natural gas requirements | 7-14 inch water column pressure |
| Environment | Outdoor or Indoor |



Fig. 4 - Nuvera Power Tap™ fuel cell [6].

Hydrogen Compression

Nuvera's PowerTap™ hydrogen production unit houses a compression and hydrogen storage station, which allows the hydrogen output at 5,000 psig. Hydrogen gas has much lower energy density by volume than fossil-fuel based sources of energy. As a result, compression of the gas to improve its energy density is a commonplace practice. Therefore, the design incorporates a Hydro-PAC high-pressure positive displacement unit to compress hydrogen to 10,000 psig, model number C15-60FX-H2/SS-EXT FLEXI-POWER™ [13], shown in Figure 5. The compressor is also capable of supplying hydrogen

at 13,000 psig required for some higher pressure hydrogen fuel cell vehicles. Table 2 shows the specifications of the selected compressor.



Fig. 5 - An image of C15-60FX-H2/SS-EXT compressor from Hydro-PAC [13].

Table 2- Specifications for C15-60FX-H2/SS-EXT [6].

| Item | Specification |
|------------------------------|--|
| Inlet pressure & temperature | 5,000 psig & 80 deg. F |
| Discharge pressure | 10,000 psig |
| Flow rate | 400 scfm |
| Motor power | 60 HP |
| Electricity requirements | 460 V, 60 Hz, 3 phase |
| Electric protection | Class I Div. 2 |
| Control Power | 120 V, 60 Hz, 1 phase |
| Operating temperature | 50 to 100 deg. F |
| Cooling water requirement | 15 gpm at 60 to 80 deg F |
| Installation | Indoors |
| Dimensions | 122 in. long, 37 in. wide, 66 in. high |
| Weight | 8,000 lb. |

The compressor is a hydraulically driven, non-lubricated piston intensifier type machine equipped with a hydraulic power unit and a high-pressure gas intensifier. Also equipped on the compressor are full length isolation spacers to prevent hydraulic oil carryover into the process gas and stainless steel wet ends to prevent hydrogen embrittlement at high pressures. The compressor also includes a control system, explosion proof reciprocating circuit, and full-length distance pieces to prevent hydraulic oil carry over. The controls and piping system for the compressor provides automatic or manual on/off operation. If an alarm is detected the controller automatically shuts off the unit and displays an alarm fault condition. Items included are as follows:

1. NEMA 4 (IP66) electrical enclosure with motor starter, Allen Bradley PLC (Micro 820/Micrologix 1100 or equivalent), Allen Bradley C400 interface and necessary I/O.
2. Valves and piping for manual isolation, air-operated isolation manual vent and safety relief.
3. Gas after cooler.
4. Inlet and discharge pressure transducers.
5. Discharge thermocouple.
6. Inlet and discharge pressure gauges.
7. Cooling water isolation valves, flow switch and sight meter.

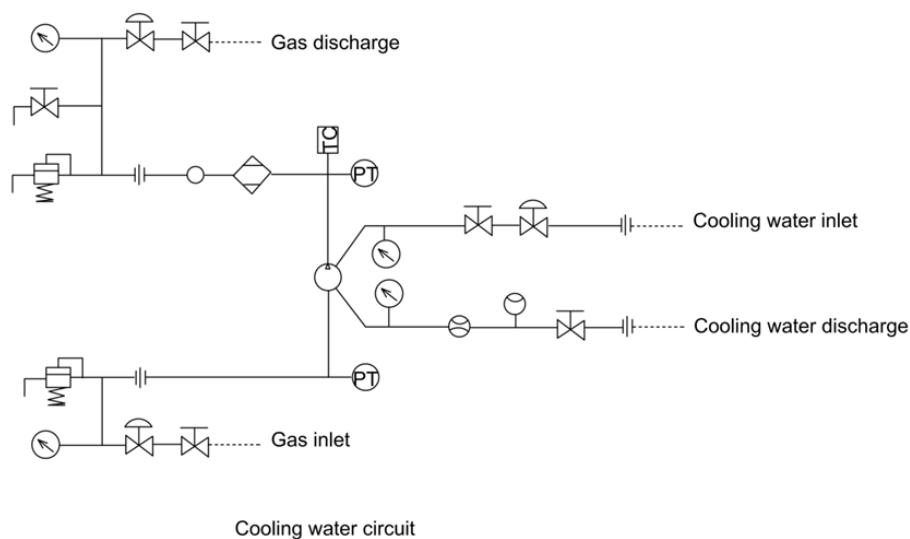


Fig. 6 - Cooling water circuit for C15-60FX-H2/SS-EXT compressor [13].

Hydrogen storage pressure vessel

Hydrogen discharge from the compressor at 10,000 psig is stored in three pressure vessels. The vessels are designed as per ASME Sec. VIII Div. III. The current design incorporates three storage pressure vessels from FIBA Technologies, Inc. Each vessel has a design pressure of 15,000 psig and is 29 ft. long and 1.33 ft. in diameter [14]. Each vessel can hold 34 kg of hydrogen. In order to meet the set demand of 100 kg/day, three such hydrogen storage vessels are considered. In order to minimize the foot print these three vessels are arranged one above the other.

Hydrogen dispensers

Air Products SmartFuel™ H70/H35 retail hydrogen dispenser [15] is selected for the customer end of the drop-in hydrogen fueling station. The dispenser provides the features similar to an existing gasoline dispenser, e.g. same look, feel and payment options, and is in compliance with SAE J2601. The dispensing equipment includes SAE certified nozzles, gas piping and valves and includes adequate safety features required to fuel high-

pressure hydrogen gas at 10,000 psig. Figure 7 shows the dispenser; Table 3 the description of various parts; and Table 4 the specifications of the dispenser. The dispenser complies with all of the industry regulations, codes and standards. Specifically, the dispenser design is in compliance with ASME B31.3, NFPA 70, NFPA 496, NFPA 497M, International Fire Code, NFPA 55, and NFPA 2.



Fig. 7- Air Products SmartFuel™ H70/H35 retail hydrogen dispenser [15].

Table 3 - Description of various parts in Figure 7 [15].

| Part No. | Description |
|-----------------|--|
| 1 | Valence with gas detection sensors for immediate leak detection |
| 2 | Enclosed and shrouded breakaway connectors |
| 3 | Reinforced polycarbonate upper door with ergonomic design to provide simple, customer-friendly user interface |
| 4 | Energy-efficient display panel with LED backlighting for clear visibility of display in all lighting conditions; all displays equipped with clear, hard-coated sacrificial lenses for increased durability and extended life |
| 5 | Debit payment system and 5.7" color LED display with on-screen training instructions for first-time users |
| 6 | Durable EPP/TDS keypad |
| 7 | Credit card reader |
| 8 | Emergency stop button and operating instructions |
| 9 | H70 and H35 unit price displays |
| 10 | Unique fueling pressure selection buttons with no moving parts for unmatched durability |
| 11 | Lower door assembly |
| 12 | RFID (radio frequency identification detector) reader for vehicle identification and communications |
| 13 | Universal metal nozzle boot—the industry's most durable |
| 14 | Protective jackets over hoses |

Table 4 - SmartFuel™ H70/H35 retail hydrogen dispenser [15].

| Item | Specification |
|-------------------------------|---|
| Dispensing Pressure | 5,000 psig and 10,000 psig |
| Compliance with SAE standards | J2600, J2601, J2719, and J2799 |
| Nominal fill quantity | 1 to 10 kg per fill |
| Complete fill accuracy | 98 % |
| Other features | Credit card and RFID payment options with store point of sale (POS) interface |

The dispenser control panel, shown in Figure 8, will allow the user to select the dispensing pressure. Based on the selection, the control sequence shown in Figure 9 (a)

will be executed. In case of any faults in the subsystems, the dispenser will be cut off, all the shut off valves will be closed, and the alarm will be activated, as shown in Figure 9 (b).

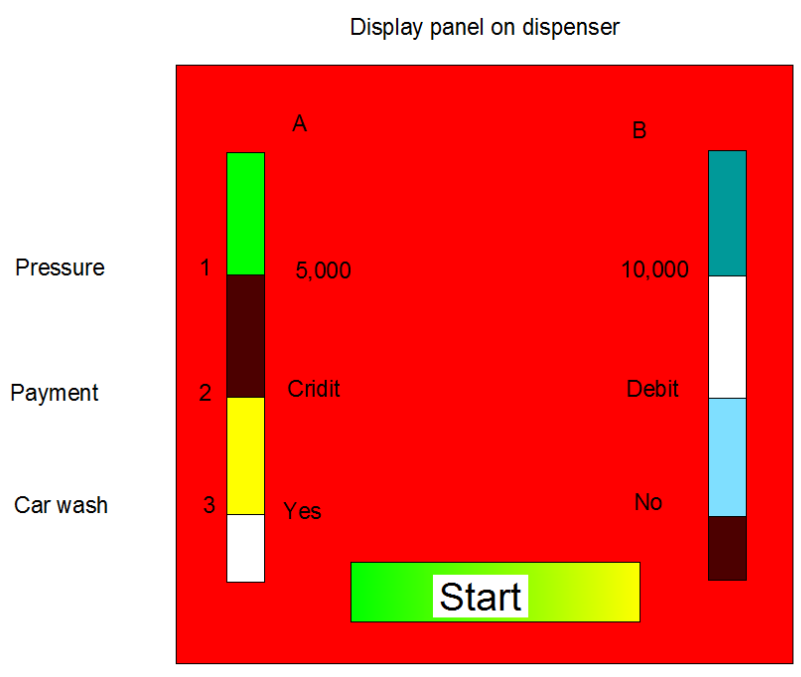


Fig. 8 - Dispenser control panel (DCP)

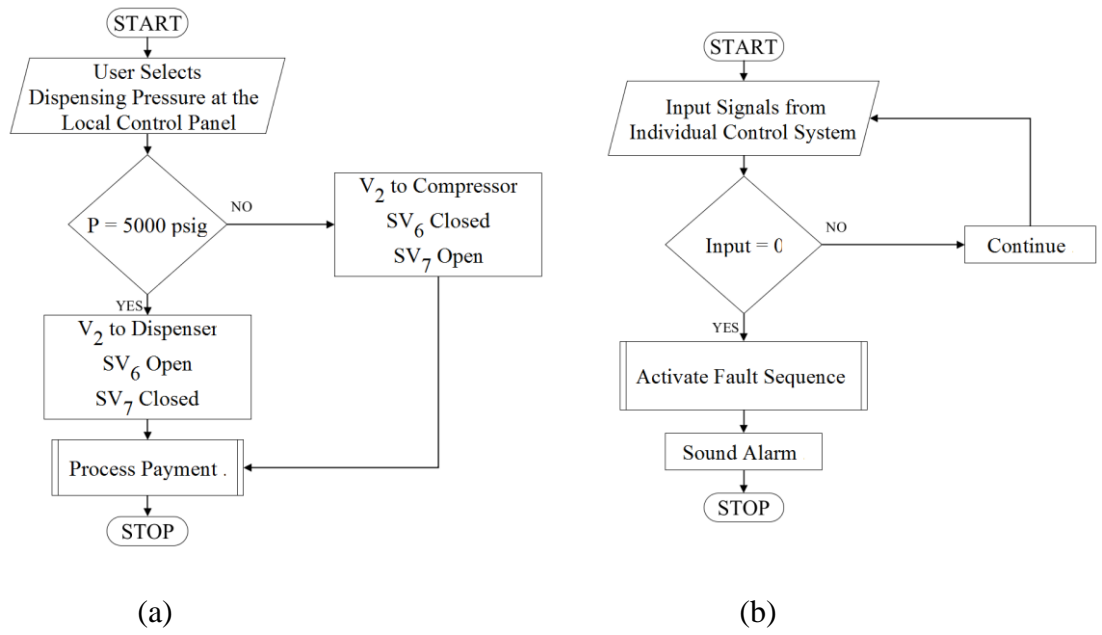


Fig. 9 - (a) Control logic in the local control panel, and (b) control logic for the drop-in fuel station control system.

Piping valves and fitting

Piping, valves and fittings form a very important group of hardware in the drop-in fuel station. SS316L is selected as the material of construction for all the components that are in contact with hydrogen. In addition, the components are selected for a design pressure of 10,000 psi. The design will utilize the piping, valves and fittings from Parker Hannifin Corporation. The three-way valve and shut-off valves will also be purchased from Parker Hannifin Corporation.

Safety equipment

Safety is of utmost importance when interacting with humans. With the hydrogen based stigma, safety becomes even more important. The design considers the following safety equipment, as shown in Figure 10.

1. Camera at hydrogen dispensing island.
2. Hydrogen detectors within the station and at the hydrogen dispensing islands.
3. Appropriate number of pressure relief valves within the station.
4. Appropriate number of shut-off valves to isolate the system in case of an accident.
5. A safety switch that will shut-off all the equipment when the door of the drop-in station is opened.
6. Fire detectors.
7. Fire suppression systems.
8. Hydrogen detection alarm and fire detection alarm.

Structural components

Because all of the sub-system will be skid mounted, the drop-in fuel station just needs the supporting structural frame. The suppliers will provide all the necessary

mounting hardware, along with the designs for the supporting structure. Structural steel A36 will be utilized as the primary material for the structure.

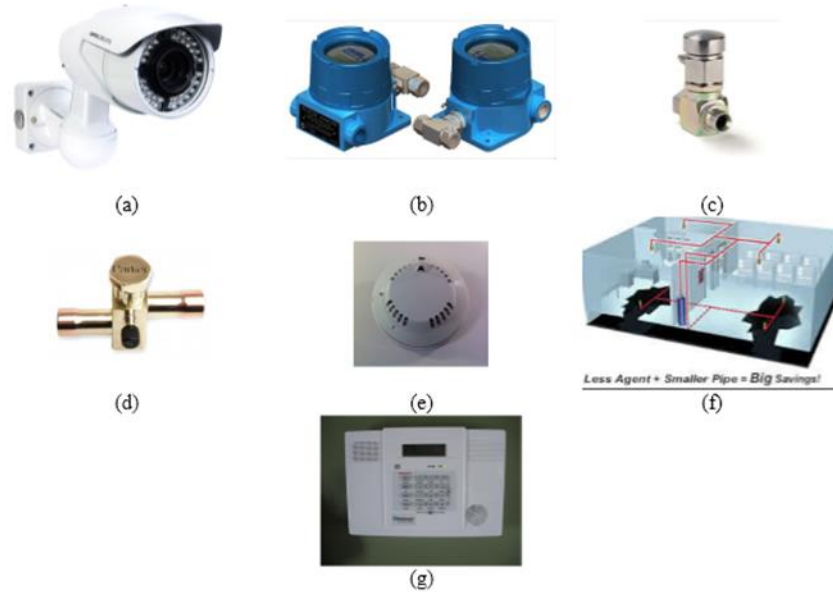


Fig. 10 - Safety equipment selected for the drop-in hydrogen fueling station: (a) CCTV camera systems by Super Circuits [16], (b) hydrogen detector from H2 Scan [17], (c) pressure relief valves from Parker Hannifin Corp. [18], (d) shut-off valves by Parker Hannifin Corp.[18]. (e) Fire detector from Bosch [19], (f) fire suppression systems from Fire Suppression Systems Inc. [20], and (g) alarm systems from Honeywell [21].

Energy saving and environmental analysis

The energy savings and environmental analysis for the system architecture is performed using the procedure provided in [22]. The analysis highlights the energy savings following the use of natural gas.

Energy saving analysis

The total energy savings can be estimated by the following equation

$$F_s = F_H - F_{NPT} - F_C - F_{HVAC} - F_{DIS} - F_{GL} \quad (1)$$

Where, $F_S, F_H, F_{NPT}, F_C, F_{HVAC}, F_{DIS}$ and F_{GL} represent total fuel savings, fuel use from avoided energy services provided by hydrogen, fuel use by the Nuvera Power Tap™ (NPT) system, Electrical Consumption for compressor, Electrical Consumption for heating ventilation air conditioning system, Electrical Consumption for dispenser and Electrical Consumption for general lighting.

a) Fuel consumption by NPT system

As mentioned in the technical design section, Missouri S&T has decided to use two Nuvera Power Tap™ units, which requires natural gas for each unit is 16.978 m³/h and delivery 50 kg of hydrogen daily. Based on the Power Tap™ Product Specifications - On-Site Generation are Electrical Consumption per kg H₂ 12 kWh and Natural Gas Consumption per kg H₂ < 0.192 MMBTU. Since, each unit Power Tap™ can generate 50 kg of hydrogen. So, it is easy to find the F_{NPT} as:

$$F_{NPT} = F_G + F_E \quad (2)$$

Where, F_G , and F_E represent the Natural Gas Consumption and Electrical Consumption for one Nuvera Power Tap™, respectively.

$$F_G = \text{mass of hydrogen per unit} \times \text{Natural Gas Consumption per kg of hydrogen} \quad (3)$$

$$F_G = 10136352 \text{ kJ}$$

$$F_E = \text{mass of hydrogen per unit} \times \text{Electrical Consumption per kg of hydrogen} \quad (4)$$

$$F_E = 50 \times 12 = 600 \text{ kWh} = 3600.5167 \text{ kJ}$$

From Eq. (2) we can get:

$$F_{NPT} = 10136352 + 3600.5167 = 10.14 \times 10^6 \text{ kJ}$$

So, this is the consumption for one unit.

$$\text{The total } F_{NPT} = 10.14 \times 10^6 \times 2 = 20.28 \times 10^6 \text{ kJ } F_{NPT} = 7.4 \times 10^9 \text{ kJ/yr}$$

b) Fuel consumption by compressor

The technical design section, Missouri S&T has decided to use High-Pressure Hydrogen FLEXI-POWER compressors, which requires hydrogen gas flow rate 24.4904 m³/hr at 350 barg and delivery 1 kg/min of hydrogen at 700 barg. Based on the FLEXI-POWER compressors Product as:

$$FLO_E = TA_{OS} / CS_{max} = 8,760 \text{ h/yr} \quad (5)$$

Where, FLO_E , TA_{OS} , CS_{max} and FI_R represent the Equivalent full load operating hrs, Total annual output by the system, Maximum capacity of the system and Fuel Input Rate, respectively. The fuel consumption for compressors system can be estimated as,

$$F_C = FI_R \times FLO_E = 0.0101 \times 10^9 \text{ kJ/yr} \quad (6)$$

c) Fuel consumption by HVAC system

The technical design section, Missouri S&T has decided to use two units Gree's DC Inverter technology; Premium efficiency and ductless mini split system which each unit has 1 RT (3.52 kW) cooling load capacity. Based on the Gree Product as:

$$\text{From eq (5), so } FLO_E = 8,760 \text{ h/yr}$$

$$F_{HVAC} = MCFI_R \times FLO_E = 0.97 \times 10^9 \text{ kJ/yr} \quad (7)$$

Where, $MCFI_R$ represent the Maximum capacity of the system and Fuel Input Rate.

d) Fuel consumption by dispenser

The hydrogen dispenser program is currently focused on providing both 350 & 700 bar (5,000 & 10,000 psig) dispensing technologies and components into the continually evolving hydrogen market. Based on the Kraus global product as:

From eq (5), so $FLO_E = 8,760$ h/yr

$$F_{DIS} = MCOFI_R \times FLO_E = 0.5 \times 10^9 \text{ kJ/yr} \quad (8)$$

Where, $MCOFI_R$ represent the Maximum capacity of the system and Fuel Input Rate.

e) Fuel consumption by general lighting system

As mentioned in previous section, the station plane area is 80 x 20 ft (148.72 m²).

The technical design section, Missouri S&T has decided to make light intensity 3.4 w/ft².

The energy services provided by the lighting can be calculated by following equation:

From eq (5), so $FLO_E = 8,760$ h/yr

$$F_{GL} = MFI_R \times FLO_E = 0.477 \times 10^9 \text{ kJ/yr} \quad (9)$$

Where, MFI_R where, $MFIR$ represent the Maximum capacity of the system and Fuel Input Rate.

f) NPT system hydrogen output and avoided fuel

As mentioned in previous section, 100 kg of hydrogen will be used per day to displace the conventional fuel. The fuel displaced by this hydrogen, the energy services provided by the hydrogen for the application that involves a savings in the fuel avoided is estimated, the conventional fuel avoided for the application, due to the hydrogen used, can be calculated by following equation:

$$AF_H = NPT_{HC} \times HCR \times HCOCF / DCFCR \quad (10)$$

Where, AF_H , NPT_{HC} , HCR , $HCOCF$ and $DCFCR$ are the Avoided Fuel Hydrogen, Nuvera Power TapTM Hydrogen Consumption, Hydrogen Consumption Rate, Heat Content of Conventional Fuel and Displaced Conventional Fuel Consumption Rate respectively.

Therefore, the avoided fuel due to hydrogen usage,

$$AF_H = F_H = 1.3 \times 10^{12} \text{ kJ/yr}$$

By using eq. (1) the total energy savings will be:

$$\begin{aligned} F_s &= F_H - F_{NPT} - F_C - F_{HVAC} - F_{DIS} - F_{GL} \\ F_s &= 1.3 \times 10^{12} - 7.4 \times 10^9 - 3.0 \times 10^9 - 0.97 \times 10^9 - 0.5 \times 10^9 - 0.477 \times 10^9 \\ &= 1.288 \times 10^{12} \text{ kJ/yr} \end{aligned}$$

Environmental analysis

The environmental impact of the proposed design is investigated through the savings in the carbon di-oxide emissions, which can be estimated by the following relationship:

$$OR_{CO_2} = (\sum k) \times (AF_H) \times (ER_{netCO_2}) \quad (11)$$

Where, OR_{CO_2} and ER_{netCO_2} are the Overall CO_2 Reduction and Net CO_2 Emissions Rate. Also, $k = -1$ for fuel consumed and 1 for fuel avoided, which includes the CHHP fuel consumption, fuel consumption for feed stock transport, avoided central station fuel, avoided thermal fuel, and avoided fuel due to hydrogen. Thus, overall CO_2 reduction, be 66,319 tons/yr.

Safety analysis

The fueling station is fully equipped with a fire suppression system and emergency warning system. The fire suppression system will coat the interior of the container in a

nonhazardous fire suppressant gel. The gel can simply be vacuumed up with no harmful effects to equipment or people after being release. The emergency warning system is equipped with multi-sensor fire detectors and hydrogen sensors. It is capable of calling local authorities and providing audible warning instruction to the public along with warning lights. A manual fire alarm pull and electrical kill switch will be located near the dispensing nozzles to manually activate fire and emergency protocols. The fuel station includes fire resistant materials to improve fire safety in addition to being completely enclosed in a steel cargo container. The interior walls of the container will be lined with fire walls constructed of Imperial[®] Gypsum Base Firecode[®] C core panels to provide a 2-hour fire rated wall in accordance with Underwriters Laboratories (UL) test number U454. The roof is outfitted with SECUROCK[®] Cement Roof Board that has a Flame Spread 0 and Smoke Developed 0 in accordance to ASTM E84 and E136. In addition, the roof will have a Haz-safe explosion relief panel in accordance with NFPA 68 to direct any explosion or gas release out through the roof and away from people and equipment (See Figure 10).

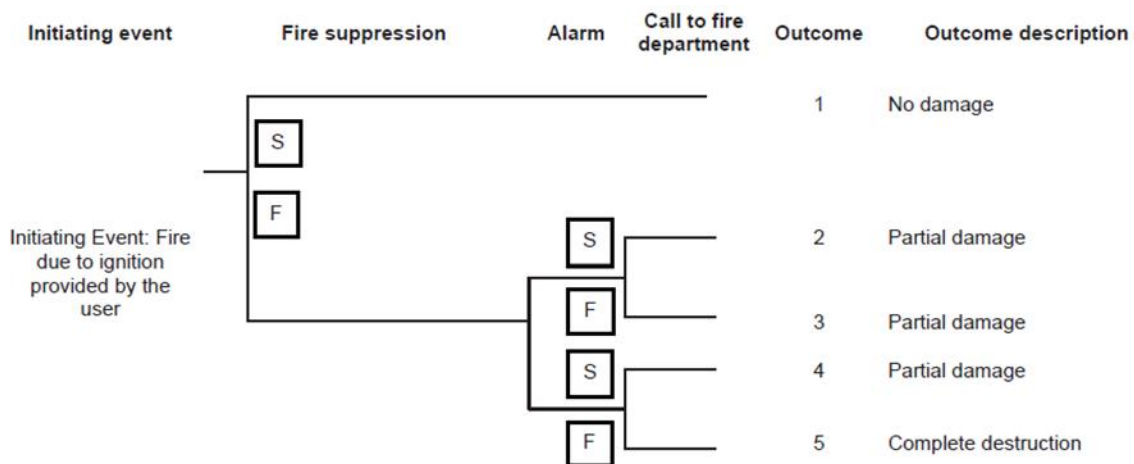


Fig. 11- Haz-safe explosion relief panel.

Table 5 - Ranking criteria used for determining the severity and frequency of occurrence for a potential system failure as well as how quickly the failure will be detected.

| Sr. No. | Codes and Standards |
|--|--|
| Codes and Standards for Hydrogen Production Locales Facility Standards Manual (FSM) | |
| 1. | FSM Division 10.03 Fire Apparatus Accessibility includes NFPA1 Fire Prevention Code, NFPA241 |
| 2. | FSM Division 2.13 Site standards: C Bollards non-removable. Dumpster pad design. |
| 3. | FSM Division 2.18 Trash Dumpster and Compactor Pads: includes placement to reduce aromatic nuisances |
| 4. | FSM Division 13.01 Fire Alarm Systems |
| 5. | FSM Division 13.02 Fire-suppression and protection system |
| 6. | FSM Division 13.03 Fuel Storage Tanks |
| 7. | FSM Division 13.04 Wet Chemical Fire Extinguishing Systems |
| 8. | FSM Division 15.06 Plumbing – Gas Lines and Piping |
| 9. | FSM Division 15.09 Scub Concept |
| 10. | FSM Division 16.03 Outdoor Power Transmission and Distribution |
| 11. | FSM Division 16.04 Basic Electrical Materials and Methods |
| 12. | FSM Division 16.05 Emergency Power |
| 13. | FSM Division 16.06 Fire Protection System |
| 14. | FSM Division 16.10 Security Guidelines – Office of Public Safety, Building Security Systems |
| 15. | FSM Division 16.12 Uninterruptible Power System |
| 16. | FSM Division 17.01 Central Control and Monitoring System CCMS |
| 17. | Maryland Department of the Environment COMAR (Code of Maryland) Title 26 |
| 18. | MOSH (Maryland Occupational Safety and Health |
| 19. | EPA Title 40 CFR parts 260-268 includes hazardous waste management systems. |
| National Fire Protection Association Codes | |
| 20. | NFPA 101 Life Safety Code |
| 21. | NFPA 70 National Electric Code, Article 692 Fuel Cell Systems |
| 22. | NFPA 72 National Fire Alarm Code |
| 23. | NFPA 110 Standard for Standby Power Systems |
| 24. | NFPA 170 Fire Safety Symbols |
| Fuel Cell Safety Standards | |
| 25. | IEC 62282-3-100 – Stationary Fuel Cells - Safety |
| 26. | ANSI/CSA America FC1-2400 Fuel Cell Power Systems (not exceeding an output voltage of 600VAC) |
| 27. | IEC (International Electro-technical Commission) 62282-3-1 (2007-04) |
| 28. | IEC 62282-2-200 (2011-10) Test Method for the Performance of Stationary Fuel Cell Power Plants |
| 29. | ANSI/INFA 853 Installation of Stationary Fuel Cell Power Plant |
| Hydrogen Safety Standards | |
| 30. | OSHA 1910.103 Subpart H Hazardous Materials |

Table 5 - cont. Ranking criteria used for determining the severity and frequency of occurrence for a potential system failure as well as how quickly the failure will be detected.

| Sr. No. | Codes and Standards |
|---------|--|
| | Electrical Standards |
| 31. | ANSI/IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems |
| 32. | IEC/PAS 63547 |
| 33. | IEEE 1547.1-3 Standard for Conformance Test Procedures for Equipment |
| 34. | |
| | Codes and Standards for Fueling Locales |
| 1. | International Fire Code – 2000 edition |
| 2. | International Building Code – 2000 edition |
| 3. | DCMR Title 20, Chapter’s 55-70- Environmental Law Requirements for Fuel Cell Storage Tanks |
| 4. | NFPA 2: Hydrogen Technologies Code |
| 5. | NFPA 30 – Flammable and Combustible Liquid Standards |
| 6. | NFPA 30 – Motor Fuel Dispensing Standards |
| 7. | NFPA 50A – Standard for Gaseous Hydrogen Systems at Consumer Sites |
| 8. | NFPA 50B – Standard for Liquid Hydrogen Systems at Consumer Sites |
| 9. | NFPA 52 – Compressed Natural Gas (CNG) Vehicular Fueling System Standard |
| 10. | NFPA 57 – Liquefied Natural Gas (LNG) Vehicular Fueling System Standard |
| 11. | NFPA 59A – Standard for the Production, Storage, and Handling of Liquefied Natural Gas |
| 12. | ASME BPV Code, Section VIII, Division I – Rules for Constructions of Pressure Vessels |
| 13. | ASME BPV Code, Section IX – Welding and Brazing Qualifications |
| 14. | ASME/ ANSI B31.3 – Piping Design Standards |
| 15. | SAEJ2600 – Hydrogen Dispensers |

A Failure Mode and Effect Analysis (FMEA) has been conducted on the key systems of the hydrogen fuel station to identify significant safety risks. All key systems were analyzed based on the severity of the failure, frequency of failure, and how fast/easily the failure will be detected. The criteria used to rank the importance, likelihood, and ability to detect failures is reported in Table 5.

Conclusion

This paper provided a design for a drop-in hydrogen fueling station. The design utilizes off-the-shelf components and is conceptualized to be implemented at the Missouri University of Science and Technology. The design develops a steam methane reformer, a positive displacement compressor and a two-pressure hydrogen dispenser. The design provides necessary sensors, isolation valves and redundancies, in line with the present day standards and regulations. A detailed failure modes and effects analysis presented assist in demonstrating the feasibility of the proposed design. The drop-in hydrogen fueling station will allow in conducting a variety of control studies, including, the economic model of hydrogen fueling infrastructure, customer outlook, and determination and implementation of technical procedures and its impact on the hydrogen fueling infrastructure.

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SECTION

2. CONCLUSIONS

The dissertation examines different alternative energy technologies that can help reduce the dependence on fossil fuels and increase the energy efficiency. Energy security will alleviate economic disruptions, increase health and safety, and potential environmental effects of energy security disruptions. The design of a research and development renewable energy was discussed and the components required at the system were identified.

Design of a hydrogen community included hydrogen production, compression, transportation, dispensing of hydrogen for various applications. It is recommended that hydrogen be produced using renewable sources such as sustainable energy, biogas, and landfill gas. Numerous hydrogen technology applications including primary power, backup power, material handling, transportation, and utility applications for the community were discussed. The hydrogen applications used in the design can be implemented around the world.

Hydrogen is gaining prominence as an energy carrier and fuel. It is being used for powering vehicles, material handling equipment, stationary and portable fuel cells. Larger number of people is being exposed to hydrogen technologies each day. Since hydrogen properties are different from other common fuels it is vital that the people handling hydrogen know about its properties. Risks and potential hazards associated with each application were identified and measures to mitigate them were discussed. Safety information for a hydrogen fueling station, hydrogen storage, and stationary fuel cell installation was reviewed.

The study discusses different hydrogen technology applications that can be incorporated into a community. The hydrogen technologies used in this design should be seen as a stepping stone towards developing a hydrogen community and should include more hydrogen technologies as it evolves. They can be used separately or collectively in different areas of the community such as schools, hospitals, banks, offices, parks, airports, transportation, warehouses, and stores.

Finally, the design of a CHHP system for the Missouri S&T campus using local resources was discussed. The CHHP system consisted of an anaerobic digester, molten carbonate fuel cell, and hydrogen applications for the campus. As part of topic one, energy savings and environmental analysis were conducted to evaluate the effect of the CHHP system on energy consumption and the environment. The CHHP system will be able to provide approximately 22,000 kWh which is 27% of the university campus' electricity need. In addition, 650 kg/day of hydrogen will be produced. The design will have an overall carbon dioxide reduction of 88,426 tons/yr if it is implemented. In conclusion, the CHHP system will reduce energy consumption, fossil fuel usage, and GHG emissions at the Missouri S&T campus. In second topic the MSW incineration system will be built in Benghazi-Libya with an electrical power plant, and seawater desalination system. On the other hand, the CHP plant provides the energy necessary to desalinate all the water usage or electricity. Energy savings analysis was conducted to evaluate the effect of the CHP system on energy consumption. Consequently, the generated of the energy by the MSW burning can be a decrease of the fuel oil energy, even if the fuel oil consumption is too small. The CHP plant is the best method to save fuel. The MED plant can satisfy the increased water demand that occurs in Benghazi-Libya in future. To sum up, the

incineration plant give Benghazi-Libya opportunity to save fossil fuel usage, raise the energy provided, and GHG emissions mitigation. CHP with back-pressure steam turbines can desalinate 15,973.8 m³/d of sea water with MED with an additional power production of 11.33 MW, and for the case, potential electric power of 14.33 MW (PG). For the design of a drop-in hydrogen fueling station are expected to be an important factor in the introduction of hydrogen fueling infrastructure.

In summary, the CHHP system will reduce energy consumption, fossil fuel usage, and GHG emissions at the Missouri S&T campus. And the incineration of the MSW generated in Benghazi-Libya could give an important contribution to mitigate energy problem, and GHG emissions.

In conclusion, the dissertation analyzed the deployment of different alternative energy technologies for real-world applications. The deployment of these technologies will help achieve energy security, higher efficiencies, and reduced emissions.

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