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Thermodynamic analysis of solar energy use for reforming fuels to hydrogen

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ABSTRACT

In this paper, a method is proposed for reforming fuels to hydrogen using solar energy at distributed locations (industrial sites, residential and commercial buildings fed with natural gas, remote settlements supplied by propane etc). In order to harness solar energy a solar concentrator is used to generate high temperature heat to reform fuels to hydrogen. A typical fuel such as natural gas, propane, methanol, or an atypical fuel such as ammonia or urea can be transported to distributed locations via gas networks or other means. The thermodynamic analysis of the process shows the general reformation reactions for NH_3 , CH_4 and C_3H_8 as the input fuel by comparison through operational fuel cost and CO_2 mitigation indices. Through a cost analysis, cost reduction indices show fuel-usage cost reductions of 10.5%, 22.1%, and 22.2% respectively for the reformation of ammonia, methane, and propane. CO_2 mitigation indices show fuel-usage CO_2 mitigations of 22.1% and 22.3% for methane and propane respectively, where ammonia reformation eliminates CO_2 emission at the fuel-usage stage. The option of reforming ammonia is examined in further detail as proposed cycles for solar energy capture are considered. A mismatch of specific heats from the solar dish is observed between incoming and outgoing streams, allowing a power production system to be included for a more complete energy capture. Further investigation revealed the most advantageous system with a direct expansion turbine being considered rather than an external power cycle such as Brayton or Rankine type cycles. Also, an energy efficiency of approximately 93% is achievable within the reformation cycle.

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1. Introduction

Solar energy is a widely available commodity with a vast capacity which to this point with the exception of biological products has been sparsely harvested. Going forward, solar energy is expected to take over an increasing portion of the energy market; however effectively using solar energy presents many challenges. Up to the present day, photovoltaics

(PV) primarily for electrical production and hot water solar collectors for heating purposes have been the main method of harnessing distributed solar energy. PV technology is progressing; however, the combination of efficiency limitations with high cost has been limiting the growth of this technology. In order to give such technology a substantial portion of the market, vast government subsidization is required [1]. Solar-thermal heating, in particular hot water collectors are also

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Nomenclature		Greek Letters	
C	mass based cost, \$/kg	ε	effectiveness
c	molar concentration	η	efficiency
CI	cost index	Δ	change in given property
CO ₂ I	CO ₂ index	Subscripts	
G	Gibb's free energy, kJ/kmol	CO ₂ /f	ratio of CO ₂ to final fuel
H	enthalpy, kJ/kmol	CO ₂ /i	ratio of CO ₂ to initial fuel
HHV	higher heating value, kJ/kmol	e	equilibrium
K	equilibrium reaction constant	f	final fuel
MM	molar mass	i	initial fuel
MR	molar ratio	i/f	ratio of initial fuel to final fuel
P	pressure, Pa	in	entering the system
Q	heat, kJ/mol	out	exiting the system
R	gas constant, kJ/kmol K	p	pump parameters
S	entropy, kJ/kmol K	r	reaction
T	temperature, K	t	turbine parameters
y	flow split factor	w	water
		w/f	ratio of water to final fuel
		0	reference state

becoming more popular. However, this technology has limited utilization due to a lower grade of heating temperatures such as the approximate 40–70 °C extraction depicted in [2]. Solar-thermal power generation, solar-chemical production, and solar-hydrogen production are three emerging technologies which at present remain limited in commercial availability. It is argued that solar-chemical energy storage is the best method to effectively capture solar energy to overcome the inconsistent nature of the solar energy supply [3].

In this paper, a method for the utilization of solar energy, related to solar-chemical production and solar-hydrogen production, is investigated. Fuel reforming is not a new technology. In fact, a majority of hydrogen produced commercially is generated through the process known as steam-methane reforming [4]. Though reforming processes are energy consuming, they produce a higher grade product in terms of heating value. If energy is supplied to such a process by renewable means, this becomes a method of fuel enhancement, adding a clean efficiency percentage to any system using the upgraded fuel relative to the efficiency of the original fuel. Putting such a method to use for localized fuel upgrading, a conventional fuel such as natural gas or propane, as well as an unconventional fuel such as ammonia may absorb the renewable source of solar energy, and store this energy as hydrogen.

Due to the availability and utilization of natural gas, the addition of hydrogen in this fuel for combustion applications

has been investigated on numerous accounts. Boilers [5] and engines [6] fueled by natural gas and hydrogen mixtures are two basic options as investigated, where engines may be used as generators at fixed locations. Hydrogen fuel enhancement of propane and ammonia are lesser known subjects, however, the proper mixtures of partially decomposed ammonia have been shown to act effectively in regular internal combustion engines [7]. The principle of the fuel upgrade technique by generating hydrogen locally and blending it with the original fuel is demonstrated in Fig. 1.

For the ammonia option simply conducting thermal decomposition results in the production of hydrogen, nitrogen, and some remaining ammonia. The product may then be mixed with some of the pure ammonia for combustion. The reformation process of fossil fuels such as methane or propane requires a different process where water is heated to a very high temperature and the resulting steam is mixed with the original fuel. This engages the chemical reformation process, converting a portion of the fuel and steam to hydrogen. Once again, the resulting hydrogen fuel may be mixed with the original fuel. Mixing the product fuel with the original fuel allows for conventional combustion appliances to remain effective with the possibility of modifications and the proper fuel mix. It is also possible for fossil fuels to be decomposed directly, in a similar manner as the ammonia reformation [8]; however, including water in the reformation process adds to the yield of hydrogen in the product stream.

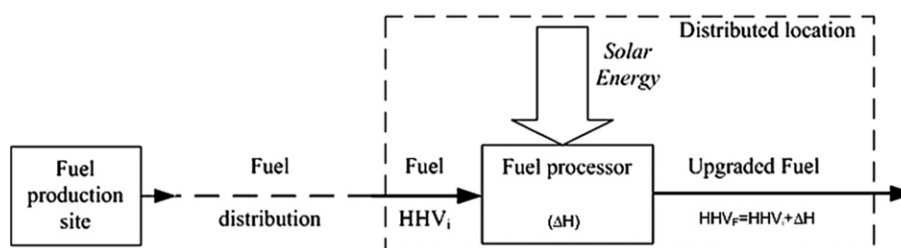


Fig. 1 – Introducing the principle of the fuel upgrading system.

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