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Life cycle analysis of HCNG light-duty vehicle demonstration project

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ABSTRACT

The demonstration is an effective initiative to bridge the gap between a premature technology and its large-scale commercialization. A systematic method of LCA was used to perform the well-to-wheel analysis of a CNG light-duty truck operated with 0%, 15%, and 30% blends of hydrogen with compressed natural gas fuel under the system boundary of "per vehicle km". The GREET simulation was performed on GREET_1 (Excel Series_2017) to evaluate hydrogen production pathways with numerous parametric assumptions adopted to base the study in the context of China. Resource use, fossil energy use, GHG emission, and major air pollutants namely NO_x and PM were studied. The idea was to demonstrate the effects of hydrogen addition throughout the entire fuel cycle of end-use of HCNG in an HCNG® LDV. The hydrogen blend of 30% with conventional CNG decreased the well-to-wheel GHG emission compared with 0%HCNG by 32.982%, 29.275%, and 9.694% with hydrogen pathways such as solar, biomass, and coke oven gas, respectively. Moreover, for 30%HCNG (Conv.NG), the well-to-wheel total energy consumption was increased by 15.176%, and 15.719% for solar and biomass-based pathways, respectively. However, although the energy consumption was increased for solar and biomass-based 15%HCNG and 30%HCNG pathways compared with 0%HCNG, the feedstock used was renewable and qualitatively cleaner. The worst scenario was found in the form of 30%HCNG (Conv.NG) with grid electrolysis pathway which showed 60.648% increment in WTW GHG and 75.479% increment in WTW total energy compared with baseline 0%HCNG (Conv.NG). The booming renewable electricity generation and availability of a tremendous amount of coke oven gas as by-products from coking industries in China can establish a prospective platform for sustainable hydrogen economy in China and is supposed to promote the commercialization of HCNG vehicles in future.

Keywords: demonstration, life cycle analysis, HCNG®, well-to-wheel, LDV, GREET

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1. INTRODUCTION

1.1 Research background

Tremendous works have been done to achieve performance and emission evaluation of HCNG vehicles since past few decades. Interestingly, most of the scientific research works have claimed numerous advantages of hydrogen addition to compressed natural gas fuel at optimized engine's operating conditions. The 20% hydrogen enrichment (HCNG®) requires no severe engine's modifications apart from slight adjustments in the fuel supply system and operating conditions. It is also obvious to find out a slight reduction in brake specific fuel consumption and exponentially decreased air pollutants and tailpipe emissions. However, it has not achieved commercialization phase till now and one thing that hinders its promotion is the 'hydrogen economy' itself. The purpose of this investigation was to perform a simplified version of life cycle analysis for HCNG® demonstration project which presents the full picture of environmental impacts of HCNG® aimed for light-duty vehicle usage and has been compared with counterpart baseline CNG vehicle. Hydrogen is not a primary energy source, rather it is an energy carrier. Henceforth, the feedstock for hydrogen production plays a vital role in the realization of cleaner and efficient HCNG vehicle technology. The stringent emission and fuel economy requirements for light-duty vehicle operations demand the use of clean-burning alternative

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fuels such as compressed natural gas. The ultimate goal of this work was to find the amount of energy (MJ/km) required 'per vehicle km' and grams of $CO_{2,equivalent}$ (GWP) per vehicle km (g/km). Results give the understanding of two perspectives; qualitative and quantitative. Generally speaking, researchers proved that the 20-30% HCNG overpasses the dominance of CNG in three major tiers: reduction on fuel consumption, air pollutants, and as greenhouse gas emissions depending upon the accuracy of operating conditions.

1.2 Previous works

In 2007, [19] suggested that China surpassed the USA as the world's largest contributor to CO_2 emissions. The rapid increase in economic growth rate, urbanization, and industrialization over the past few decades (in particular for last 10 years) in China has resulted in the tremendous booming of transportation services and automobile markets. Currently, China is the world's largest automobile market and among one of the fastest growing nations in the global automobile market according to [9]. Compared to conventional buses, AFVs offer better performance and reduced GHG emission. However, only half of the AFVs analyzed proved to be fulfilling dual benefits (energy saving & lower GHGs) [14]. According to Anadolu Agency [17], China is currently leading with the most natural gas vehicles. It has been pointed out that China has the largest population of natural gas vehicles globally followed by Iran and India at the end of 2017, according to the current statistics of NGV Global.

Hydrogen is a zero-emitter fuel with a very fast laminar burning speed and wide range of flammability which confirms it as one of the superlative energy carrier to enhance the slow burning rate of CNG at lean burn and constitute tremendous possibilities to empower the present generation internal combustion engines together with compressed natural gas which sounds promising at the current era of transition to a greener future transportation [12]. NO_x, CO, NMHC, CH_4 emissions, and BSFC decreases by 51%, 36%, 47%, and 7%, respectively whereas the maximum power remains the same with $HCNG^{®}$ (20% HCNG) as compared to baseline CNG engine (6.234L-SI) [11]. The experimental evaluation of a 6-cylinder (6.014L) natural aspirated compressed natural gas engine optimized with 18% hydrogen addition and tested according to a simulated city driving cycle in accordance with ETC specifications equipped with 600-hours of endurance testing (15 models each cycle of 100 hours) demonstrated that 18% hydrogen blended CNG results in reduction of CO, THC, and CH_4 by 39%, 25%, and 25%, respectively as well, on the other hand, increases NO_x by 32%. The engine power was not affected significantly by the complete 600-hours of an endurance test with 18% hydrogen enrichment. The emission results over 600-hours of endurance testing with 18% HCNG met Euro IV emission standards for heavy-duty engines [16].

Road tests carried out by running fixed tracks (60km, $V_{mean} = 20kmph$, $V_{max} = 40kmph$) which may be considered as urban and sub-urban driving cycles for a fleet of two buses tested with 5% HCNG on a sub-urban track whereas the other with 8 m length tested with various volumetric fractions of hydrogen such as 5%, 10%, 15%, 20% and 25% with CNG. The buses include Vivacity CNG Mercedes (turbo-charged) with 6 cylinders (6880 CC) and rated power as 170 kW. This work demonstrated that 5%HCNG improved energy consumption by 4%. The 25% HCNG produced the largest reduction of CO_2 by 25% compared with baseline CNG operation. The levels of HC emission were constant and could not meet the EEV limits. NO_x reduced by 47% with 5% HCNG [3]. A chassis dynamometer test bench experiment performed on a passenger car with L4-SI (PFI) engine equipped with a TWC as per NEDC cycle procedure highlighted the effects of 12% hydrogen addition with compressed natural gas on engine efficiency and emissions without changing ignition timing. Results showed that CO and CO_2 were reduced by 19% and 3% respectively whereas HC was almost unchanged. The amount of NO_x increased by 70%. No significant changes occurred in fuel consumption on both bases; mass and energy. Therefore, this work made an obvious explanation that it is impossible to enhance engine performance and emission without a proper hydrogen fraction and optimum spark timing [18].

One of the biggest challenges with the implementation of $HCNG^{®}$ is associated with the development of supporting infrastructure. Therefore, HCNG allows for initial use of hydrogen while taking advantage of the current CNG infrastructure. It also allows for the hydrogen infrastructure to slowly become established until the production and efficiency demands can be met for the hydrogen economy. Although there is currently a huge number of research works taking place regarding HCNG, there are certainly many steps to take before wide-spread implementation can occur [10]. In this regard, an LCA of a demonstration project for a vehicle use of hydrogen blended natural gas performed by [8] accesses and compares the environmental aspects of natural gas, HCNG with 15% and 30% by volume, and hydrogen as vehicular fuels within the scope of a demonstration project. Two different types of light-duty vehicles with internal combustion engines were tested in this study. The general conclusion revealed by this study claims that the potential environmental impact from the fuel supply chain considerably increases towards a hydrogen share of 100% in the fuel.

The transition to new fuel chains demands large investments and long time frames for adjustments since the adaptation of fuel supply, retail stations, and vehicles is required. Furthermore, the transition strategy must endorse a trade-off between environmental benefits, costs and implementation obstacles which are obvious. The author commented in a very witty way HCNG could be a sustainable solution for the chicken-or-the-egg problem of which comes first-the fuel cell vehicles or the hydrogen infrastructure to fuel them; it arises from the fact that existing natural gas networks could be used for the distribution of HCNG. The author also added that no significant changes in the performance trends of modified HCNG 15% and HCNG 30% compared with baseline CNG vehicle. However, the corresponding fleet of hydrogen vehicles would have the best environmental performance [8]. Greener hydrogen can support a significant reduction of CO_2 emissions. However, if the goal is ultimately CO_2 reduction, HCNG may not be an effective choice as it offers only 10% reduction in CO_2 emissions which can be achieved in many parts of the world just by replacing CNG with biogas. Lastly, this study also proved that HCNG is best suited for the primary goal of air pollution reduction rather than CO_2 reduction [13].

Currently, there is no commercial production of hydrogen energy in China and is limited to the petroleum industry and small-scale production only. [2] revealed that the hydrogen production amount in China is about 12.42 million tonnes per year. It is mostly produced from coal, natural gas and oil and accounts for 57.4%, 23%, and 19.7% of total production. The author mentions that 75.8% of the hydrogen is consumed for ammonia refining, whereas 10.5% and 13.7% for methanol and oil refining respectively. Lastly, it has been pointed out that 5.7 million tons of by-product hydrogen could fuel 17.7 million fuel cell vehicles in China [2].

A study carried out to perform WTW study of hydrogen fuel cell vehicle pathways in Shanghai with ten hydrogen pathways in Shanghai founded that the two naphtha-based hydrogen pathways showed about 20% reduction in WTW petroleum. All the hydrogen pathways also showed significant reductions in WTW urban criteria pollutants except the two pathways which resulted in the increased amount of SO_x emissions. The NG-based hydrogen pathways proved to be the best in terms of WTW energy efficiency and the electrolysis-based pathways showed the worst characteristics. The WTW energy efficiencies of hydrogen pathways from naphtha and hydrogen pathways from coal are between lie between NG-based pathways and electrolysis pathways. The pathways from naphtha have higher energy efficiencies than the pathways from coal. Moreover, changes in WTW GHG emissions have nearly identical results to changes in WTW energy use. However, WTW criteria pollutants such as VOCs and CO were found to be reduced for all pathways whereas NO_x, PM10, and SO_2 have certain reductions in NG and crude oil-based hydrogen pathways, but have a significant increase in electrolysis and coal-based pathways [5].

In order to realize the extensive commercialization and marketization of HCNG vehicles, the demonstration project is a pre-commercial initiative and formative period. The formative period is categorized into two further classifications: experimental phase, and take off phase. The experimental phase is a roadway to technological development and is interlinked with initial uncertainties. The continuous learning and knowledge curve is a possible outcome of an experimental phase. The “take-off” phase is related to the formative of networks. The word ‘network’ is a collective cluster of suppliers, users, research institutes, universities, organizations, and professionals. The demonstration project is aimed at 2-tier goals. Namely, they are direct goals and indirect goals. The direct goals include profits, technological success, etc. whereas the indirect goals include technological development in all three main spectrums of sustainability: technology, economy, and society [8].

2. MATERIALS AND METHODS

This research work used a typical life cycle approach for well-to-wheel analysis (excl. vehicle lifecycle). According to the International Organization for Standardization (ISO) 14040 &14044 series guidelines for conducting an LCA study, four phases were identified i.e. (i) goal & scope of definition, (ii) inventory analysis (LCI), (iii) impact assessment (LCIA), and (iv) Interpretation.

2.1 Definition of goal & scope

Life cycle analysis of HCNG demonstration project in Chinese context based on an LCA framework of ‘fuel cycle WTW’.

2.1.1 Product definition

HCNG light-duty truck [7]

The vehicle operation data has been obtained from U.S. Department of Energy FreedomCAR & Vehicle Technologies Program-Hydrogen and Hydrogen/Natural Gas Station and Vehicle Operations -2006 Summary Report by [7], Idaho National Laboratory. The detailed information about vehicle operation has been tabulated in preceding section 'Data'.

2.1.2 System boundary

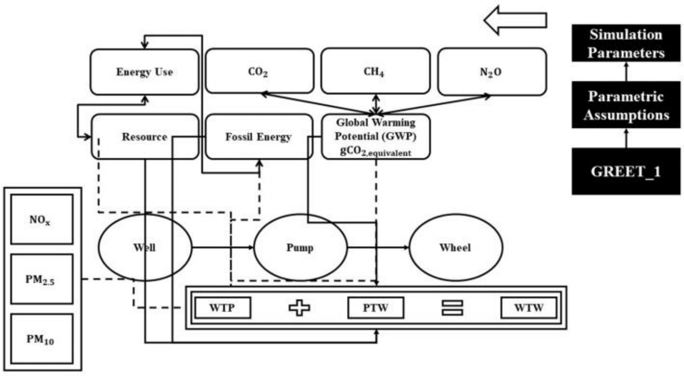

Figure 1: System boundary

Figure 1 shows the system boundary of this study. GREET_1 (2017) excel series was used for well-to-pump simulation of gaseous hydrogen from the various feedstock. The well-to-pump data for compressed natural gas pathway was sourced from [15] & [1]. The parametric input data assumptions prior to GREET simulation were made on GREET_1 to base this study in the Chinese context. The pump-to-wheel data was sourced from [7]. The well-to-pump data of gaseous hydrogen and CNG were integrated to form $\mathbf{WTP_{xHCNG}}$ **LCI** (x indicates % of hydrogen in the mixture fuel by using a principle of weighted average on an LHV (lower heating value) basis. The similar, procedure has been used to calculate $\mathbf{PTW_{xHCNG}}$ **LCI**. Here, LCI indicates life cycle inventory for example; resource use, fossil use, GHG and air pollutants. $\mathbf{CO_2}$, $\mathbf{CH_4}$, and $\mathbf{N_2O}$ were combined according to their GWP-100 years based on IPCC report. The method suggested by [6] has been used to evaluate the well-to-wheel results. Moreover, fossil energy use was evaluated for the well-to-pump stage of gaseous hydrogen pathways to evaluate the potential benefits of renewable hydrogen pathways. $\mathbf{LDV_s}$ are one of the major sources of $\mathbf{NO_x}$ and PM emissions in China due to the dominance of fossil fuel. In this regard, $\mathbf{GH_2}$ was assessed in terms of WTP $\mathbf{NO_x}$ & PM emissions.

2.1.3 Functional unit

A functional unit is defined for comparison of life cycle inventory use (LCI) for both baseline CNG and HCNG. LCI refers to resource use, fossil use, GHG, urban air pollutants, etc. The functional unit assigned may differ from a study to another and is basically defined for both WTP and PTW stages differently.

- Per MJ energy in fuels

$\mathrm{WTP_{Resource}} = \frac{\mathrm{MJ}}{\mathrm{MJ_f}}$; $\mathrm{WTP_{GHG}} = \frac{\mathrm{gCO_{2e}}}{\mathrm{MJ_f}}$

- Per vehicle km (1 vehicle km)

$\mathrm{PTW_{Resource}} = \frac{\mathrm{MJ}}{\mathrm{km}}$ (fuel economy); $\mathrm{PTW_{GHG}} = \frac{\mathrm{MJ}}{\mathrm{km}}$; $\mathrm{WTW_{Resource}} = \frac{\mathrm{MJ}}{\mathrm{km}}$; $\mathrm{WTW_{GHG}} = \frac{\mathrm{gCO_{2e}}}{\mathrm{km}}$;

Note: The functional unit for air pollutants was chosen similar to that of GHG mentioned above.

2.2 Data

The data can be categorized into two groups of a fuel cycle: (i) well-to-pump (WTP), & (II) pump-to-wheel (PTW).

2.2.1. Pump-to-wheel

The pump-to-wheel vehicle operation data was extracted from [7]. The complete demonstration of HCNG is out of the context of the chosen study framework. The test description and vehicle specifications have been shown in the diagram shown in Figure 2.

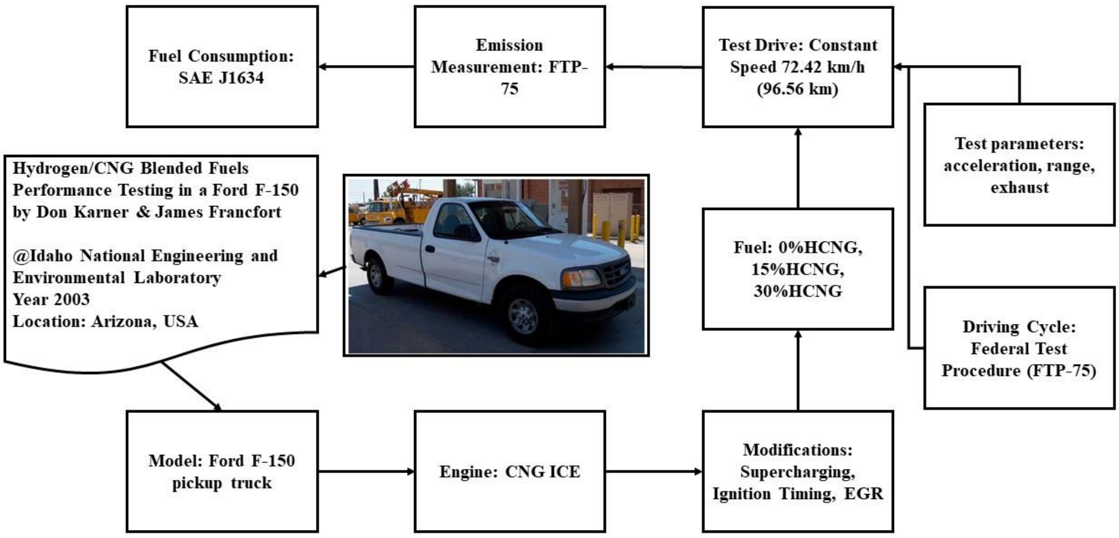

Figure 2: Pump-to-wheel light-duty vehicle demonstration

Table 1: The light-duty vehicle demonstration pump-to-wheel performance and emission data

FUEL	FUEL ECONOMY (MJ/KM)	$CO_2(\frac{g}{km})$	$CO(\frac{g}{km})$	$CH_4(\frac{g}{km})$	$NO_x(\frac{g}{km})$	$NMHC(\frac{g}{km})$	$HC(\frac{g}{km})$
CNG	5.48	2.94E2	3.52E-1	7.95E-2	6.84E-2	1.43E-2	1.07E-1
15% HCNG	5.64	2.81E2	2.90E-1	8.20E-2	7.71E-2	1.55E-2	1.11E-1
30% HCNG	5.43	2.78E2	2.63E-1	8.57E-2	7.83E-2	8.08E-3	1.09E-1

Table 2: The well-to-pump data for natural gas pathways

PATHWAY	STUDY	ENERGY SOURCE	PROCESS	WTP_{Energy} $(\frac{MJ}{MJ_f})$	WTP_{GHGs} $(\frac{gCO_{2e}}{MJ})$	CODE
Con.NG (N1)	[15]	(Coal + Raw NG+ Petroleum)	Conventional Raw NG to NG	1.15	137.81	$NG_{Conv.}$
Synthetic_CNG (N2)	[1]	Wind Electricity	Synthetic-CNG	1.04	3.3	CNG_{SynNG}

2.2.2 Well-to-pump

"H" and "N" refer to hydrogen and natural gas pathways. The letter is followed by a pathway number. This nomenclature was assigned for the simplicity of mentioning these HCNG pathways in Conclusions section. HN denotes HCNG pathway. For example, H1N1 means a mixture of gaseous hydrogen from central NG SMR and conventional NG. In the section Conclusions, the discussion has been done for only 0%HCNG and 30%HCNG, as the vehicle performance with 15%HCNG is not significant.

Table 3: Description of gaseous hydrogen pathways for GREET modeling

GH_2 PATHWAY CODE	DESCRIPTION
GH2_NG_CT_C_CN (H1)	Central Plants: NG or FG to Gaseous Hydrogen
GH2_Solar_CT_C_CN (H2)	Central Plants: Solar Energy to Gaseous Hydrogen
GH2_Nucl_CT_C_CN (H3)	Central Plants: Nuclear to Gaseous Hydrogen
GH2_HTGR EC_CT_C_CN (H4)	Central Plants: Electrolysis (HTGR) to Gaseous Hydrogen
GH2_Coal_CT_C_CN (H5)	Central Plants: Coal to Gaseous Hydrogen
GH2_Bio_CT_C_CN (H6)	Central Plants: Biomass to Gaseous Hydrogen
GH2_COG_CT_C_CN (H7)	Central Plants: Coke Oven Gas to Gaseous Hydrogen
GH2_NG_RF_C_CN (H8)	Refueling Stations: NG or FG to Gaseous Hydrogen
GH2_Elect_RF_C_CN (H9)	Refueling Stations: Electricity to Gaseous Hydrogen

2.3 Governing equations

After the complete set of data was obtained, integration of hydrogen and CNG pathways was necessary to calculate the combined result for HCNG.

$$\mathrm{k_{HCNG}} = \frac{\%\ \mathrm{of\ H_2 * LHV_{H_2} * k_{H_2}} + \%\ \mathrm{of\ CNG * LHV_{CNG} * k_{CNG}}}{\%\ \mathrm{of\ H_2 * LHV_{H_3}} + \%\ \mathrm{of\ CNG * LHV_{CNG}}};\ \mathrm{LHV - basis}$$

(1)

$$\mathrm{k = Desired\ output\ parameters\ (LCI;\ for\ e.g.\ total\ energy, GHG, Lower\ heating\ value, etc.)}$$

Note: ‘k’ needed to be calculated for both stages of WTP and PTW and then can be integrated by the following way.

[6] suggested the integration of well-to-tank and tank-to-wheel results to combine and form well-to-wheel results.

$$\mathrm{WTW_{Total\ Energy}}\left(\frac{\mathrm{MJ}}{\mathrm{km}}\right) = \mathrm{PTW_{Total\ Energy}}\left(\frac{\mathrm{MJ}}{\mathrm{km}}\right) * \left(1 + \mathrm{WTP_{Total\ Energy}}\left(\frac{\mathrm{MJ}}{\mathrm{MJ}}\right)\right) \tag{2}$$

$$\mathrm{WTW_{GHG}}\left(\frac{\mathrm{gCO_{2eq}}}{\mathrm{km}}\right) = \mathrm{PTW_{GHG}}\left(\frac{\mathrm{gCO_{2eq}}}{\mathrm{km}}\right) + \mathrm{PTW_{Total\ Energy}}\left(\frac{\mathrm{MJ}}{\mathrm{km}}\right) * \mathrm{WTP_{GHG}}\left(\frac{\mathrm{gCO_{2eq}}}{\mathrm{MJ_{fuel}}}\right) \tag{3}$$

$$\mathrm{WTP\ LCI}_{\mathrm{xHCNG}} = \frac{\mathrm{x * LHV_{H_2} * WTP\ LCI_{H_2}} + (1-\mathrm{x}) * \mathrm{LHV_{CNG} * WTP\ LCI_{CNG}}}{\mathrm{x * LHV_{H_2}} + (1-\mathrm{x}) * \mathrm{LHV_{CNG}}} \tag{4}$$

$$\mathrm{PTW\ LCI}_{\mathrm{xHCNG}} = \frac{\mathrm{x * LHV_{H_2} * PTW\ LCI_{H_2}} + (1-\mathrm{x}) * \mathrm{LHV_{CNG} * PTW\ LCI_{CNG}}}{\mathrm{x * LHV_{H_2}} + (1-\mathrm{x}) * \mathrm{LHV_{CNG}}} \tag{5}$$

Where x= fraction of hydrogen in HCNG (e.g. 0.15 for 15% hydrogen)

3. RESULTS AND DISCUSSION

The results were divided into three main categories for the demonstration. The brown color represents baseline CNG, light green represents 15%HCNG and dark green represents 30%HCNG. Two sets of results: WTP and WTW were presented here; for each baseline pathway of natural gas with a series of HCNG pathways. In the first part, various 15%HCNG & 30%HCNG pathways were compared with baseline CNG (from conventional natural gas) whereas, in the second part, HCNG pathways were compared with baseline synthetic CNG.

3.1 Well-to-pump energy & emission analysis

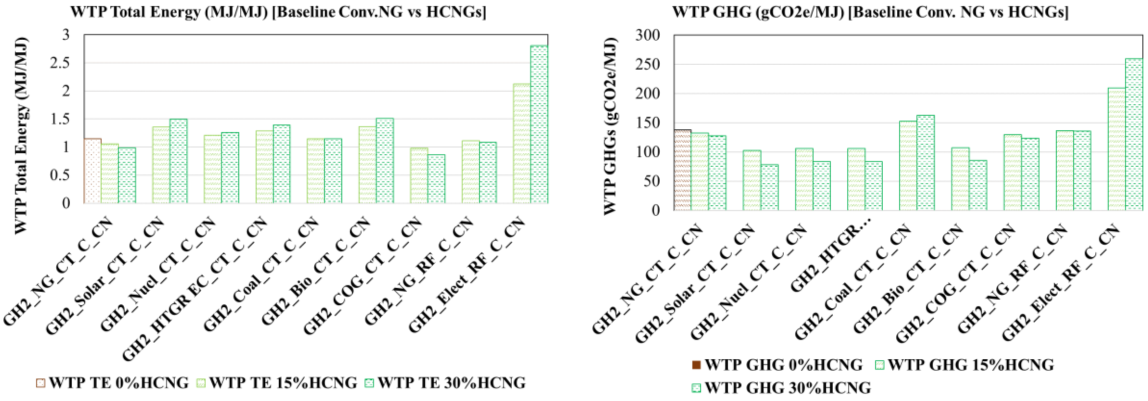

Figure 3 (a): WTP Total Energy (Baseline Conv.NG) **(b)** WTP GHG (Baseline Conv.NG)

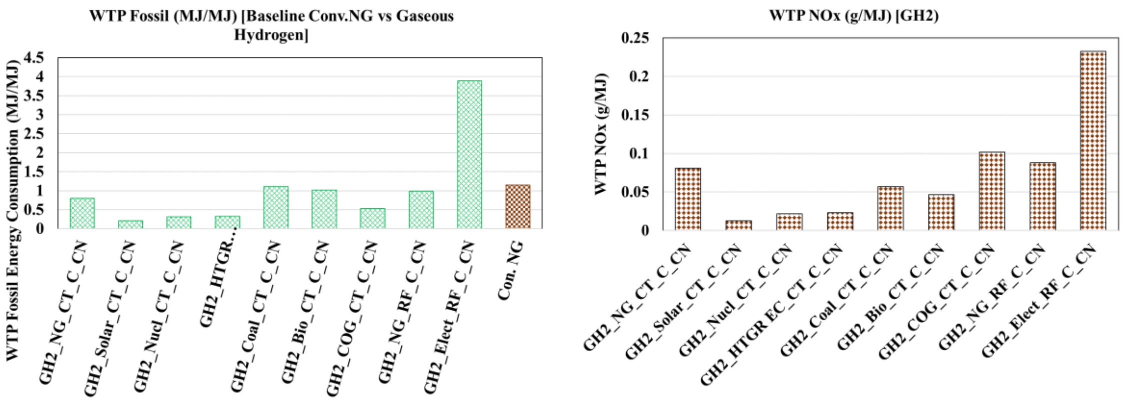

Figure 4 (a): WTP Fossil Energy (Conv.NG & GH2 pathways) **(b)** WTP NOx (Gaseous hydrogen pathways)

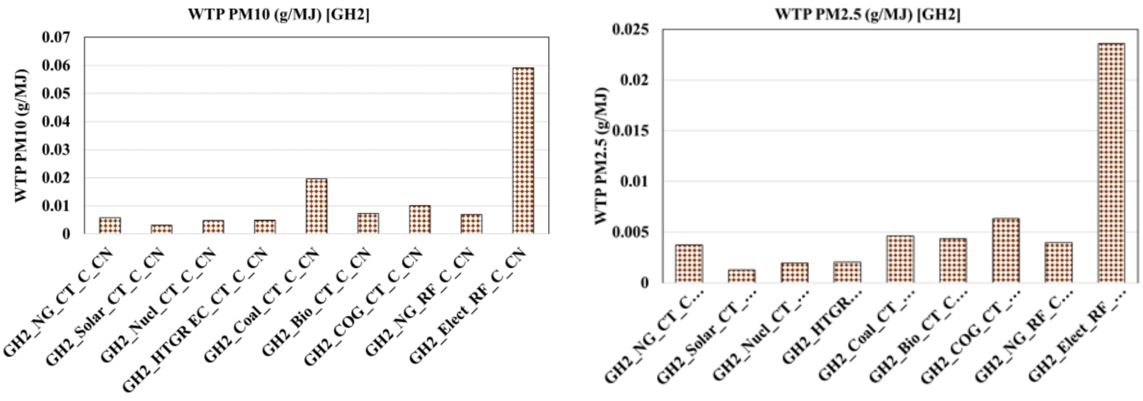

Figure 5 (a): WTP PM10 (GH2 pathways) **(b)** WTP PM2.5 (GH2 pathways)

Figure 3 shows the well-to-pump energy use and GHG emission for 0%, 15% and 30%HCNG pathways with CNG from conventional natural gas and hydrogen from the various feedstock. Figure 4 (a) shows the fossil energy intensity of gaseous hydrogen pathways compared with conventional natural gas and Figure 4 (b) shows the NOx emissions for various gaseous hydrogen pathways compared with conventional gasoline. Similarly, Figure 5 shows the well-to-pump PM emissions for various pathways of gaseous hydrogen. These calculations were performed by GREET simulation with localized parametric data assumptions to relate this study in the context of China. Figure 3, Figure 4, and Figure 5 claimed that compared with conventional natural gas, HCNG pathways have cleaner and lower energy intensity especially for renewable pathways such as biomass, solar and nuclear energy. Coke oven gas is a surplus by-product from coking plants in China and possesses dual benefits of lower energy consumption and lower GHG emission.

3.2 Well-to- wheel total energy & ghg emission analysis

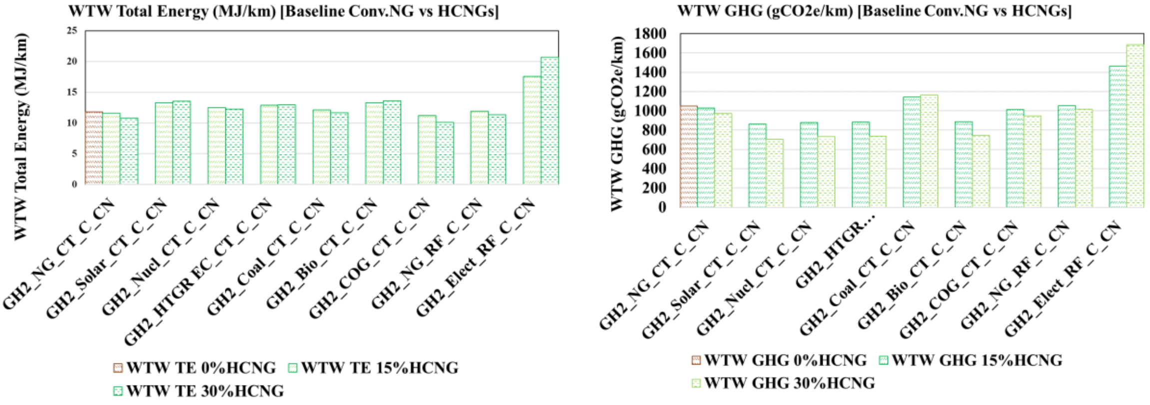

Figure 6 (a): WTW Total Energy (Baseline Conv.NG) **(b)** WTW GHG (Baseline Conv.NG)

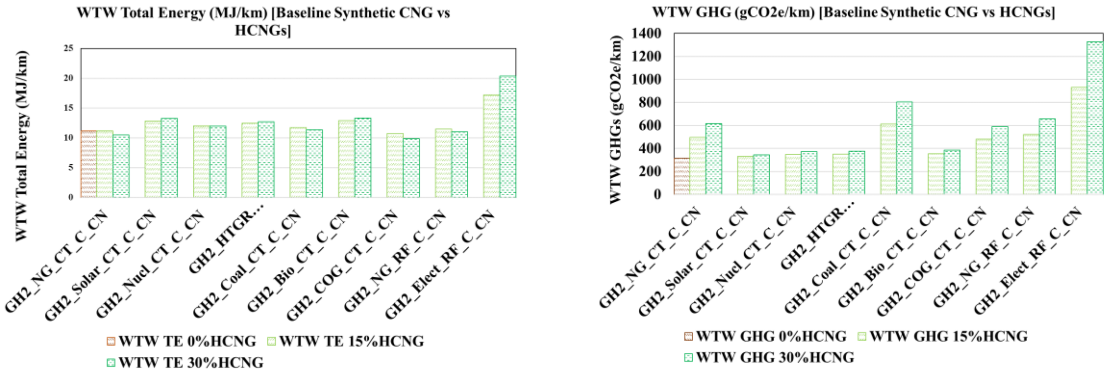

Figure 7 (a): WTW Total Energy (Baseline Syn.CNG) **(b)** WTW GHG (Baseline Syn.CNG)

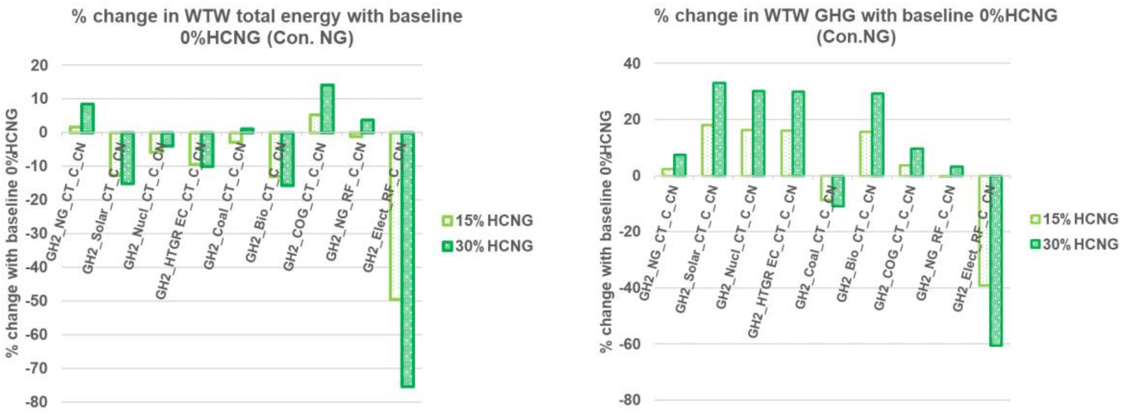

Figure 8: % Change in WTW total energy & WTW GHG with baseline 0%HCNG (Conv.NG)

Figure 6 and Figure 7 illustrate the well-to-wheel results calculated for comparison of various HCNGs pathways and a CNG pathway based on total energy per vehicle km and total grams of $CO_{2,\mathrm{equivalent}}$ per vehicle km. Although HCNGs showed better pump-to-wheel characteristics due to hydrogen enrichment, still natural gas remained a major constituent in the mixture fuel HCNG. Hydrogen is just an energy carrier used as a supplement fuel. Therefore, the natural gas pathways showed a significant effect on total WTW LCI use. This was the reason synthetic CNG was compared with different HCNGs pathways (15% and 30% HCNG). LCI refers to energy use and GHG emitted and is known as life cycle inventory according to the ISO 14040 guidelines of LCA.

The baseline vehicle option is 0%HCNG which means only CNG. The two pathways of CNG were considered in this study such as conventional and synthetic CNG which signify two different scenarios. Figure 8 shows the % change in WTW total energy and % change in WTW GHG with baseline Conv.NG which is the horizontal line. The positive % change signifies 'decrement' compared with baseline whereas negative % signifies 'increment' compared with baseline. The desired goal was a decrement in energy consumption which can be termed as 'energy saving' and decrement in GHG termed as 'reduced GHG'. So, the alternative HCNG options lying above the x-axis are desirable and higher is the magnitude, higher is the effectiveness and benefits of energy saving and reduced GHG.

The hydrogen blend 30% with conventional compressed natural gas (Conv.NG) decreased well-to-wheel GHG emission compared with 0%HCNG (Conv.NG) by 32.982%, 29.275%, and 9.694% with hydrogen pathways such as solar, biomass, and coke oven gas, respectively. On the other hand, for the same operation, the well-to-wheel total energy was increased by 15.176%, and 15.719% for solar and biomass-based pathways respectively. However, although the energy consumption was increased for solar and biomass-based 15%HCNG and 30%HCNG pathways compared with 0%HCNG, the feedstock used was renewable and qualitatively cleaner. Coke oven gas based 30%HCNG pathway reduces the WTW energy consumption by 9.694% compared with 0%HCNG. The worst scenario was found in the form of 30%HCNG with grid electrolysis pathway which showed 60.648% increment in WTW GHG and 75.479% increment in WTW total energy compared with baseline 0%HCNG (conventional CNG). The booming renewable electricity generation and availability of a tremendous amount of coke oven gas as by-products of coking industries in China establishes a prospective platform for sustainable hydrogen economy in China and is supposed to promote the commercialization of HCNG use in future. Comparing Figure 6 and Figure 7, it is evident that replacing conventional natural gas with a synthetic CNG gas can further decrease the energy use and GHG emission as it is lesser carbon-intensive and energy intensive.

The synthetic CNG mentioned here is produced by using wind electricity. The pump-to-wheel data showed only 0.91% improvement in fuel economy for 30%HCNG whereas increasing fuel consumption by 2.92% for 15%HCNG compared with 0%HCNG. This contrasts the results presented by [11] which demonstrated a 7% decrease in fuel consumption and a 11% reduction in GHGs during HDV operation with 20%HCNG. The reason is that the pump-to-wheel data used here was quite old and a series of R&D works recently has improved the performance and emission to a larger extent than before. The reason for considering this pump-to-wheel data is in this LCA study is because of its originality and existence as a real demonstration of HCNG vehicle. Another study [4] demonstrated 11% reduction in fuel consumption and a 21% reduction in GHG emission for 30%HCNG compared with CNG as per European codes of fuel consumption analysis.

The well-to-pump energy use for hydrogen production by NG SMR in the study [8] showed 1.10, 1.13, and 1.16 MJ/MJ, respectively for 0%, 15%, and 30%HCNG which in our finding is 1.02, 1.11, and 1.08 MJ/MJ total energy use for natural gas-to-hydrogen pathways of 0%HCNG, 15%HCNG and 30%HCNG at refueling station. This validated that the modeled results made sense for this pathway as well as other pathways. As there is not much work done on LCA of HCNG vehicles in China, it is hard to find the data for validation of the results obtained here as well as difficult to compare our WTW results with other studies. It is evident from Figure 6 and Figure 7 that the natural gas based pathways have the best energy efficiency, grid electrolysis as the worst and coal-to-hydrogen in between these. Coke oven gas-to-hydrogen pathways can be the best choice for both 15%HCNG and 30%HCNG options due to the dual benefits of lower energy use and GHG emission. Comparing Figure 6 and Figure 7, it is clearly evident that operating vehicles entirely with synthetic CNG is lesser energy and GHG intensive as compared with every 15%HCNG and 30%HCNG pathways which is quite optimistic as it is rare to find the exploration of synthetic CNG in a country like China on a very large scale.

4. CONCLUSIONS

In this research work, our significant contribution included a collection of localized input data for GREET simulation in order to evaluate the well-to-pump data of energy use, fossil energy use, GHG emitted and air pollutant emissions in the context of China. Secondly, the integration of well-to-pump results of hydrogen and CNG was achieved on a weighted average principle which is a simplified way which can be used for other studies involving a blend of different fuels such as hydrogen-methanol, hydrogen-gasoline, etc.

The general conclusion that can be drawn from Figure 6 summarized in terms of best-to-worst scenarios of total energy and GHG emissions.

GHG Emission: H2N1(best)<H3N1<H4N1<H6N1<H7N1<H1N1<H8N1<N1<H5N1<H9N1(worst)

Total Energy: H7N1(best)<H1N1<H8N1<H5N1<N1<H3N1<H4N1<H2N1<H6N1<H9N1(worst)

The 30%HCNG pathways except H5N1 and H9N1 showed lower well-to-wheel GHG emissions compared with baseline 0%HCNG (N1). Additionally, 30%HCNG pathways such as H7N1, H1N1, H8N1, and H5N1 showed lower well-to-wheel energy consumption compared with baseline 0%HCNG (N1). The exact increase and decrease amount with baseline 0%HCNG or N1 were shown in Figure 8. Hence, it can be concluded that solar, biomass and coke oven gas based 30%HCNG pathways have dual benefits of lower GHG emissions and lower energy consumption compared with 0%HCNG (Conventional NG only) on an entire well-to-wheel fuel cycle scale. Even though the energy consumption might be slightly higher for 30%HCNG pathways based on solar and biomass compared with 0%HCNG, the sources of feedstock are renewable in case of the solar pathway and usually organic wastes or agricultural by-products in case of biomass. As China has a tremendous amount of coke oven gas from coking and steel industries as by-products, it possesses a great prospect of hydrogen production in large quantity in a near-term future.

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APPENDIX 1 ABBREVIATIONS

WTW	Well-to-Wheel
WTP	Well-to-Pump
PTW	Pump-to-Wheel
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
HCNG	hydrogen-enriched compressed natural gas
US EPA	the United States Environmental Protection Agency
SI/CI	Spark-Ignition/ Compression Ignition
HDT/MDT/LDT	Heavy-Duty Trucks/Medium-Duty trucks/ Light-Duty Trucks
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
NGV	Natural Gas Vehicle
CNG/LNG	Compressed Natural Gas/ Liquefied Natural Gas
IEA	International Energy Agency
AFV	Alternative Fueled Vehicles
H/C	ratio hydrogen-to-carbon ratio
EEV	Enhanced Environmentally Friendly
TWC	Three-Way Catalyst
NEDC	New European Driving Cycle
PFI	Port-Fuel Injection
AFR	Air-to-Fuel Ratio
FCV	Fuel Cell Vehicle
EVs	Electric Vehicles
NG	Natural Gas
CNG	Compressed Natural Gas
ETC	European Transient Cycle
WHTC	World Harmonized Transient Cycle
GVW	Gross Vehicle Weight
GHG	Greenhouse Gases
GWP	Global Warming Potentials
LHV/HHV	Lower Heating Value/ Higher Heating Value
CCS	Carbon Capture & Storage
NMHC	Non-Methane Hydrocarbons
CO_2	Carbon dioxide
NO_x	Nitrogen Oxides
SO_x	Sulphur Oxides
CO	Carbon Monoxide
BSFC	Brake Specific Fuel Consumption
VOC	Volatile Organic Compounds
SO_2	Sulfur Dioxide
CH_4	Methane
HC	Hydrocarbons

APPENDIX 2 NOMENCLATURE

GH_2: Gaseous Hydrogen

LH_2: Liquid Hydrogen

CT: Central Station

RF: Refueling Station

C: Current Technology

F: Future Technology

CY: with CCS

CN: without CCS

WTP TE: Well-to-pump total energy (MJ) per MJ of fuel

WTW TE: Well-to-wheel total energy (MJ) per kilometer vehicle distance traveled

WTP GHG: Well-to-pump greenhouse gas emissions (grams of CO2 equivalent) per MJ of fuel

WTW GHG: Well-to-wheel greenhouse gas emissions (grams of CO2 equivalent) per kilometer vehicle distance traveled

x: fraction of hydrogen in HCNG

k: life cycle inventory (LCI)

Conv.NG: Conventional Natural Gas

gCO_{2eq}: grams of carbon-dioxide equivalent

MJ_f: Megajoules of energy in the finished fuel

Km: kilometers

MJ: Megajoules

APPENDIX 3

30%HCNG pathways

H2N1, H3N1, H4N1, H6N1, H7N1, H1N1, H8N1, H5N1, H9N1

0%HCNG Pathways

N1: Conventional Natural Gas

30% ***HCNG*** PATHWAY CODE	DESCRIPTION
H1N1	Central Plants: NG or FG to Gaseous Hydrogen+ Conventional Natural Gas
H2N1	Central Plants: Solar Energy to Gaseous Hydrogen+ Conventional Natural Gas
H3N1	Central Plants: Nuclear to Gaseous Hydrogen+ Conventional Natural Gas
H4N1	Central Plants: Electrolysis (HTGR) to Gaseous Hydrogen+ Conventional Natural Gas
H5N1	Central Plants: Coal to Gaseous Hydrogen+ Conventional Natural Gas
H6N1	Central Plants: Biomass to Gaseous Hydrogen+ Conventional Natural Gas
H7N1	Central Plants: Coke Oven Gas to Gaseous Hydrogen+ Conventional Natural Gas
H8N1	Refueling Stations: NG or FG to Gaseous Hydrogen+ Conventional Natural Gas
H9N1	Refueling Stations: Electricity to Gaseous Hydrogen+ Conventional Natural Gas