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Hydrogen Fuel Based Public Transport for Delhi

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Abstract-Given the success of Delhi's CNG vehicle program, energy stakeholders are now investigating a transition to hydrogen-compressed natural gas (H-CNG) blends in the city. Past research has shown H-CNG can reduce tailpipe emissions of both criteria and greenhouse gas pollutants relative to diesel, CNG, and gasoline. However, an unanswered question is how Delhi will satisfy the potential hydrogen demand in a sustainable manner. We conduct a techno-economic assessment of hydrogen production from gasification of the three most abundant agricultural residues near Delhi e rice straw, cotton stalk, mustard stalk e and find these residues could provide the city with up to 270,700 metric tons per year of hydrogen. This quantity far exceeds what is needed to run all existing CNG vehicles on 18%-82% H-CNG blends. The cost of each step of the bio-hydrogen supply chain is calculated and the total cost is estimated at 149.6 rupees ($3.39) per kg. Lastly, we show that the price of H-CNG at the pump would be roughly equivalent to CNG on a per mile basis.

Keywords: H-CNG, Gasification, Biomass, Delhi, India, Pollution

I. INTRODUCTION

Since 2000, Delhi has rapidly increased the use of compressed natural gas (CNG) in its transportation sector (Fig. 1) as a means of mitigating high air pollution levels. Despite initial improvements in some criteria pollutant levels, air quality has again deteriorated [1,2] and encouraged government and industry stakeholders to explore using a cleaner fuel hydrogen-compressed natural gas (H-CNG). H-CNG blendsoffer significantly lower tailpipe emissions of criteria pollutants and greenhouse gases (GHGs) relative to CNG and diesel and increased vehicle efficiencies relative to CNG [3-5]. Also, as discussed by Amrouche et al. [6] and others, H-CNG is a "bridging technology" which facilitates the build-out of a hydrogen infrastructure prior to the introduction of hydrogen fuel cell vehicles (FCVs). Lastly, the utilization of HCNG in a CNG engine requires only a minor engine modification, making the fuel an attractive option in cities with large CNG vehicle fleets. H-CNG was proposed in India's National Hydrogen Energy Road Map (NHERM) in 2003. Subsequently, the Indian Oil Corporation (IOC) conducted performance and emissions tests on passenger cars and Light Commercial Vehicles (LCVs) using 5%-25% volumetric blends. An 18% by volume or 2.9% by weight H-CNG blend was selected to be used in Delhi based on its combination of low emissions and superior engine performance. With a consortium of partners including the Society of Indian Automobile Manufacturers and the Ministry of New Renewable Energy (MNRE), IOC built two H-CNG dispensing stations near Delhi by 2007. Despite enthusiasm over H-CNG's potential within Delhi, a major question remained: how would Delhi produce enough hydrogen for a city-wide H-CNG program?

Hydrogen production is currently quite limited in India, with the majority of the gas being produced by oil refineries, fertilizer plants, and Chlor-alkali plants. The two active HCNG dispensing stations in Delhi generate hydrogen from onsite electrolysis units using grid electricity. Electrolysis is not desirable for the large-scale hydrogen production needed in a city-wide H-CNG program because it is an energy and emissions-intensive production process [8]. Hydrogen from coal gasification may be equally undesirable because of its high emissions when carbon sequestration is not used [9].

Hydrogen from nuclear power has much lower emissions than electrolysis [9] but is not a near-term option in India, a nation with four active nuclear power plants. Hydrogen from biomass gasification of agricultural residues, on the other hand, offers low emissions and may be possible at low cost [10]. India has decades of experience with biomass gasification for rural electricity generation [11]. Furthermore, Delhi is uniquely situated near the agricultural hubs of India where biomass residues are abundant and relatively inexpensive. Gasification has been shown to exhibit an economy of scale and is a suitable conversion technology for large demand centers [12]. Natural gas steam reformation, photo-biological water splitting, and hydrogen from wind and solar are also potential production pathways in Delhi but are not explored in this paper.

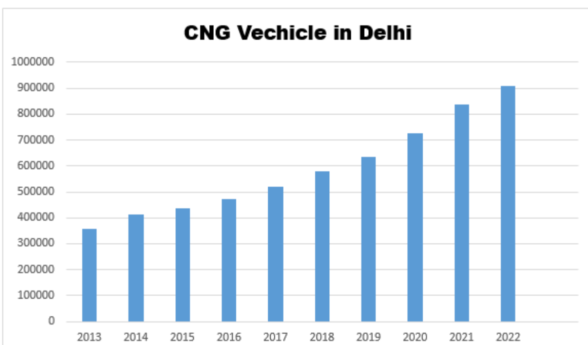

Fig. 1: Number of CNG vehicles (buses, auto, road-transit vehicles, others) in Delhi from 2013 to 2023 [7].

After providing background information on Delhi's transportation system, H-CNG fuels, and biomass gasification in Section 1, we assess the bio-hydrogen potential from agricultural residues within 150 km of Delhi in Section 2. This distance is chosen because it represents a conceivable distance for one-day's travel and return for a biomass truck on Indian roads. We focus on the three most abundant agricultural residue feedstocks near Delhi: cotton stalk, mustard stalk, and rice straw. Next, we calculate the quantity of hydrogen needed to run all 344,000 CNG vehicles in the city on 18%-82% volumetric blends of H-CNG.

In Section 3 we estimate a cost of each of the five steps in the biohydrogen supply chain. Residue-based hydrogen supply chains discussed in the literature typically have 5-7 steps (Fig. 2) including biomass procurement; transportation of biomass from the field or central market to the gasifier; conversion of biomass to hydrogen; compression of hydrogen, and distribution of hydrogen to the dispensing stations.

Depending on the system configuration, biomass densification and biomass storage may also be included between the procurement and biomass to hydrogen conversion steps.

These last two steps are only briefly discussed below. The cost of each step is presented in rupees (Rs.) per kg of hydrogen, allowing for comparability between steps (on April 12, 2011, $1 ¼ Rs. 44.2).

Finally, in Section 4 we provide a sensitivity analysis which varies several input parameters in the biohydrogen supply chain. This analysis suggests a cost range between Rs. 123 and Rs. 199 per kg of hydrogen ($2.78 to $4.25). We also discuss the potential price changes at the pump when using H-CNG instead of CNG. A simple price analysis reveals that the price of H-CNG at the pump will be on par with CNG on a per mile basis.

To our knowledge, this is the first study to investigate the cost and feasibility of hydrogen production used for H-CNG.

The conventionally held belief that hydrogen from renewable sources is only available at high production costs is challenged. The study has important implications for other developing countries with large CNG fleets and air quality problems.

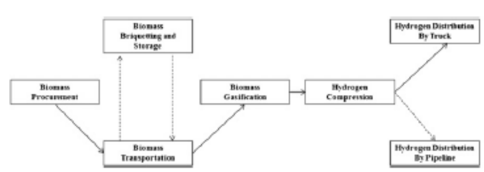

Fig. 2: Schematic diagram of bio-hydrogen supply chain.

1. Study Area

With a population of 16.7 million, Delhi is the second largest city in India [13]. Known for its poor air quality, the city boasts a rapidly expanding vehicle fleet; the number of vehicles per 1000 people increased from 192 in 1991 to 295 in 2006. The road length per 1000 vehicles decreased from 9.87 km to 6.46 km in that same time period [7]. Aneja et al. [14] find that particulate matter, NOx, and CO grossly exceeded India's National Ambient Air Quality Standards in the late 1990s. By 2000, the Indian Supreme Court mandated that all taxis, three-wheel vehicles, and public buses be immediately converted to CNG and that all new commercial vehicles sold in Delhi be CNG powered (see World Bank [15] for more information on the court intervention). The subsequent years represent one of the swiftest fuel transitions in history e since the year 2000, Delhi has added 344,000 CNG vehicles to its public and private vehicle fleets [7]. Despite small gains in CO and SO2, most criteria pollutants e and in particular NOx e remain at extremely high levels [16].

Natural gas is supplied by Indraprastha Gas, Ltd. (IGL) and is used in both the transportation sector and in homes and offices. CNG is widely available to vehicle operators with 213 dispensing stations throughout the city. IGL uses the mother daughter CNG distribution system whereby CNG is transported to the city via a network of pipelines which feed several mother stations. At the mother stations, mobile storage cascades are filled and transferred by truck to daughter stations where the gas is dispensed to the on-board CNG storage cylinders. Refueling takes place between 200 and 250 bar.

2. H-CNG Emissions

Two mechanisms help reduce tailpipe emissions when using H-CNG blends instead of CNG. First, the 18% hydrogen fraction of the H-CNG blend has zero tailpipe GHG emissions and lower criteria emissions than CNG for most pollutants (the major exception is NOx which is discussed below). Second, hydrogen improves the performance characteristics of the CNG by reducing the quenching gap, increasing the flame speed, and reducing the heat transfer losses for the CNG combustion [3].

However, quantifying the exact emission reductions from a transition to H-CNG in Delhi is difficult for a number of reasons. First, the conditions under which past H-CNG tests have been performed vary considerably. The measured emission levels depend on the H-CNG blend ratio; drive cycle; ignition timing; equivalence ratio; and engine power, speed, and size [17]. Additionally, the emission characteristics and fuel consumption of H-CNG vehicles have been tested in small-scale demonstration projects in India, Germany, China, Australia, and the United States, but to date no large-scale deployment of H-CNG vehicles exists. Finally, to properly estimate emission reductions from a city-wide program, one would need to make assumptions about the counterfactual fuel type (e.g., diesel, CNG, gasoline). Below we present results for a few selected studies to give a sense of the potential emission reductions.

Akansu et al. [17] provide a review of 22 H-CNG emission tests. They find that researchers generally agree H-CNG reduces tailpipe emissions of CO, hydrocarbons, and CO2 compared to CNG in nearly every engine operating condition.

Moreover, reductions continue with increasing hydrogen contents. On the other hand, for many studies NOx emissions increase in H-CNG engines due to higher combustion temperatures in H-CNG engines. NOx is a group of pollutants which adversely affects the human respiratory system and contributes to the formation of acid rain and ground-level ozone [18]. For a given drive cycle, NOx production is most dependent on the equivalence ratio and the hydrogen-CNG blend ratio [3]. However, studies have demonstrated that NOx emissions can be reduced by retarding the spark timing and by modifying the engine control unit mapping [3,4].

Burke et al. [4] collect data on engine emissions and power from two modified passenger buses in Northern California powered by 20e80 volumetric

H-CNG blends. From this dataset, they model engine performance, emissions, and power.

They find that constant power can be achieved while reducing NOx emissions between 85 and 91% and increasing fuel economy by 15e25% from pure CNG buses. However, hydrocarbon and carbon monoxide emissions increase. Other criteria emissions were not measured. The authors report that NOx formation is most sensitive to the equivalence ratio.

Other research also examines greenhouse gas (GHG) emissions from H-CNG. Studies undertaken by US-DOE under the Freedom Car Project use H-CNG blends up to 30% by volume in a modified Ford-150 truck [19]. The modifications include addition of a supercharger, changing ignition timings, and addition of an exhaust gas re-circulator. Compared to gasoline, H-CNG combustion reduced CO2 from 621 to 439 g per miles and increased CH4 from 0.01 to 0.08 g per mile, with a net reduction in GHGs. Other GHGs were not measured.

Table 1 GHG emissions from a municipal passenger bus [5].

	Diesel	Std. Dev	CNG	Std. Dev	H-CNG	Std. Dev	GWP*
CO_2 (g/km)	1411	63	1170	119	1035	39	1
CH_4 (g/km)	0.076	0.053	6.26	0.63	5.03	0.65	21
N_2O (g/km)	0.0966	0.0209	0.058	0.0302	0.0348	0.0147	310

Graham et al. [5] measure GHG tailpipe emissions of urban passenger buses for diesel, CNG, and a 20e80 hydrogen-CNG mixture (Table 1). They find that despite a marked increase in CH4 emissions, the net tailpipe GHG emissions for H-CNG are 20% lower per km than diesel and 13% lower than CNG.

They use the 100-year global warming potential (GWP) indexes from the IPCC Second Assessment Report. Since then, IPCC has updated these GWPs from 21 to 25 for CH4 and from 310 to 298 for N2O [20]. This lowers the GHG benefits of H-CNG relative to diesel but increases it relative to CNG. In sum, past research suggests that H-CNG reduces tailpipe criteria and GHG emissions over CNG, diesel, and gasoline. The exact emission reductions are dependent on engine specific characteristics, the hydrogen blend ratio, and the vehicle's drive cycle. A better understanding of the emissions resulting from different vehicle types and drive cycles for 18%-82% volumetric H-CNG blend is needed before an estimate of the overall emission benefits of a city-wide H-CNG program can be made.

3. Background on Bio Hydrogen Production Using Gasification

India has the highest number of biomass gasification units of any nation e nearly all of these are used for electricity production in rural areas. As of 2007, the country had 838 Mw of installed biomass gasification electricity production, mostly from cogeneration power using bagasse [21]. Other common feedstocks used in Indian gasification units include rice straw, rice husk, cotton stalk, and mustard husk.

Gasification to produce hydrogen is a process by which carbonaceous material containing between 10 and 20% moisture is fed into an oxygen-deficient environment and heated to high temperatures. The resulting syngas is primarily composed of CO, CH4, H2, C2H2, H2O, CO2, N2, and tars. Following filtration of the syngas to remove impurities, the gas passes through a water shift reactor to produce primarily H2 and CO2. One benefit of gasification is it offers higher daily production capacity than other biomass to hydrogen pathways like anaerobic digestion, biophotolysis, and fermentation and therefore could potentially be used to meet large-scale energy demand [11]. In addition to criteria emission reductions over most other hydrogen production pathways, biohydrogen production has relatively low GHG emissions. The National Academy of Science declared that hydrogen from biomass gasification "could play a significant role in meeting the DOE's goal of greenhouse gas mitigation" [8].

The cost of producing biohydrogen from gasification remains a point of contention in the literature. The EIA [8] estimates that a midsized biohydrogen production facility could provide hydrogen at a price of $7.05 per kg (Rs. 311.6 per kg) when including the cost of the construction of the dispensing station and $3.60 per kg (Rs.159.1 per kg) with future technology. Parker et al. [10] demonstrate that a spatially optimized biomass to hydrogen supply chain offers significant cost savings in the state of California when using two agricultural residues: rice straw and wheat straw. They calculate a delivered cost between $3 per kg for a high demand scenario of 735.7 kilotons (1 kiloton ¼ 1000 metric tons) of hydrogen per year and $5.50 per kg for a low demand scenario of 14.3 kilotons of hydrogen per year.

II. POTENTIAL HYDROGEN SUPPLY AND DEMAND IN DELHI, INDIA

Cotton stalk, mustard stalk, and rice straw were chosen for this study for several reasons. First, they are the three most abundant agricultural residues found near Delhi e the greatest quantities are in districts west and north of Delhi (Fig. 4).

Further, as non-fodder and non-fertilizer residues, they have few alternative uses outside of domestic heating and cooking. Often, they remain in the field after harvest and decay or are burned to comply with phytosanitary laws [22]. These residues would be useful in a coordinated biohydrogen supply chain because they are available at staggered times of the year (Fig. 3). All three residues have been used in limited quantities in India's distributed biomass gasification units.

Data on the availability of these residues comes from the MNRE's nation-wide biomass assessment conducted between 2000 and 2004 in which MNRE estimates crop production and biomass surplus by district in India [23]. For districts that lie within 150 km of Delhi's city center, MNRE reports a total of 4717 kilotons (kilotons) per year of the three residues considered here. This quantity reflects the air-dried quantity after other uses such as domestic heating have been removed. One important note is that typical biomass measurements are given in "wet" or "bone-dry" tons with moisture contents of 20-85% and w0%, respectively. Air-dried biomass, on the other hand, is biomass that sits in or near an agriculture field and dries in the sun. Here, we assume air-dried biomass has a 15% moisture content biomass [24].

To calculate the hydrogen production potential for this geographic region, the energy density of the biomass and hydrogen as well the gasification conversion efficiency are needed. Energy density of biomass is dependent on the biomass type (Table 2). For our calculations, we use the average higher heating value (HHV) for the three residues of 17.4 MJ per kg. We also use a HHV for hydrogen of 142 MJ per kg [24]. Many estimates of gasification conversion efficiencies exist in the literature; values range from 39% [8] to 67% [30]. We use the same efficiency as [9] of 55%. Thus, the theoretical hydrogen yield of biomass residues around Delhi is calculated as follows:

$$P=B*(1-M)* *E\_b/E\_h$$

where P is the hydrogen potential in kilotons per year, B is the air-dried biomass in kilotons per year, M is the moisture content of the biomass (%) used to convert from air-dried biomass to bone-dry biomass, h is the efficiency of conversion from bone-dry biomass to hydrogen, Eb is the energy density of bone-dry biomass, and Eh is the energy density of hydrogen. From Eq. 1, the theoretical hydrogen yield from biomass residues for the 150 km ring around Delhi is 270.7 kilotons of hydrogen per year for B ¼ 4717 kilotons. For comparison [9], find the hydrogen potential using gasification of biomass waste streams in California (including municipal solid waste, landfill gas, and forest waste) is 2345 kilotons per year (335 PJ per year).

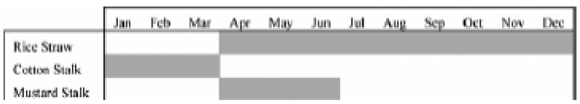

Fig. 3: Availability of residues in India.

A simple calculation demonstrates that these three biomass residues could easily satisfy hydrogen demand in Delhi if all CNG vehicles are converted to run on 18% H-CNG by volume. According to Delhi's Department of Transportation [7], the annual consumption of CNG in passenger vehicles in
Delhi in 2010 was 527 kilotons per year or 7.9-1011 L at standard temperature and pressure. Thus, the required hydrogen in kg to satisfy all of Delhi's current CNG demand is:

R ¼ H _ 0:18 _ V (2)

Where R is the hydrogen required in kilotons per year, N is the annual CNG demand for transportation in the city in liters per year, and V is the conversion of liters of hydrogen to kg of hydrogen (2 g of hydrogen per 22.4 L of hydrogen at standard temperature and pressure). Eq. (2) equals 12.8 kilotons per year of hydrogen when Delhi's 2010 CNG demand is assumed.

Using Eq. (1), then, the required amount of air-dried biomass to produce 12.8 kilotons per year of hydrogen is 222.6 kilotons per year, meaning these three biomass residues could provide roughly 20 times the required hydrogen for the existing CNG fleet (4717/222.6 z 20). Of course, in planning for an H-CNG transition, policymakers would need to consider the future demand of hydrogen, which could be significantly larger if fuel cell vehicles enter the market.

III. BIOHYDROGEN SUPPLY CHAIN COSTS

1. Biomass Procurement Costs

Unlike mostcrops in India, agricultural residues are largely free of government price controls and therefore have costs that reflect market equilibrium. If there is no demand for the residues then their prices should be the cost of the labor in harvest and collection of the residues as done by Tripathi et al. [31]:

C=W/(A*N)

Where C is the collection cost, W is the daily wage rate for a day laborer, A is the carrying capacity of one laborer (in tons per trip), and n is the number of trips made by a person in a day. In 2010 in the area around Delhi, the government-mandated wage for day laborers was Rs.167.23 per day. Using the same
assumptions as Tripathi et al. [31] that C is 0.030 tons per trip and n is 50 trips per working day means that A * N ¼ 1.5 and the cost of collection of biomass per ton is 167/1.5 Rs. 111.5 per ton of air-dried biomass. However, we feel Tripathi's approach likely underestimates the procurement cost because it does not account for the cost of supervisors, the capital needed to collect the residues, or market competition.

Table 2 Values for Energy and Bulk Densities

	HHV (MJ/kg)	Source	Uncompacted Bulk	Source	Briquetted Bulk	Source
Cotton Stalk	18.12-18.80	[25]	100-130	[25]	542-794	[28]
	15.83-18.26	[22]	100-105	[28]		
Rice Straw	12.9	[26]	235	[27]	1010	[29]
	15.5	[27]				

Mustard Stalk	20.5	[27]	150-200	[27]	100	
Average	17.4	-	172.9	-	892.7	

Another method for estimating residue costs, which we use in this study, is to report costs of residues at a local marketplace. These costs vary by marketplace, time of year, and residue type. In Fig. 5, we present cost estimates from two agricultural professors [32,33] at universities near Delhi and two Deputy Directors of Agriculture for district governments near Delhi [34,35]. These estimates were collected in phone and email interviews. The outlying estimate for mustard stalk comes from the Deputy Director of Agriculture in Fatehabad, a district with a relative paucity of mustard stalk residue. The average marketplace procurement costs of cotton stalk, mustard stalk, and rice straw are Rs. 483, Rs. 850, and Rs. 369 per ton of air-dried biomass, respectively. Using Eq. (2) to represent these in rupees per kg of hydrogen rather than per ton of air-dried biomass, these costs are Rs. 9.8, Rs. 17.2, and Rs. 7.5 per kg of hydrogen with an average of Rs. 11.5 per kg.

It appears residue procurement is one step of the bio-hydrogen supply chain in which India holds a considerable cost advantage over developed nations. Typical agricultural residue procurement costs given in the U.S. range from $1.5e5 per GJ biomass at the field [9,36]. After converting to dollars per GJ, the three residues considered here range in cost from $0.59-0.93 per GJ. However, because the costs in Fig. 5 are single point estimates for residues with few alternative uses, they likely represent the cheaper end of the residue supply curve. At higher demand levels for residues, the costs will almost certainly go up. Developing residue-specific supply curves in India could help advance the Indian biofuel industry by providing greater cost certainty to potential biofuel producers.

2. Briquetting Costs

Briquetting is a form of biomass densification common in India. The cost of purchasing and operating a briquetting unit is high and presents a tradeoff with the reductions in the biomass transportation cost.

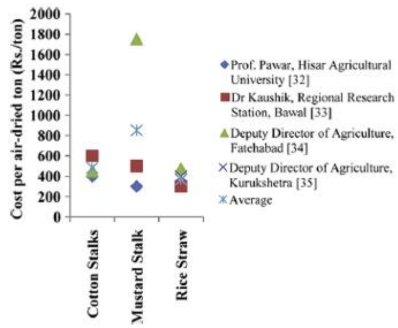

Fig. 5 Biomass procurement costs estimates.

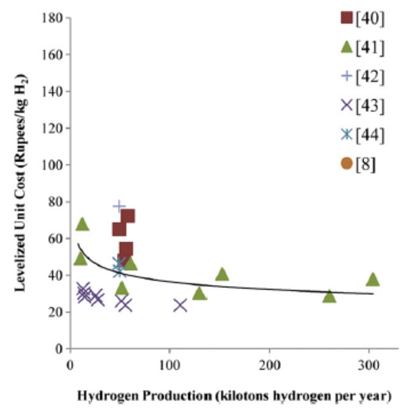

Fig. 6 Levelizedunit cost (Rs/kg) of different sized gasifiers.

Therefore, whether such machines will reduce total supply chain cost depends on the cost of owning and operating a truck and briquetting unit, the loose biomass density, the briquetted biomass density, and the total distance from the field to the gasification unit(s). Also, uncertainties such as power supply failures may present a barrier to smooth and profitable operation of briquetting plants [37]. There are two main types of briquetting machines used in India: a piston-type and a screw-type. Bhattachary [38] finds that the piston-type is slightly more common. Tripathi et al. [39] report that the cost of briquetting was about Rs. 500 per ton of biomass in 1997. After accounting for changes in purchasing power parity, this amount is equivalent to Rs. 998 per ton today or Rs. 17.39 per kg of hydrogen.

3. Storage Costs

The storage cost includes the cost of handling and the capital invested in the storage facility. Storage costs are also the rental cost of the space and the cost incurred to cover the residues to protect them from rain. Normally, residues are stored on the farm in an open space where they are produced and are transported as early as possible. In the analysis presented here, the contribution of storage cost to the cost of residues is assumed to be negligible due to the low cost of land and labor in rural areas outside of Delhi.

4. Biomass Transportation Costs

While a number of different vehicles move biomass in India, in this study we assume commercial grade trucks are used rather than animal carts and tractors. Biomass freight trucks in India vary in capacity between 8.6 and 33.7 cubic meters.

Also, the maximum carrying capacity of a single truck is limited to 15 tons by government regulation [28]. For comparison, the maximum weight carried in the U.S. is 25 tons of biomass [12]. Given the bulk densities of the agricultural residues considered above (Table 2), the largest Indian biomass trucks could carry 3.2, 5.2, and 7.0 tons of undensified cotton stalk, mustard stalk, and rice straw, respectively, or an average of 5.83 tons. When the residues are briquetted, all three residues are constrained by the 15 ton weight limit rather than the truck capacity. Borrowing from Tripathi et al. [31], the transportation cost can be expressed as: where the variables have definitions according to Table 3.

We assume a total one-way transportation distance of 75 km (10 on rural roads and 65 on primary roads) because, as mentioned early, the residue availability within 150 km is more than sufficient to supply the necessary 12.8 kilotons per year of hydrogen needed per year. Utilizing Eq. (4) and the parameter values in Table 3, the biomass transportation cost is Rs. 7.1 per kg of hydrogen.

5. Hydrogen Production from Biomass Gasification Cost

Singh and Gu [11] present a useful summary of gasification production costs, utilization factors, electricity output, hydrogen production, and internal rates of return for 38 biomass to hydrogen gasification facilities. Using these, we calculate and plot (Fig. 6) a levelized unit cost of production which clearly shows the cost benefits of larger production facilities [8,40-44]. The best fit curve describes the levelized unit cost of production, L, in rupees/kg of hydrogen:

Where Q is the gasifier size in kg of hydrogen produced per day. The assumptions embedded in this equation are as follows.

The fixed operating cost is 5% of the annualized gasifier cost and the assumed lifetime of the biorefinery is 15 years. The internal rates of return are assumed to be 10%. The gasifier's capacity factor is 90% (the gasifier is used 90% of all days) and the electricity cost is Rs. 0.05 per kW-h, consistent with current electricity prices in Delhi. Lastly, some of the biomass to hydrogen gasifiers in Fig. 6 use natural gas for startup, at a cost of Rs. 265 per GJ of natural gas. Eq. (5) allows policymakers to estimate hydrogen production costs of any sized biorefinery given the above assumptions.

To calculate the size of the gasifier, we assume all 344,000 CNG vehicles are converted to H-CNG. Thus, M ¼ 12.8 kilotons per year and L ¼ Rs. 52.4 per kg of hydrogen.

Two units half this size would mean M ¼ 6.4 kilotons per year and L ¼ Rs. 59.2 per kg of hydrogen. A sensitivity analysis is presented below to account for other hydrogen demand levels.

6. Hydrogen Compression and Distribution Cost

India faces numerous challenges in distributing hydrogen from central production facilities. The road infrastructure has poor connectivity, is inadequately maintained, and is often congested, even in rural areas. Movement of heavy vehicles is restricted in Delhi to the hours of 10 pm to 6 am, but even at these hours roadways suffer from severe congestion.

Furthermore, due to regulatory barriers, hydrogen is delivered almost exclusively by low pressure (200 bar) gaseous cylinders, thus limiting the amount of hydrogen per truck. Two common delivery methods in developed countries are high pressure (700 bar) tube trailers which carry 300-400 kg per truck and cryogenic liquefied hydrogen (LH2) which carry roughly 4000 kg per truck [45]. However, both methods in India are approved only on a case by case basis. Also, the DOE [45] recommends that liquefied hydrogen only be used for deliveries over 350 km due to the energy expended in the liquification process, likely making this an unsuitable delivery option in Delhi.

Below we present distribution costs for gaseous truck delivery by cylinders for 200, 350, and 700 bar (Table 4). We assume the biomass gasifier is located on the periphery of Delhi and that the one-way delivery distance from gasifier to dispensing station is 50 km. Such an arrangement is consistent with Parker et al.'s [10] finding that the lowest cost biorefinery siting option is close to the demand centers rather than close to the biomass.

Another potential delivery option is to locate the gasifier(s) for Delhi adjacent to the natural pipeline and mix 18% hydrogen with the city's natural gas. This could reduce costs by allowing the gasifier(s) to be located closer to the residue supply and by removing the gaseous truck transportation costs. An analysis of this delivery method is not conducted here, but is recommended for future research. Two technical questions that would need to be answered prior to introducing hydrogen into an existing CNG pipeline are: (1) what effect will hydrogen embrittlement have on the existing CNG pipeline and (2) what effect will hydrogen have on non-vehicular end users of natural gas? The first question is most recently discussed by Dickinson et al. [46] who find that no consensus exists on whether hydrogen can safely be mixed with natural gas in existing CNG pipeline without concern of failure by hydrogen embrittlement. They state that while most research supports using small proportions of hydrogen mixtures without unsafe hydrogen embrittlement, the quoted maximum acceptable levels vary from 3 to 25%. Therefore, more research is needed. Lowesmith et al. [47] study the safety implications related to unexpected escapes of H-CNG gas within homes and find that the explosive risk of accidental escapes of H-CNG blends are higher than pure CNG due to the higher flowrates and diffusivity of H-CNG. Also, using a computer simulation model, Middha et al. [48] compare explosive pressures of hydrogen, H-CNG, and pure methane. The explosion scenarios are modeled in a private garage, a public parking garage, and a tunnel. In general, the danger of H-CNG is slightly higher than pure methane in the private and public parking garages, but lower in the tunnel. H-CNG is deemed less dangerous in all scenarios compared to hydrogen.

IV. TOTAL COST AND SENSITIVITY ANALYSIS

Fig. 7 presents the hydrogen cost per kg of each step in the bio-hydrogen supply chain. The production and compression steps each account for about 1/3 of the total supply chain cost. As stated above, these estimates assume all CNG vehicles in 2010 are converted to H-CNG. In reality, during the initial transition to H-CNG, smaller gasification units could be used to meet demand but this would increase the cost per kg. Indeed, the "chicken and egg" problem is a well-known barrier to a full hydrogen economy [8].

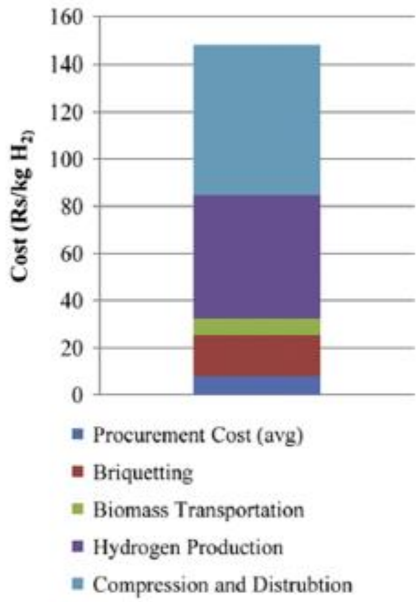

Fig. 7 Supply chain costs.

A cost of Rs. 149.6 per kg of hydrogen far exceeds India's national hydrogen roadmap 2020 cost targets of Rs. 60-70 per kg at the delivery point but is comparable to the cheapest future biohydrogen cost estimates in the U.S. [8,9]. Fig. 8 is a sensitivity analysis showing how various inputs into the model affect the final cost of hydrogen per kg. We can see that the internal rate of return has the steepest curve, indicating the highest sensitivity. Varying these parameters between p-10% and 10% results in a cost of hydrogen between Rs. 123 and Rs. 199 per kg ($2.78 to $4.25). Understanding how the price of H-CNG at the pump compares to CNG requires an economic analysis that accounts for demand elasticities, taxes, and government price controls.

This analysis is not conducted here. However, we can approximate the price difference using the following calculation. In June 2011, the price of CNG in Delhi at the pump was 29.8 per kg [49]. From above, the estimated bio-hydrogen cost of 149.6 rupees per kg includes production and distribution costs up to the end-user but does not account for markups by the distributor. For simplicity, we assume this markup is 10% of the production costs. Thus, the price of pure bio-hydrogen at

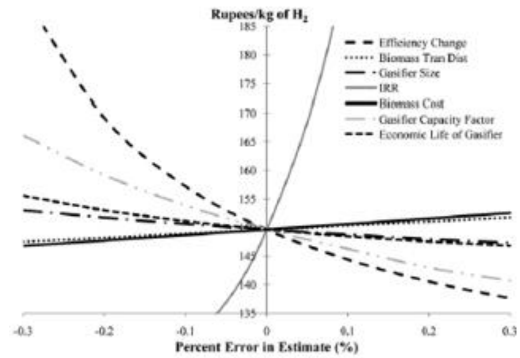

Fig. 8 Sensitivity analysis: change in delivered cost with change in parameter.

The pump would be 164.6 rupees per kg (149.6*1.1). Since the hydrogen fraction is 2.9% by weight, the cost increase of HCNG on a weight basis will be:

However, CNG and H-CNG are not equivalent on an energy basis (MJ/kg). Rather, the addition of 2.9% hydrogen by weight to CNG increases the energy content by 11% (when using HHV) [50]. This is calculated by: (7)

Where Ex is the energy per kg (MJ/kg) of H-CNG and CNG.

Furthermore, engine efficiencies increase when using H-CNG over CNG. Dimopoulos et al. [51] demonstrate that an optimized four-cylinder Volkswagon H-CNG passenger vehicle running on hydrogen blends of 5-15% will be 3-5% more efficient than its CNG equivalent. Others have demonstrated similar engine efficiency gains using H-CNG [52,53]. Thus, it is reasonable to expect the cost per mile of H-CNG is on par with CNG. An important final note e our analysis makes no effort at predicting the cost of the engine alterations needed to run the vehicle on H-CNG.

V. CONCLUSION

The city of Delhi has an excellent opportunity to improve its air quality and reduce GHG emissions by blending small amounts of hydrogen with CNG. The agricultural region near Delhi has 20 times more biomass residue than is needed to fuel the current CNG vehicle fleet with an 18%e82% H-CNG mixture by volume. Also, H-CNG fuel may be price competitive with CNG on a per mile basis. Cleaning the air over Delhi will not be easy, but a large-scale H-CNG program is a positive step and could help pave the way for other cities with large CNG fleets to begin their own transitions to hydrogen economies.

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