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Hydrogen Transportation in Dehli? Investigating the Hydrogen Compressed Natural Gas (H-CNG) Option

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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. Past research has shown H-CNG can reduce tailpipe emissions of both criteria and greenhouse gas pollutants relative to diesel and CNG. Here, we examine hydrogen production via gasification of three abundant, non-fodder residues: rice straw, cotton stalk, and mustard stalk. The total availability of these three residues in districts within 150 km of Delhi is 4,717 kilotons (KTs) per year, enough to produce 270.7 KT per year of hydrogen using gasification. This amount far exceeds what is needed to support the current CNG vehicle population with 18%-82% H-CNG blends. The cost of each step of the biohydrogen supply chain is reported in terms of rupees per kg of hydrogen and the total cost of using biohydrogen in Delhi is estimated to be 149.6 rupees (₹) ($3.39) per kg.

Keywords: H-CNG, gasification, biomass, Delhi, India, pollution

1. 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 blends offer significantly lower tailpipe emissions of criteria pollutants and greenhouse gases (GHGs) relative to CNG and diesel and increased vehicle efficiencies relative to CNG [3,4,5]. Also, as discussed by Amrouche et al. [6] and others, H-CNG is a "bridging technology" which allows the build-out of a hydrogen infrastructure prior to the introduction of hydrogen fuel cell vehicles (FCVs). Lastly, the utilization of H-CNG 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 (SIAM) and the Ministry of New Renewable Energy (MNRE), two H-CNG dispensing stations were built 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?

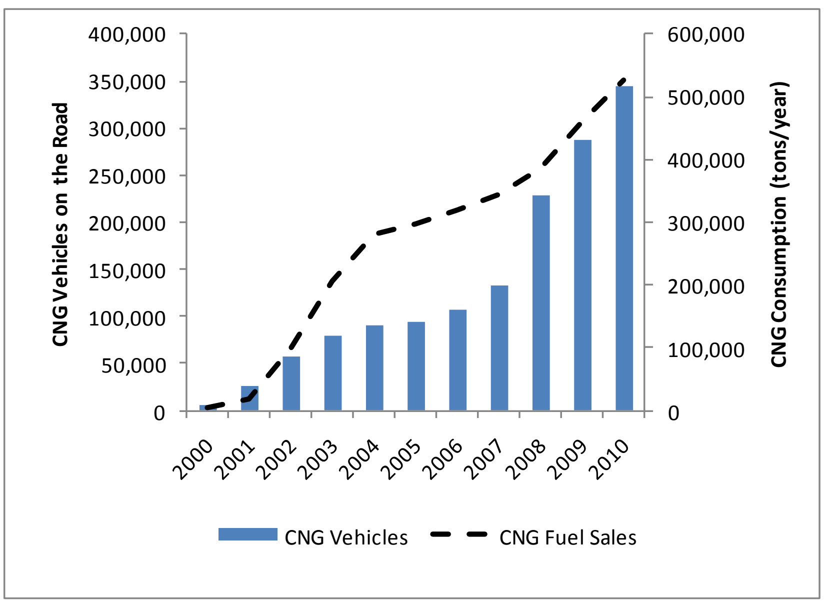

Figure 1 - Growth in CNG vehicles and fuel sales in Delhi from 2000-2010 [7].

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 H-CNG 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 and hydrogen from wind and solar are also potential production pathways in Delhi but are not explored in this paper.

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. The first task of this paper is an assessment of the hydrogen potential from residues within 150 km of Delhi. This distance is chosen because it represents a conceivable distance for one-day's travel and return for a biomass truck on Indian roads.

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. This quantity, then, determines the size of the gasification unit. We focus on the three most abundant agricultural residue feedstocks near Delhi: cotton stalk, mustard stalk, and rice straw. Lastly, the main focus of this paper is estimating a cost of each of the five steps in the biohydrogen supply chain. The cost of each step is presented in rupees per kg of hydrogen (₹/kg), allowing for comparability between steps (on April 12, 2011, $1 = ₹44.2).

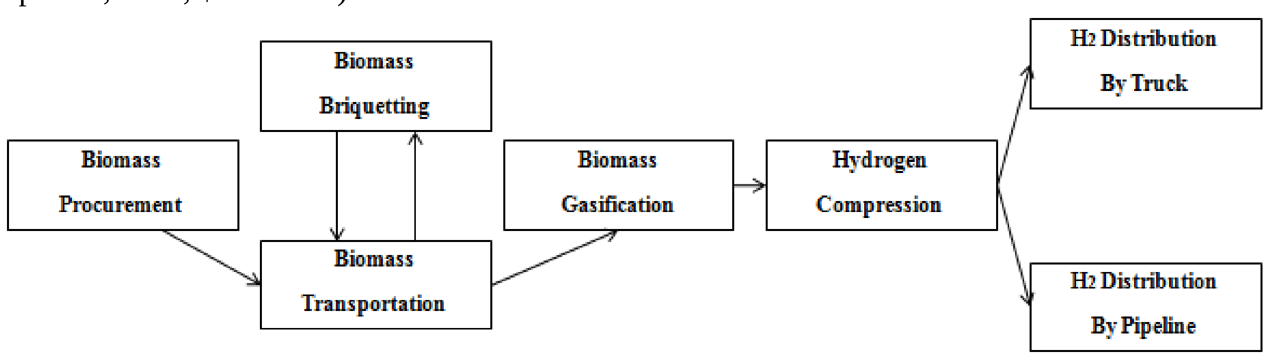

Figure 2 - Schematic diagram of bio-hydrogen supply chain

1.1 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 1,000 people increased from 192 in 1990-91 to 295 in 2005-2006 and the road length per 1,000 vehicles decreased from 9.87 km to 6.46 km [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 -- 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 SO_2, most criteria pollutants – and in particular NOx - remain at 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 200-250 bar.

1.2 H-CNG Emissions

Two mechanisms help reduce tailpipe emissions when using H-CNG blends instead of CNG. First, the main combustion product of hydrogen is water; thus, the 18% hydrogen fraction of the H-CNG blend has zero tailpipe emissions. 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 that H-CNG reduces tailpipe emissions of CO, hydrocarbons, and CO_2 compared to other fuels 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 ECU mapping [3,4].

Burke et al. [4] collect data on engine emissions and power from two modified passenger buses in Northern California powered by 20-80 volumetric H-CNG blends. From this dataset they build an engine model that predicts emissions and engine power for three drive cycles. They find that constant power can be achieved while reducing NOx emissions between 85-91% and increasing fuel economy by 15-25%. However, hydrocarbon and carbon monoxide emissions increase in all drive cycles. Other criteria emissions were not measured. The authors report that NOx formation is most sensitive to the equivalence ratio.

Other research examines greenhouse gas (GHG) emissions from H-CNG. Studies undertaken by US-DOE under the FreedomCar 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 a gasoline, H-CNG combustion reduced CO_2 by 29.4% but increases CH_4 by 6.8 times. Other GHGs were not considered.

Graham et al. [5] measure CO_2e tailpipe emissions of urban passenger buses for diesel, CNG, and a 20-80 hydrogen-CNG mixture (Table 1) [5]. They find that despite a marked increase in CH_4 emissions, the net tailpipe CO_2e emissions for H-CNG are 20% lower per km than diesel and 13% lower than CNG. They use the 100-year global warming potential indexes from the IPCC Second Assessment Report. Since then, IPCC has updated these GWPs from 21 to 25 for CH_4 and from 310 to 298 for N_2O [20]. This lowers the CO_2-e benefits of H-CNG relative to diesel but increases it relative to CNG.

Table 1. CO2e emissions from a municipal passenger bus [5].

	Diesel	Std. Dev	CNG	Std. Dev	H-CNG	Std. Dev	GWP[a]
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

In sum, past research suggests that H-CNG reduces tailpipe criteria emissions over CNG and diesel and may reduce GHG emissions relative to the same fuels. The exact emission reductions are dependent on engine-specific characteristics, the hydrogen blend ratio, and the vehicle's drive cycle. It may be possible to characterize a city's pollution reduction from H-CNG with more research on vehicle-specific emissions.

1.3 Background on Biohydrogen Production using Gasification

India has the highest number of biomass gasification units of any nation – 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 10-20% moisture is fed into an oxygen-controlled environment and heated to high temperatures. The resulting syngas is primarily composed of CO, CH_4, H_2, C_2H_2, H_2O, CO_2, N_2, and tars. Following filtration of the syngas to remove impurities, the gas passes through a water shift reactor to produce primarily H_2 and CO_2. 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/kg (₹311.61/kg) when including the cost of the construction of the dispensing station and $3.60/kg (₹159.12/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/kg for a high demand scenario of 735.7 KT of hydrogen/yr and $5.50/kg for a low demand scenario of 14.3 KT of hydrogen/yr.

2. 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 -- 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.

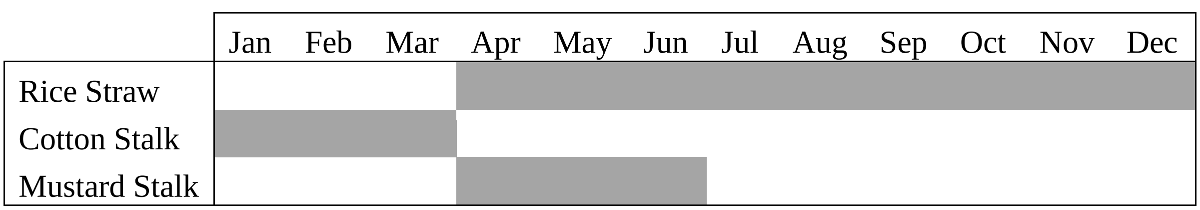

Fig. 3 - Availability of residues in India

Data on the availability of these residues comes from the Ministry of New and Renewable Energy's (MNRE) 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 4,717 kilotons (KT) 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 ~0%, 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. A moisture content of 15% is assumed for the air-dried biomass [24].

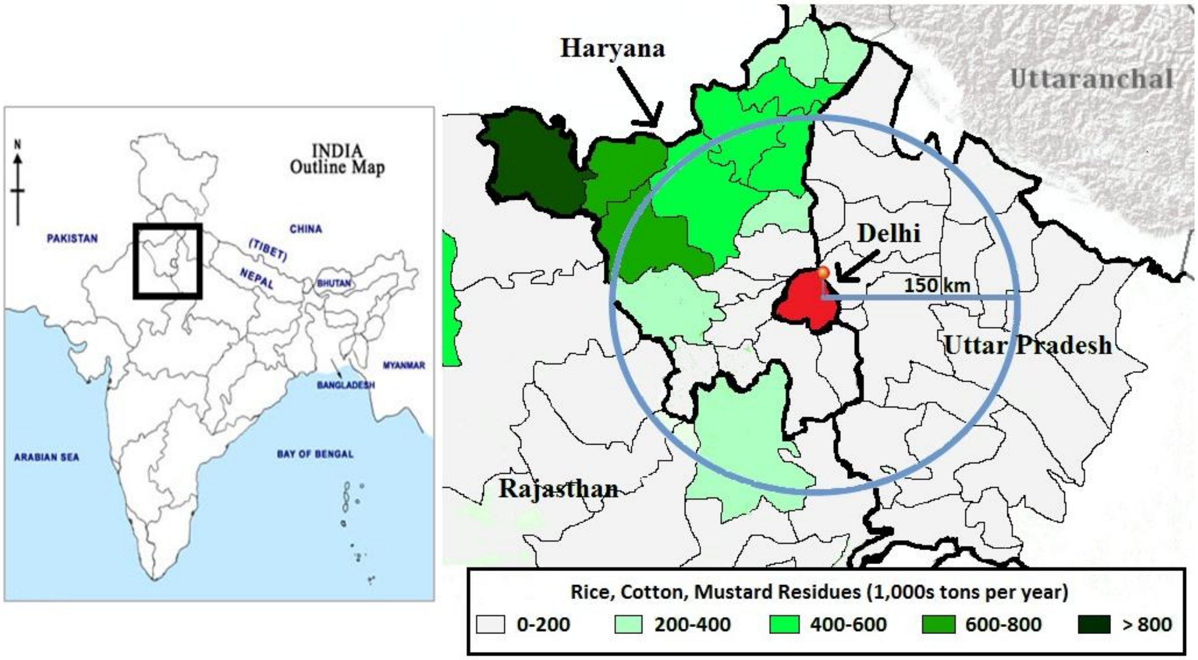

Fig. 4 - Residue availability of cotton stalk, mustard stalk, and rice straw

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/kg. We also use a HHV for hydrogen of 142 MJ/kg [24].

Table 2. Values for energy and bulk densities

	HHV (MJ/kg)	Source	Uncompacted Bulk Density (kg/m^3)	Source	Briquetted Bulk Density (kg/m^3)	Source
Cotton Stalk	18.12-18.80; 15.83-18.26	[25] [22]	100-130 100-105	[25] [28]	542-794	[28]
Rice Straw	12.9, 15.5	[26] [27]	235	[27]	1010	[29]
Mustard Stalk	20.5	[27]	150-200	[27]	1000[a]	
Average	17.4	-	172.9	-	892.7	

[a]No value found for mustard stalk. 1000 kg/m3 assumed.

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 are is calculated as follows:

$$H_p = B * (1 - MC) * eff * ED_b / ED_h \quad (1)$$

where H_p is the hydrogen potential per year, B is the air-dried biomass in kilotons per year, MC is the moisture content of the biomass (%) used to convert from air-dried biomass to bone-dry biomass, *eff* is the efficiency of conversion from bone-dry biomass to hydrogen, ED_b is the energy density of bone-dry biomass, and ED_h is the energy density of hydrogen. From Equation 1, the theoretical hydrogen yield from biomass residues for the 150km ring around Delhi is 270.7 KTs of hydrogen per year for B = 4,717 KT. 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 2,345 KT/year (335 PJ/year).

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 KT per year or 7.9 x 10^{11} liters at standard temperature and pressure. Thus, the required hydrogen in kg to satisfy all of Delhi's current CNG demand is:

$$H_r = CNG * 0.18 * C \tag{2}$$

Where H_r is the hydrogen required in KT per year, CNG is the annual CNG usage of the city in liters per year, and C is the conversion of grams of liters of hydrogen to kg of hydrogen (2 grams of hydrogen per 22.4 liters of hydrogen at standard temperature and pressure). Equation 2 equals 12.8 KT per year of hydrogen. Using Equation 1, the required amount of air-dried biomass to produce 12,775 tons/year of hydrogen is 222.6 KT per year, meaning these three biomass residues could provide roughly 20 times the required hydrogen for H-CNG for the entire city ($\frac{4717}{222.6} \approx 20$). Of course, policymakers would need to consider future demand of hydrogen, could be large if H-CNG vehicles have similar adoption rates as CNG.

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3. Biohydrogen Supply Chain Costs

3.1 Biomass Procurement Costs

Unlike most crops in India, agricultural residues are largely free of government price controls and therefore have costs that reflect market equilibrium. These costs can either be expressed as the cost at the agricultural field or the cost in a central marketplace. Tripathi et al. [31] estimate residue costs in India at the agricultural field by accounting for the cost of labor in collection and assuming the residues have no price competition:

$$C_{rc} = W/(C_c*n) \tag{3}$$

where C_{rc} is the collection cost, W is the daily wage rate for a day laborer, C_c 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 ₹167.23 per day. Using the same assumptions as Tripathi et al. [31] that C_c is 0.030 tons/trip and n is 50 trips per working day means C_c*n = 1.5 and the cost of collection of biomass per ton is ₹167/1.5

= ₹111.5/ton of air-dried biomass. We expect the feedstock costs to be higher than this since Equation 3 fails to account for field supervisors or capital needed to collect the residues.

The other method for estimating residue costs, which we use in this study, is to find costs of residues at a local marketplace. These costs vary by marketplace, time of year, and residue type. In Figure 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 ₹483, ₹850, ₹369/ton of air-dried biomass, respectively. Using Equation 2 to represent these in rupees per kg of hydrogen rather than per ton of air-dried biomass, these costs are ₹9.8, ₹17.2, and ₹7.5/kg of hydrogen with an average of ₹11.5/kg.

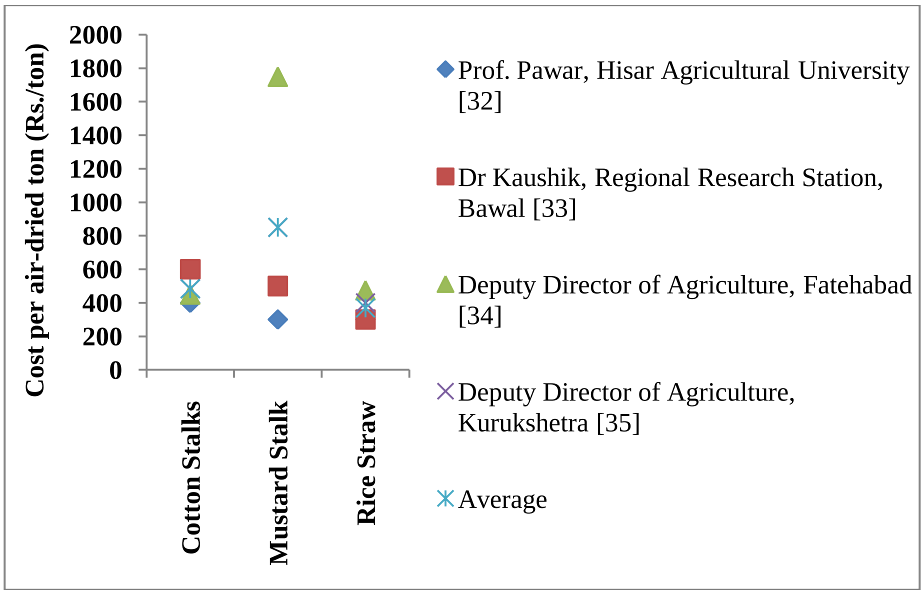

Fig. 5 - Biomass procurement costs estimates

It appears residue procurement is one step of the biohydrogen 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 $1.5-5/GJ biomass at the field [9, 36]. After converting to $/GJ, the three residues considered here range in cost from $0.59-0.93/GJ. However, because the costs in Figure 6 are single point estimates for residues with few alternative uses, they 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.

3.2 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. 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 ₹500/ton of biomass in 1997. After accounting for changes in purchasing power parity, this amount is equivalent to ₹998/ton today or ₹17.39/kg of hydrogen. Whether or not a briquetting step makes economic sense in a biohydrogen supply-chain near Delhi is discussed more in section 3.4.

3.3 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.

3.4 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 and 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 [11]. 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:

$$Tc_n = 2 \ x \ d_n \ x \ (Fc_n \ x \ Cf + Wd + Cp)/(Cc_n \ x \ Ts_n) \qquad (4)$$

where the variables have definitions according to Table 3.

Table 3. Variable descriptions for transportation costs		
Variable Name	**Parameter**	**Value**
Tc_n	Total cost of transporting biomass in Rs./kg for undensified (n=1) or briquetted (n=2) biomass	Variable
d_n	One-way transportation distance of biomass	10 miles (n=1); 65 miles (n=2)
Fc_n	Truck's fuel consumption per hour	6 liter/hr on rural roads (n=1); 10 liter/hr on primary roads (n=2)
Cf	Cost of fuel	Rs.36.79 /liter[a]
Wd	Driver's hourly wage	Rs.30/hr
Cp	Capital cost of truck per hour of operation + 10% O&M	Rs.715/hr[b]
Cc_n	Capacity of biomass freight truck	5.83 tons/truck (n=1); 15 tons/ truck (n=2)
Ts_n	Transportation speed of truck	20 km/hr on rural roads (n=1); 30km/hr on primary roads (n=2)

[a] diesel fuel cost Dec 2010 in Delhi;
[b] based on one truck capital cost Rs. 1.4 million; lifetime 300,000km; operational for 16 hours/day, 330 days/year; 10% IRR; 10% O&M costs

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 12,775 KT/year of hydrogen needed per year. Utilizing Equation 4 and the parameter values in Table 3, the biomass transportation cost is ₹7.1/kg of hydrogen.

3.5 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.

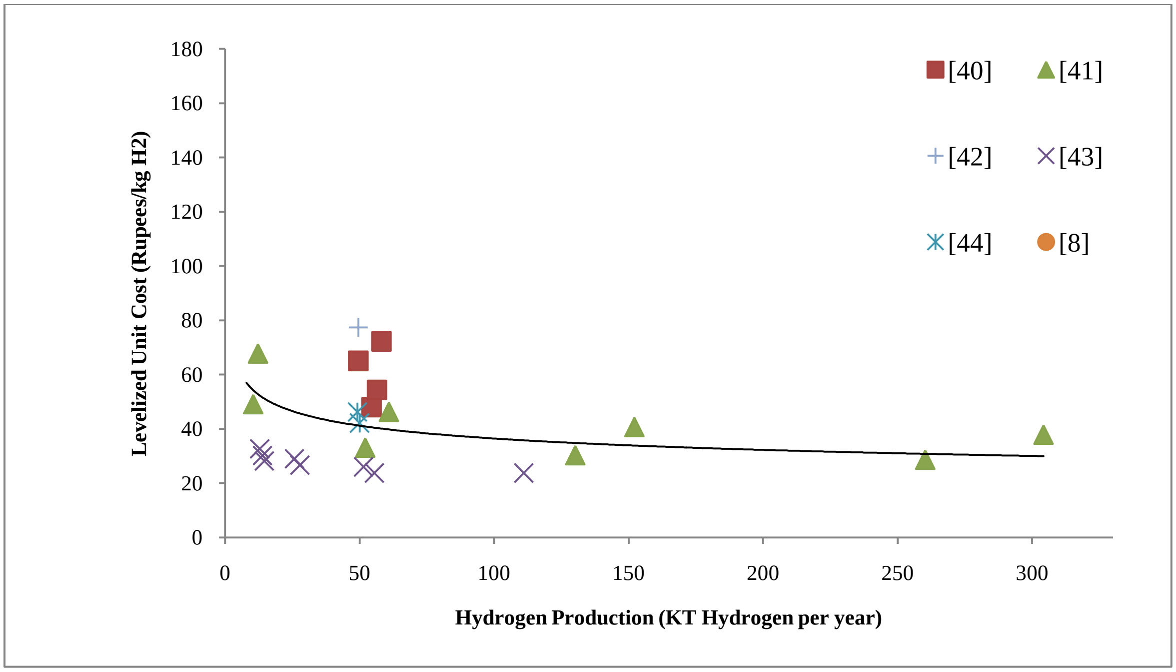

Figure 6 – Levelized unit cost (Rs/kg) of different sized gasifiers

The best fit curve describes the levelized unit cost of production, LUC, in ₹/kg of hydrogen:

$$LUC = (336.51 * M^{-0.176}) \tag{5}$$

where M 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 0.05₹/kw-hr, consistent with current electricity prices in Delhi. Lastly, some of the 38 biomass to hydrogen gasifiers use natural gas for startup, at a cost of 265₹/GJ of natural gas. Some gasifiers in Figure 6 appear to have very small or negative levelized costs because in these gasifiers, electricity is sold back to the grid. These gasifiers, therefore, are apparently benefiting from the sale of an end-product whereas the others are not.

Equation 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 and that the gasifier operates 330 days per year. So, M=38,700 kg/day and LUC = ₹52.4/kg of hydrogen. Two units half this size would mean M=19,350 and LUC = ₹56/kg of hydrogen. A sensitivity analysis is presented below to account for other hydrogen demand levels.

3.6 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

10pm to 6am, 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 other countries are high pressure (700 bar) tube trailers which carry 300-400 kg per truck and cryogenic liquefied hydrogen (LH2) which carry roughly 4,000 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 350km 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.

Table 4. Compression and distribution costs for CNG and hydrogen at different pressures

Compression and Distribution	Unit	Hydrogen @ 200 bar	Hydrogen @ 350 bar	Hydrogen @ 700 bar
Cylinders				
Hydrogen in 800m3 cascade	kg	71	102	203
Cylinders per truck	cylinders	40	40	40
Compression energy to get to pressure	MJ/kg	14	17.5	22
Compression energy in kw-hr	kw-hr/kg	3.89	4.86	6.11
Cascade deliveries per day	cylinders/day	493	343	172
Cost: Per cylinder per day [a]	Rs./cylinder/day	6	8	10
Cost: Cylinders per kg of H2	Rs./kg	3.38	3.14	1.97
Cost: Compression [b]	Rs./kg	19.44	24.31	30.56
Compressor				
Compressor output	kg/day	90,000	90,000	90,000
Lifetime of compressor	years	10	10	10
Cost: Compressor capital per compressor	Rs.	20 million	20 million	20 million
Cost: Compressor capital per kg H2	Rs./kg	7.3	7.3	7.3
Cost: Compressor maintenance	Rs./kg	0.28	0.28	0.28
Cost: Internal rate of return for compressor	%	10	10	10
Hydrogen Storage				
Cost: Temporary storage tank at gasifier	Rs./kg	4.62	4.62	4.62
Cost: Maintenance of storage tank	Rs./kg	0.18	0.18	0.18
Truck				
Internal rate of return	%	10.0	10.0	10.0
Lifetime of truck	km	300,000	300,000	300,000
Cost: Fuel for distribution by truck	Rs./kg	5.2	3.6	1.8
Cost: Driver for distribution by truck	Rs./kg	1.7	1.2	0.6
Cost: Truck capital per kg H2	Rs./kg	17.0	11.9	6.0
Cost: Fuel per liter	Rs./liter	36.8	36.8	36.8
Cost: Truck capital per truck	Rs.	1.4 million	1.4 million	1.4 million
Total compression and distribution cost	Rs./kg	63.1	52.1	48.4

[a] Based on cylinder rental price
[b] 1 Kw-hr = Rs.5

Another potential delivery option is 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 census 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 3-25%. 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 unintentional escapes result in higher concentrations of hydrogen than CNG, despite the increased buoyancy and diffusivity of hydrogen. 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.

4. Total Cost and Sensitivity Analysis

Figure 8 presents the hydrogen cost per kg of each step in the biohydrogen supply chain. The production and compression costs account for more than 2/3 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]. A cost of ₹149.6/kg of hydrogen far exceeds India's national hydrogen roadmap 2020 cost targets of Rs. 60-70/kg at the delivery point but is comparable to the cheapest future biohydrogen cost estimates in the U.S. [8, 9].

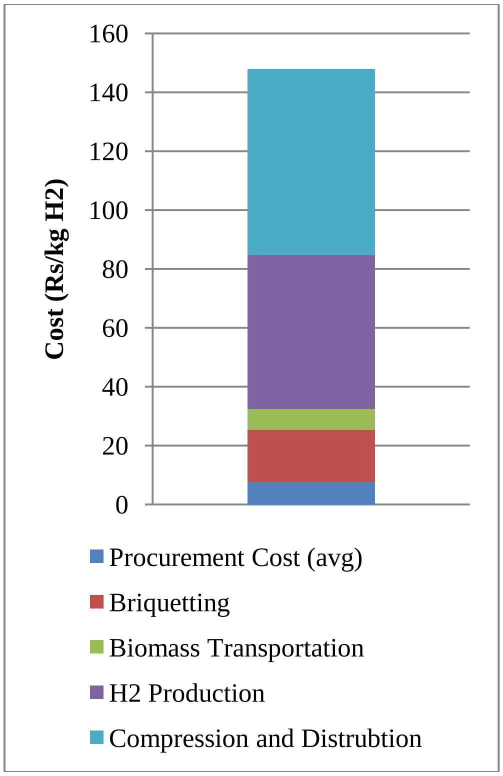

Figure 7 - Supply chain costs.

Figure 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 capital interest rate has the steepest curves, indicating the highest sensitivity. Varying these parameters between +10% to -10% results in a cost of hydrogen between ₹123 and ₹199/kg (\$2.78-\$4.25).

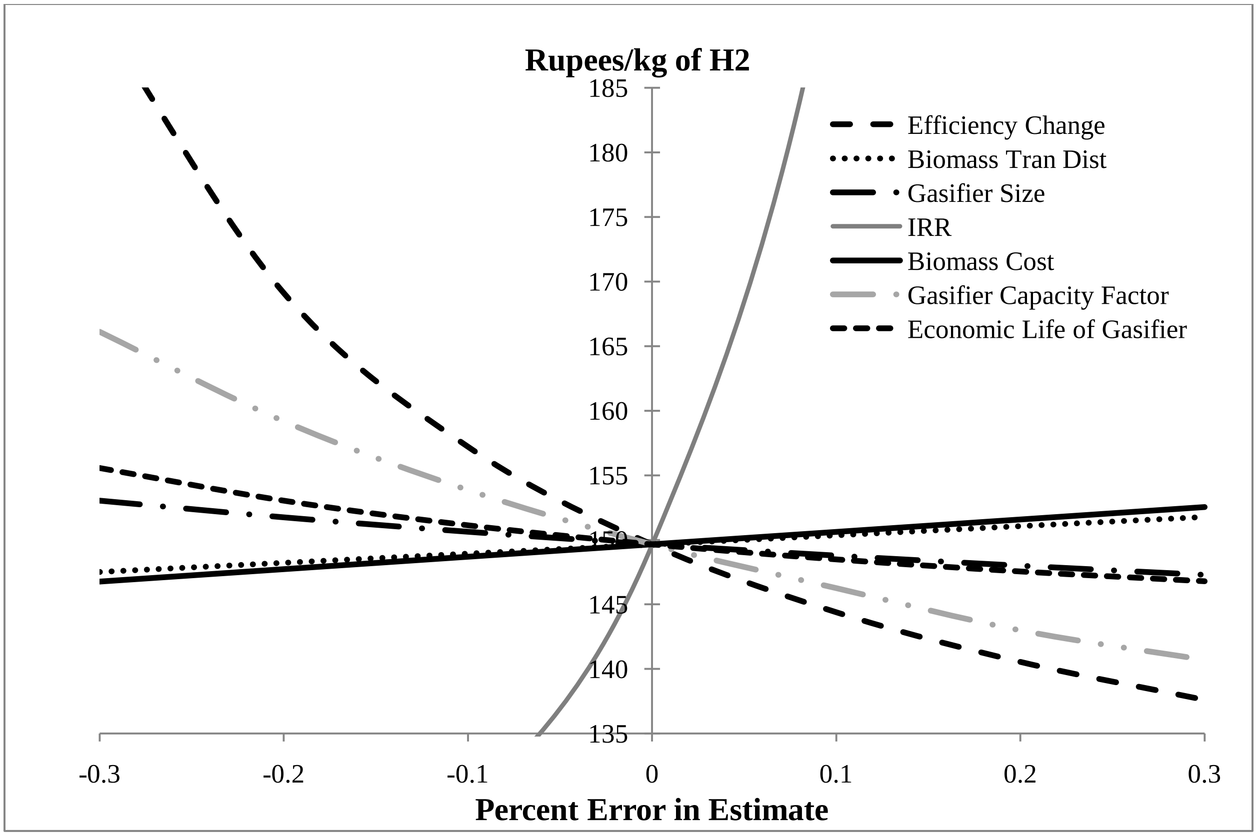

Fig. 8 – Sensitivity analysis: change in delivered cost with change in parameter

5. 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%-82% HCNG mixture. At first, the cost of ₹149.6 ($3.39) per kg seems somewhat high for a developing nation such as India. However, since the hydrogen component of the fuel is only 2.9% of its total weight, we expect the price increase over pure CNG to be a couple rupees per kg at most. This price increase could be offset by equivalent tariff increases on petrol or diesel. Cleaning the air over Delhi will not be easy, but a large-scale HCNG program. Not only would a large-scale HCNG program clean the air over Delhi, it could help pave the way for other cities with large CNG fleets to begin their own transitions to hydrogen economies.

Highlights

- Hydrogen needed to run all 344,000 CNG vehicles in Delhi on 18%-82% blend ratio of H-CNG: 12.8 KT per year of hydrogen.
- Hydrogen and biomass potential: The total availability of rice straw, cotton stalk, and mustard stalk in districts within 150 km of Delhi is 4,717 KTs per year, enough to produce 270.7 KT per year of hydrogen using gasification.
- The cost of biomass procurement, densification, transportation, hydrogen production, hydrogen compression and distribution is: ₹11.5/kg, ₹17.4/kg, ₹7.1/kg, ₹52.4/kg, and ₹63 .1/kg respectively ($1 = ₹44.2).
- The total cost of biohydrogen in Delhi is estimated to be ₹149.6 ($3.39) per kg.
- This total cost varies between ₹123-199 per kg given +/-10% changes in seven key parameters: internal rate of return, biomass transportation distance, efficiency of conversion, biomass cost, economic life of gasifier, gasifier capacity factor, and gasifier size.

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