HYDROGEN-ENRICHED NATURAL GAS

BRIDGE TO AN ULTRA-LOW CARBON WORLD

A Paper by National Grid and Atlantic Hydrogen Inc. for Gas Industry Executives, Utility Regulators, Policy Makers and Energy Administrators

1. EXECUTIVE SUMMARY

Hydrogen-enriched natural gas, or HENG, addresses two dominant energy and environmental issues: decarbonization and improved energy management. As a mixture of hydrogen and natural gas, HENG widens our efforts to build a bridge to an ultra-low carbon world. Yet combining hydrogen and natural gas can also be seen as going "back to the future." For about 150 years, we relied on 10 per cent to 50 per cent hydrogen in manufactured gas, or "town gas," for lighting, heating and cooking, before converting to natural gas. With HENG, it is now possible to reduce emissions, improve the efficiency of end-use equipment, and lower the overall carbon intensity of natural gas in the years to come.

HENG leverages existing natural gas pipelines and local delivery systems, and takes advantage of the growing recoverable gas reserves in North America and LNG supplies globally. HENG can be produced without generating carbon dioxide (CO_2), using abundant and low-cost off-peak power. The carbon from HENG production avoids emissions associated with conventional carbon black production and has potential in a number of energy management applications, including absorbed natural gas storage, batteries, ultra capacitors and high voltage cables for infrastructure renewal and expansions.

From wellhead to burner tip, HENG has many potential applications and could reduce CO_2 emissions in the United States by over 111 million tonnes per year. This is equivalent to the emissions from 20 million passenger vehicles or 10 million homes per year. In addition, HENG can be highly cost-competitive with many energy-related CO_2-reduction strategies under consideration. On the basis of cost per tonne of CO_2 abated, HENG costs an estimated $12 per tonne, which is less than most projections for carbon capture and storage technologies.

Experience with the use of a gaseous fuel containing hydrogen and methane in places such as Hong Kong and Hawaii indicates that there are no insurmountable technical or safety barriers to delivering HENG. The key to introducing it is government policy and regulation. The following policy developments are urgently required:

- Regulatory frameworks to provide incentives and to clarify the roles and responsibilities of the gas utilities and local distribution companies;
- Continued support for R&D in low-carbon technologies, and extending funding for capturing carbon from natural gas before combustion;
- Commercial incentives that level the playing field between HENG and renewable technologies, and that are sufficient to allow the utilities that will own and operate HENG plants to recover their costs; and
- Consistent and clear rules for materials, system requirements, safety measures and test procedures for hydrogen in natural gas.

2. BACKGROUND

Reduction of CO_2 emissions, referred to in this paper as decarbonization of the energy system, is becoming increasingly important. Multiple solutions are being pursued, but the focus to date has arguably been on power generation and transportation. Achieving significant decarbonization — a reduction on the order of 60 per cent to 80 per cent from current levels of annual CO_2 emissions — requires aggressive pursuit of all options, including the development and deployment of low-carbon solutions for heating and other direct uses of fuels in residential, commercial and industrial markets. These end uses, which depend mainly on safe and reliable natural gas, represent over 25 per cent of energy-related CO_2 emissions in the United States.

Natural gas is already recognized as an important part of the solution to climate change, as it has the smallest carbon footprint among fossil fuels and can be used with high efficiency. But this alone is not enough. Supplementing natural gas with sustainable gas technologies, such as biomethane from renewable biomass, is one option that is being considered. Another is hydrogen-enriched natural gas (HENG), where the hydrogen comes from a low- or zero-carbon energy source. HENG, the subject of this paper, can leverage existing natural gas infrastructure to reduce CO_2 and other emissions, improve the efficiency of end-use equipment, and lower the overall carbon intensity of energy consumption.

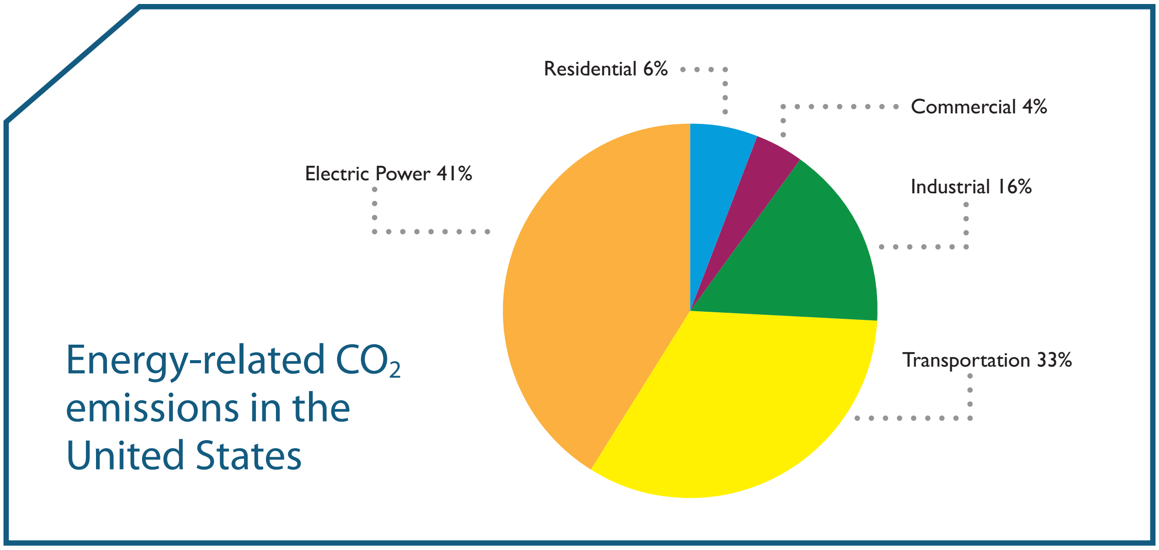

Figure 1: 2007 U.S. energy-related CO_2 emissions, totaling 5,988 million tonnes.[1]

3. WHAT IS HYDROGEN-ENRICHED NATURAL GAS?

Hydrogen-enriched natural gas, or HENG, is a mixture of hydrogen and natural gas. In theory, the two can be mixed in any proportion, but typically, HENG in the range of 10 per cent to 20 per cent hydrogen by volume represents the most promising near-term option. At these concentrations, HENG is generally compatible with existing natural gas transmission and distribution infrastructure, as well as end-use equipment. Moreover, codes and standards in many jurisdictions treat HENG with less than 20 per cent hydrogen as natural gas, which will facilitate its initial deployment into gas networks. Also, at these levels HENG offers important emissions and potential efficiency benefits, compared with natural gas.

4. BENEFITS

In broad terms, HENG enables the initial deployment of hydrogen in the energy system without the need for expensive infrastructure investments. This resolves the classic "chicken and egg" problem of hydrogen production and the dedicated storage, transmission and other equipment needed to use it directly as a fuel. The use of HENG enhances combustion and reduces CO_2 emission from natural gas. It also leads to lower emissions of pollutants such as nitrogen oxide (NOx), carbon monoxide (CO) and unburned methane and other hydrocarbons. HENG can also improve the fuel efficiency of gas-fired combustion in boilers, engines and turbines, using existing natural gas delivery infrastructure and end-use equipment.

- HENG decreases the carbon intensity of natural gas. For every tonne of carbon removed before combustion, approximately 3.7 tonnes of CO_2 are prevented when HENG is burned.[2]
- HENG increases the efficiency of natural gas conversion into useful energy. Adding even small amounts of hydrogen leads to more complete combustion of the fuel, including CO, methane and other hydrocarbons in the gas stream. This can improve engine efficiency and lower emissions of harmful pollutants.
- HENG helps avoid the formation of thermal NOx, because it allows stable combustion at leaner gas mixtures to achieve lower flame temperatures than is possible with conventional natural gas.

5. DECARBONIZATION AND IMPROVED ENERGY MANAGEMENT

HENG is a low-carbon gas that has less carbon and more hydrogen than natural gas. Today it is possible to make HENG in a single-stage process without generating CO_2 emissions. This process involves passing natural gas through a plasma arc to separate some of the methane in the gas into solid carbon and gaseous hydrogen. When the gas exits the plasma, the carbon is removed as a fluffy powder, and the hydrogen stays in the gas stream as it moves to the end-use appliance.

Atlantic Hydrogen Inc. is commercializing such a plasma-arc process. Called CarbonSaver™, it produces HENG in a compact plasma reactor that is in-line with the fuel delivery system. This addresses two dominant issues facing our energy and environmental future: decarbonization and improved energy management.

- CarbonSaver™ is carbon capture for natural gas, a resource that is becoming more abundant in North America, with new shale gas and other non-conventional gas discoveries. With liquefied natural gas production, natural gas use is also growing in international markets.
- CarbonSaver™ can produce HENG without generating any CO_2, using abundant off-peak power, which can trade near or below zero cost, due mainly to off-peak wind supplies.[3] This is a variation of the wind-to-hydrogen model. But instead of using off-peak wind power to produce pure hydrogen that is stored and used later at or near the generation source, CarbonSaver™ can convert off-peak power to HENG that is transported to markets and delivered to end users through existing pipelines and distribution infrastructure.
- Carbon from HENG production can enhance energy supply and delivery management, without generating the high emissions associated with conventional carbon black production. Targeted applications include absorbed natural gas storage in vehicles and at peak-shaving facilities on the distribution network, batteries and ultra capacitors for electric vehicles and grid storage, and semi-conductive insulations for cable infrastructure replacement.

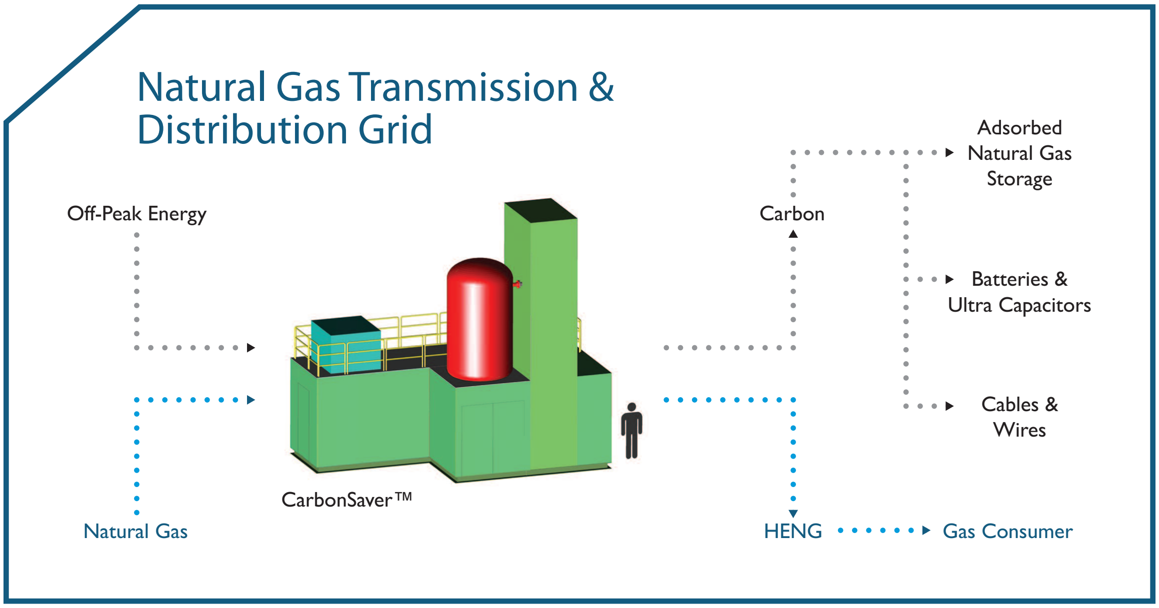

Figure 2: Conceptual diagram for the production and distribution of HENG using CarbonSaver™ in natural gas networks.

6. BACK TO THE FUTURE

The application of hydrogen as an energy carrier has been investigated over many decades, with the promise that a hydrogen economy could greatly reduce CO_2 emissions and lead to energy independence and energy security. But two major hurdles — the lack of critical infrastructure and cost-effective production of hydrogen without emitting CO_2 — continue to push the vision of the hydrogen economy out into the future. The truth is that we have been relying on hydrogen to power economic development for over 150 years, twice as long as electricity and four times as long as natural gas. Reintroducing hydrogen into the natural gas grid as HENG is actually going "back to the future."

Before the development of natural gas supplies and transmission systems, during the 1940s and 1950s, virtually all gaseous fuel and lighting gas used in North America, the U.K., Europe, and throughout the world was manufactured from coal. Originally a by-product of the coking process, manufactured gas was extensively exploited in the nineteeth and early twentieth centuries, initially for lighting, and then for cooking and heating. Commonly referred to as "town gas" or "illuminating gas," it was a mixture of hydrogen, carbon monoxide and methane, with small amounts of carbon dioxide and nitrogen. Depending on the gasification process, hydrogen concentrations ranged from 10 per cent to 50 per cent. However, with the discovery of large reserves of natural gas in North America, the North Sea, North Africa and Russia, the gas industry gradually converted the manufactured-gas system to deliver and use natural gas, which typically now contains only trace amounts of hydrogen.

Even so, manufactured gas continues to be made and used today in selected areas.

The Hong Kong and China Gas Company has been producing and distributing manufactured town gas since 1862. Town gas, derived from naphtha, consists of 49 per cent hydrogen, 28.5 per cent methane, 19.5 per cent carbon dioxide and 3 per cent carbon monoxide. The supply network extends over 1,900 miles (3,000 kilometres), covering 85 per cent of Hong Kong's households and serving about 1.6 million customers. Town gas is Hong Kong's primary gaseous fuel, especially for household heating and cooking, and now accounts for about 30 per cent of the total energy consumed in the territory.

Meanwhile, in Hawaii, The Gas Company (TGC) has produced and distributed synthetic natural gas (SNG) for the greater Honolulu market since 1967. That gas is also derived from naphtha and consists of 77 per cent methane, 11 per cent hydrogen, 6 per cent butane and 6 per cent CO_2. TGC supplies the SNG through a 1,100-mile (1,770-kilometre) pipeline network of steel pipes at high pressure and high-density polyethylene pipes for local delivery to over 28,000 commercial and residential customers. The hydrogen-gas mixture is used in standard appliances for cooking, water heating, drying and lighting. Emerging uses include fuel for cars, trucks and cogeneration. More importantly, to our knowledge there have been no reports of leaks, embrittlement or poor performance of appliances specifically due to the presence of the hydrogen.

7. FROM WELLHEAD TO BURNER TIP

Natural gas is a major source of energy in North America, the U.K. and Europe. In the United States, for example, it meets nearly 25 per cent of all of the energy demand. In 2008, natural gas consumption in the United States exceeded 23 trillion cubic feet, with gas utilities serving 65 million customers.[4] In recent years, much of the growth in natural gas demand has come from electricity generation, with power producers turning to natural gas because it is the cleanest-burning fossil fuel and allows for significant increases in efficiency using combined-cycle combustion technology.

Nevertheless, natural gas can be even cleaner. HENG from natural gas, whose supply is more secure than oil, provides a bridge to an ultra-low-carbon future that includes hydrogen and other renewable energy sources. HENG can enhance the benefits of natural gas as a clean and convenient source of energy for residential, commercial and industrial users, as well as power generators, the exploration and production sector and pipeline operators.

From wellhead to burner tip, HENG has many potential applications and could reduce CO_2 emissions in the United States by more than 111 million tonnes per year at a capital cost of $42 billion. This would be equivalent to the CO_2 prevented by more than 100,000 MW of wind-power capacity at a cost of over $100 billion and covering a landmass the size of Massachusetts.[5] It also corresponds to the emissions from 20 million passenger vehicles or 10 million homes per year.[6]

Supply Chain Stage	Application	Annual U.S. consumption (in billions of cubic feet)[7]	Annual gross CO_2 saved using 10% HENG (in millions of metric tonnes — MMT)[8]	Estimated capital cost for CarbonSaver™ (in millions)
Lease and Plant Fuel	Upstream exploration and production	1,200	6.1 MMT	$2,350
Pipeline Fuel	Operation of pipelines, primarily in compressors	700	3.9 MMT	$1,140
Distribution	Injection into local distribution systems for residential and commercial users	8,000	38.0 MMT	$14,600
Industrial	Large boilers and furnaces	6,700	31.6 MMT	$12,160
Power Generation	Gas-fired turbines and steam boilers	6,700	31.6 MMT	$12,160
Transportation	NGV fleets	100	0.2 MMT	$60
Total		23,400	111.4 MMT	$42,470

Figure 3: Applications for HENG and its potential impact on CO_2 emissions and estimated capital cost.

8. KEY TECHNICAL CONSIDERATIONS

The real-world experiences of Hong Kong and Hawaii show that HENG can be supplied and delivered using existing infrastructure. This is supported by research establishing that HENG can be injected into the medium-pressure pipeline and the low-pressure distribution systems.[9] But industry, governments, regulators and utilities need to be educated about the issues, in order to support the safe and efficient introduction of HENG as an energy carrier.

1. Safety transcends all applications and is crucial to successful commercialization of hydrogen-based technologies. For lower concentrations of HENG, there is no substantial difference in risks, compared to natural gas.
2. Current results give confidence in the technical feasibility of using HENG at up to 20 per cent hydrogen, by volume, in natural gas pipes, with respect to burst resistance, fast crack propagation, adhesion resistance of internal coatings and fatigue crack behavior.
3. Gas-quality management ensures that end users remain supplied with gas, in accordance with contractual specifications in order to guarantee safety, performance of appliances and billing accuracy. Although it is difficult to provide a general figure for acceptable hydrogen concentrations in natural gas, HENG up to 20 per cent hydrogen by volume requires no significant modifications to most existing natural gas networks, meters and standard appliances.

9. CARBON

Tests on carbon from CarbonSaver™, performed by the University of New Brunswick in Canada and a global supplier of carbon black, have demonstrated the potential of a value-added carbon, justifying capture and use in downstream products. Carbon black is an important industrial commodity used as a reinforcing agent in tires and rubber compounds, as a pigment in inks and paints, and as an additive to plastics and polymers to improve performance. World capacity of carbon black is about 11.5 million tonnes per year. Yet carbon black plants are inherently large emitters of CO_2 and other harmful pollutants.[10] In total, they consume over 300,000 barrels of low-grade oil per day and generate 2.5 to 5 tonnes of CO_2 for every tonne of carbon black they produce. Most of the carbon black goes to tire and rubber applications associated with car and truck production. More recently, there is a growing interest in carbon for advanced materials and energy storage.

When incorporated in composites, carbon from CarbonSaver™ has the potential to provide enhanced conductivity for cable and wire in the new "smart-grid" infrastructure, as well as batteries and ultra capacitors for electric vehicles. CarbonSaver™ carbon also shows promise as an adsorbent to enhance the storage of natural gas in vehicles and in utility storage tanks on the gas distribution grid. It may also be used to remove mercury in the flue gas of coal-fired power plants.

10. ECONOMICS

A 2007 study by McKinsey & Company found that the United States could reduce annual greenhouse gas emissions by as much as 3,000 to 4,500 million tonnes by 2030, at a marginal cost of less than $50 per tonne of CO_2. The opportunities for abatement are highly fragmented and widely spread across the economy. However, reducing the carbon intensity of energy production is the most capital-intensive and requires the longest lead-time of all possible options.

The estimated cost of CO_2 abatement from HENG is $12 per tonne, or about $0.07 per thousand cubic feet (MCF) of natural gas. This is equivalent to an additional 1 per cent on the price of gas, assuming $7 per MCF. [12] The projected capital cost of a CarbonSaver™ facility is comparable to the cost of equivalent-sized hydrogen and plasma gasification plants available today. The largest single operating cost is the electricity for the plasma arc, and this power may be drawn at an attractive price from abundant off-peak generation capacity. Notwithstanding the slightly lower heating value of HENG compared with natural gas, the hydrogen in the natural gas improves the fuel conversion rate of appliances, leading to an overall reduction in natural gas consumption in many cases. Finally, revenue from the sale of carbon black for industrial applications significantly offsets the fixed and operating costs.

Cost of CO_2 Abatement	Per MCF
Capital recovery	$ 0.26
Operation and maintenance	0.06
Natural gas efficiency gain	(0.09)
Electrical energy	0.34
Fixed and operating costs	0.57
Carbon revenue	(0.50)
Total annual sales cost	$ 0.07
Cost per tonne of CO_2 abatement	$ 12.00

Figure 4: Cost of CO_2 abatement.

Based on the cost per tonne of CO_2 abated, CarbonSaver™ is highly competitive with many energy-related CO_2 reduction strategies under consideration. It is less expensive than some of the more optimistic projections for post-combustion carbon capture and storage (CCS) technologies that are estimated to be $40 to $60 per tonne of CO2 abated by 2030.[13]

11. CONCLUSIONS AND RECOMMENDATIONS

Global energy demand is projected to increase by 60 per cent in the next 25 to 30 years, according to the International Energy Agency. However, it is expected that the rate of growth of energy demand will outpace affordable clean supplies, unless both incremental improvements and revolutionary breakthroughs occur. It is here that HENG can play a major role, bridging the gap between leading-edge, multi-disciplinary research and its application in the commercialization of clean-energy technologies.

There are no insurmountable barriers to delivering HENG using existing natural gas infrastructure. Historically, gas distribution systems carried hydrogen in manufactured gas for 150 years, a practice that continues today in places such as Hong Kong and Hawaii. Technically, HENG production and injection into the distribution network is possible and safe, as long as the gas meets local gas-quality specifications. And while HENG has a lower calorific value than regular natural gas, the gain in fuel efficiency in the end-use appliance means that the customer may actually consume less gas.

In the short to medium term, we believe that the plasma-arc separation of methane into hydrogen and carbon using CarbonSaver™ technology presents the most promising approach for HENG production. It relies on a science that is mature and widely used in various industries, especially semiconductor manufacturing and waste remediation. Also, the hydrogen can be produced in the fuel line, before combustion, and the carbon extracted without interruption of the flow of gas to the end user. While the electrolysis of water using renewable energy may be a preferred source of HENG for a narrow range of applications, the cost is not competitive with other, more established industrial sources. As for HENG supplied by steam reforming of methane (SMR), the system is economical but also produces two to eight times more CO and CO_2 than hydrogen, making it an unattractive proposition.

All this, however, should not serve to underestimate the effort required to deliver HENG. The following policy developments are urgently required.

11.1. Regulatory Framework

Government and industry research has helped to demonstrate that widespread utilization of HENG production and injection is feasible. But to realize the potential of HENG, a regulatory framework is necessary to provide incentives and clarify roles and responsibilities regarding HENG for gas network owners and local distribution companies. Our view is that, provided HENG does not enter the transmission and distribution network at concentrations greater than 20 per cent hydrogen by volume, the presence of hydrogen in natural gas will not cause any technical or safety problems. This view is supported by the fact that gaseous fuels containing hydrogen have been used in Hong Kong and Hawaii without any identified degradation of distribution piping and appliance operations.

11.2. Funding R&D and Demonstrations

The government should continue to fund R&D into low carbon technologies. This should be extended to cover the decarbonization of natural gas before combustion and the development of value-added applications for the carbon once it has been captured. Demonstration plants should be built quickly to jump-start the industry and provide valuable technical and commercial data to support and guide the development of energy policy.

11.3. Incentives

While HENG has the potential to be economically and competitively attractive, the market potential will be greatly enhanced by the same government support that is now offered to renewable energy. In the short to medium term, the production and use of HENG can benefit from commercial subsidies and/or incentives to level the playing field with other clean technologies and post-combustion CCS. The subsidy should be sufficient to allow the utilities that will own and operate CarbonSaver™ plants to recover their costs.

11.4. Codes and Standards

HENG within gas networks requires consistent and clear rules for materials, system requirements, safety measures and test procedures. This means stakeholder groups must begin discussions now on the need for the revision and amendment of existing standards or development of new standards in jurisdictions where limitations exist regarding hydrogen in natural gas.

12. DISCLAIMER AND COPYRIGHT

REFERENCES

[1] Energy Information Administration (2008). Emissions of greenhouse gases in the United States, 2007. DOE/ EIA-0573. Office of Integrated Analysis and Forecasting.

[2] The molecular weight of CO_2 is 3.67 times that of carbon.

[3] Wynn, Hugh. Power Prices Below Zero: The promise and threat of renewables. Bernstein Research, May 21, 2009.

[4] Energy Information Administration. Natural Gas Consumption by End Use in 2008. http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm.

[5] Major assumptions include: Cost of wind turbine at $1 million per MW installed; land use requirement is 50 acres per MW capacity; load capacity is 30%; CO_2 intensity of power grid is 0.40 tonnes of CO_2 per MWh; Massachusetts is 7,838 square miles.

[6] Environmental Protection Agency. Greenhouse Gas Equivalencies Calculator. http://www.epa.gov/cleanenergy/energy-resources/calculator.html#conversiontable

[7] Energy Information Administration. Natural Gas Consumption by End Use in 2008. http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm.

[8] Estimated CO_2 abatement is in the range of 9% to 12%, depending on the context of application. Abatement is realized in the following areas: lower carbon intensity of gaseous fuel, displacement of conventional carbon black production, and increased fuel conversion efficiency.

[9] Alliat, I. (2008). To what extent can the existing pipelines accommodate hydrogen? International Gas Research Conference, Paris, The 3rd NaturalHy Workshop.

[10] The greenhouse gas intensity of carbon black production averages about 2.4 tonnes of CO_2 for every tonne of carbon black. However, some of the finer grades, such as the carbons from CarbonSaver™ process, can have intensities up to 5 tonnes CO_2 per tonne of carbon black. Sources: Columbian Chemicals Company and Crump, E. L. (2000). Economic impact analysis for the proposed carbon black manufacturing NESHAP. Environmental Protection Agency, EPA-452/D-00-003.

[11] McKinsey & Company (2007). Reducing US greenhouse gas emissions: How much at what cost? http://www.conferenceboard.ca/documents.aspx?did=2341

[12] Major assumptions include: HENG with 10% hydrogen by volume; capex of $15,000 per MCF/h of throughput; load capacity of 90%; capital recovery of 12% over 25 years; annual maintenance 3% annually of capital expenditure; natural gas at $7 per MCF; power cost at $100 per MWh from a zero-emission source; efficiency gain of end-use equipment is 1%; net carbon price to plant operator is $750 per tonne; escalation rate of 2%; total CO_2 saved is 9%, including 4% from HENG, 4% from displaced carbon black production, and 1% from efficiency gains.

[13] For new coal power installations, CCS costs could be $40 to $60 per tonne of CO_2 abated in 2030 – which is in line with expected carbon prices in the period. Early demonstration projects will typically have a significantly higher cost of $85 to $130 per tonne. Source: McKinsey & Company (2009). Carbon Capture & Storage: Assessing the Economics. http://www.mckinsey.com/clientservice/ccsi/pdf/CCS_Assessing_the_Economics.pdf

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