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A syngas network for reducing industrial carbon footprint and energy use

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Abstract

This paper makes a case for building syngas networks as a means of contributing to the reduction of industrial carbon footprints. After exploring historic and conventional approaches to producing syngas (or synthesis gas) from fossil fuels on increasingly large scales, the paper looks at ways of producing it from renewable sources and from surplus resource (or waste) from industrial, domestic, urban and agricultural systems. The many ways of converting syngas into power, industrial heat, fuels, chemical feedstocks and chemical products are then outlined along with the associated syngas purification requirements. Some of the processes involved provide an opportunity for cost-effective capture and storage of CO₂. Pathways through this range of possibilities that enable a net reduction in energy footprint or in CO₂ emissions are identified and exemplified. Recognising that those opportunities are likely to involve industrial facilities that are distributed spatially within a geographic area, the case for building an interconnecting syngas network is explored. Issues surrounding sizing the network, timing its growth, determining ownership and access arrangements, and planning/regulatory hurdles are found to be similar to the analogous case of building an industrial CO₂ network, with the added complication that the term “syngas” tends to be used to cover a fairly wide range of gas compositions.

Keywords: syngas; synthesis gas; pipelines; networks; carbon footprint

1. Introduction

Industry accounts for 40% of global energy-related CO₂ emissions. In 2007 the global figure for CO₂ emissions from industry was 7.6 Gte of direct CO₂ emissions to which could be added 3.9 Gte of indirect CO₂ emissions from power stations supplying electricity to industry [1]. Governments around the world are setting targets and taking action to reduce CO₂ emissions in general. In the UK, for example, the Climate Change Act 2008 sets a target for 2050 that UK greenhouse gas emissions must be 80% below the 1990 level, with intermediate 5-yearly binding carbon budgets being set along the way [2]. Energy supplies of around 1200 PJ per year for manufacturing industry are still dominated by fossil fuels [3, page 18].

There is also a cost issue as energy prices continue on their inexorable upward trend. Natural gas prices in particular are expected to rise very sharply as China’s demand continues to grow and countries like Japan and Germany revise their policy on nuclear power. The importance of finding ways of reducing CO₂ emissions from energy-intensive manufacturing plants is underlined in a recent report by the social policy think tank Civitas where they suggest that UK government green taxes in their present form will spell the end for Britain’s chemical industry [4].
The chemical and petrochemical industries use natural gas not only as an energy source or fuel but also as a chemical feedstock. As supplies come under pressure, the question is starting to be asked in various regions around the world: is natural gas too good to burn? Those same industries produce waste gases which are sometimes used as alternative fuels where the calorific value is sufficiently high.

Gas mixtures that contain varying amounts of carbon monoxide (CO) and hydrogen are usually referred to as syngas or synthesis gas. The term derives from its use as a chemical intermediate for the production of ammonia, methanol and many other chemicals and derivatives. There is increasing interest in its use as an intermediate in producing synthetic petroleum oils for use as fuels and lubricants. Since it is combustible it is often also used as a fuel source. Because of its flexible use as a chemical feedstock or as a fuel source within many production processes, there is sometimes a financial case for moving syngas between chemical production plants in pipelines, leading to mini-networks. With some sources of syngas there is often a significant methane component within the gas mixture. Depending on the proposed end use for the syngas, this may be an unwanted contaminant or a useful addition.

This paper examines the case for building syngas networks as a means of contributing to the reduction of industrial carbon footprints. The structure of the paper is as follows. The paper looks first at traditional ways of producing syngas from fossil fuels across a range of industries, including chemicals and petrochemicals, power generation and steel-making. It then turns to ways of producing syngas from renewable sources, with particular emphasis on routes that can produce the large volumes that are typically required in energy-intensive industries. The gas mixtures produced can have a wide range of compositions depending on production route. The paper then goes on to look at the wide range of uses to which syngas has been put in the past and also explores some newer uses which are currently attracting interest, drawing attention to the varying requirements on syngas purity. The ideal ratio of hydrogen to CO (and to any other components that may be present) depends very much on the intended end use for the syngas. A range of processes for purifying syngas to make it suitable for various end uses is then explored.

Having mapped out a range of syngas sources and an array of purifying steps and upgrading technologies that enable its use in many different processes, the paper considers the practical implications of building a comprehensive, versatile syngas network. From the many possibilities identified, the paper then goes on to examine the net effect on CO₂ emissions and energy consumption, determining the conditions under which a significant net reduction is achieved.

2. Syngas sources

2.1. Syngas from fossil fuels

The history of producing syngas from coal goes back a long way [5]. The conversion of coal into coke plus a “coal gas” by-product dates back to 1665 in England. The conversion of coke into hydrogen and CO goes back to the late eighteenth century. Coal gas was first used for lighting purposes in Philadelphia in 1796. By the 1850s, “town gas” (produced from the gasification of coal) was widely used in London for lighting. Over time, the use of industrial gas extended from direct use in lighting
and cooking to heating, and then as a chemical feedstock for producing ammonia, methanol and their many derivatives including various fertilisers.

The development of fully continuous gasification processes like the Lurgi moving-bed pressurised gasification process in 1931 and the Koppers-Totzek entrained-flow process in the 1940s had to await improvements in gas-tight equipment to enable operation above atmospheric pressure and also the commercialisation of cryogenic air separation technology in the 1920s [6]. When other countries started to switch to oil and natural gas as the basis of their petrochemicals industry, in South Africa Sasol continued to develop their coal gasification and alkane synthesis technology, with the result that they now have the largest gasification centre in the world [7]. Meanwhile, oil crises in 1973 and in 1980 rekindled interest in coal gasification on a wider basis. Parallel technology paths have opened up for gasification of solids and for gasification of liquids. Complex refineries now generally have a gasification unit for upgrading heavy residual oil fractions into a more valuable syngas stream.

The exothermic reactions which generate the heat for the main gasification reactions are:

\[
\text{(1)} \quad C + O_2 \rightarrow CO_2 \quad \Delta H = -393.8 \text{ kJ/mol}
\]

\[
\text{(2)} \quad C + \frac{1}{2} O_2 \rightarrow CO \quad \Delta H = -123.1 \text{ kJ/mol}
\]

The gasification reactions are:

\[
\text{(3)} \quad C + H_2O \leftrightarrow CO + H_2 \quad \Delta H = 118.5 \text{ kJ/mol}
\]

\[
\text{(4)} \quad C + CO_2 \leftrightarrow 2 CO \quad \Delta H = 159.9 \text{ kJ/mol}
\]

In these reversible, endothermic reactions (3 and 4), higher temperatures favour the production of hydrogen and carbon monoxide. Lower pressures also favour the production of carbon monoxide while higher pressures favour the production of carbon dioxide, providing some control over syngas composition. The other main reaction is the exothermic water gas shift reaction in which CO reacts with steam to form CO$_2$ and additional hydrogen:

\[
\text{(5)} \quad \text{CO + H}_2O \leftrightarrow \text{H}_2 + \text{CO}_2 \quad \Delta H = -41 \text{ kJ/mol}
\]

There is also an important methanation reaction:

\[
\text{(6)} \quad C + 2 \text{H}_2 \leftrightarrow \text{CH}_4 \quad \Delta H = -87.5 \text{ kJ/mol}
\]

The relative proportions of gases at the gasifier exit depend on process conditions and the composition of the feedstock.

There is a vast, largely untapped source of additional syngas in the form of the world’s 18 trillion tonnes of unmineable coal resource [8]. The basic idea is that by using directional drilling technology to drill a small pilot hole through deep or narrow coal seams, oxygen and steam can be injected in order to gasify the coal \textit{in situ}, with the syngas being brought to the surface via a production borehole. Work on this development path has migrated over the last hundred years from North East England to Russia, to China, to the USA, then South Africa and now Australia as the
economics of alternatives have changed. The range of gas compositions produced is quite wide depending on gasification depth and coal rank: 11-35% hydrogen; 2-16% CO; 1-8% methane; 12-28% CO₂ [9]. The deeper seams being considered in North East England now lead to relatively high methane yields, which can be helpful or unhelpful depending on the proposed end use.

Another source of hydrogen-rich gas is the coke oven on a steel works. Table 1 captures the composition of a typical coke oven gas, consisting predominantly of hydrogen and methane. For some end uses the methane component is desirable: for others it would need to be removed or converted (for example by reforming it with steam to produce hydrogen, CO and CO₂). On a steel works it is normal to use about half of the coke oven gas to fire the coke ovens themselves, with the remainder being available for other uses. It could be used, for example, to boost the hydrogen content of a syngas derived from coal or from hydrocarbon residues.

<table>
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**Table 1:** An example of coke oven gas composition, in which 93% of the components can also be found in a typical raw syngas in varying proportions.

2.2. Syngas from renewables and waste streams

Biomass from a wide range of sources can be converted into syngas via gasification [5, 10, 11]. If the biomass is a coppiced wood grown in a short rotation (eg short rotation coppice willow harvested on a 3-year cycle), then the syngas comes close to being carbon-neutral since the CO₂ emitted if the syngas is burnt is effectively reabsorbed during the photosynthetic growth of the next crop. A similar argument (on a timescale of a few decades) applies to wood sourced from sustainable forestry operations apart from any use of fossil fuels in harvesting or transport operations. With agricultural straws, the same near-carbon-neutral argument applies. The gasification process readily converts all major components of biomass including lignin, which is resistant to biological conversion, to synthesis gas. Conversion of the lignin, which is typically 25-30% of the biomass, is essential to achieve high efficiencies.

The other main sources of biomass are waste streams that would otherwise be destined for landfill. Putrescible wastes (eg food waste) which would otherwise decompose into methane (a powerful greenhouse gas) in a landfill site can be gasified to produce syngas, and are often available at zero or negative cost as a feedstock. However, variability in the physical form, especially particle size and moisture content, of the biomass will have an important impact on the feed system and on consistency of plant operation. In addition, the initial synthesis gas produced will contain particulates and other contaminants and must be cleaned and conditioned prior to use.

A wide range of gasifier configurations has been developed globally, each tailored to different feedstock materials (both type and form), different scales and different required qualities of syngas [5, 12]. There are three basic forms of gasification system: fixed bed (updraft and downdraft),
fluidised bed, and entrained flow [13]. Gasification processes typically seek to operate either below the ash softening point (above which it starts to become sticky and prone to agglomeration) or above the slagging temperature (whereupon it becomes fully liquid and therefore removable). The various gasifier technologies are available at a range of overlapping sizes [13] – see Table 2.

| Table 2 around here |

Table 2: A range of gasifier technologies, indicating the scale at which they are typically used with biomass feedstocks (adapted from [13])

The Entrained Flow gasifier benefits from economies of scale and produces a high-quality syngas, but it requires considerable pre-processing to produce a finely divided feedstock with a low moisture content [5].

A number of biomass gasifiers have been built with capacities of around 100,000 te/year biomass feedrate or 50 MW\textsubscript{th} output rate. Entrained Flow gasifiers can be designed for much higher throughputs having been designed originally for operation on coal at levels of 600 MW\textsubscript{th} and above [5].

There are other possible renewable routes to syngas apart from autothermal biomass gasification. Work has been underway for many years to develop the idea of using concentrated solar energy as a source of high-grade heat to drive syngas production processes [14, 15], originally based on fossil fuel feedstocks. More recently, an approach based on using concentrated solar energy to drive a steam gasification process for a range of carbonaceous materials including biomass has been shown to produce a high quality syngas with the added benefits of reducing the feedstock requirement and eliminating the need for a high-energy air separation process [16, 17].

There is particular interest in the concept of converting captured CO\textsubscript{2} (perhaps from a post-combustion Carbon Capture and Storage scheme [8]) into syngas by using renewable energy to drive the process. In reviewing possible pathways for converting CO\textsubscript{2} plus water into syngas, Graves et al highlight a co-electrolysis process based on a high-temperature solid oxide electrolysis cell which could be run on renewable electricity [18]. Alternatively, concentrated solar energy from a parabolic dish can be used directly to drive the thermochemical splitting of CO\textsubscript{2} at temperatures in excess of 800 °C to produce CO for conversion to syngas via the water gas shift reaction of equation (5) above [19]. Such routes, whilst still under development, hold the attraction of avoiding many of the constraints associated with biomass cultivation.

3. **Syngas uses**
3.1. Possible syngas end uses and associated requirements

Ammonia for fertiliser production and other uses is made by reacting hydrogen and nitrogen at high pressure and moderate temperature in the presence of an iron/alumina catalyst. Most ammonia plants today get their hydrogen from a steam methane reformer with its associated CO₂ emissions. However, if a hydrogen-rich syngas is available, there is no need for such a reformer, and CO₂ emissions have effectively been eliminated upstream. An ammonia synthesis process requires syngas desulphurisation to 100 ppbv and also a CO₂ content below 10 ppmv [6].

A number of petrochemical sites around the world are embracing GTL (Gas To Liquids) technology, converting natural gas into liquid hydrocarbon feedstocks and fuels via the Fischer-Tropsch process. The first step – which is unnecessary with a syngas feedstock – is to reform the natural gas into syngas. The Fischer-Tropsch process is a catalysed chemical reaction in which CO and hydrogen are converted into liquid hydrocarbons [20]. Traditionally the process has been used to synthesise long-chain alkanes as a substitute for petroleum diesel [21]. The usual catalysts are based on iron and cobalt, and are vulnerable to poisoning by sulphur, chlorides and carbonyl groups. The Fischer-Tropsch process is described by the equation:

\[(2n + 1)H_2 + nCO \rightarrow C_nH_{2n+2} + n H_2O\]  \(\text{(7)}\)

The reaction takes place in the temperature range 200-350 °C at pressures of 20-40 bar. As \(n\) increases, the ideal molar ratio of hydrogen to CO tends to 2:1. Some authors would reserve the term “syngas” for an ideal 2:1 mixture of hydrogen and CO. The Fischer-Tropsch process is optimised for the desired product slate (eg diesel for road and rail transport, kerosene for air transport, naphtha for petrochemicals production) and followed by cracking and separation stages as necessary. It can also be used to produce light alkenes for petrol blending.

A different set of options opens up if syngas is converted into methanol [13]. Syngas for use in methanol production typically requires desulphurisation to 100 ppbv [6]. Methanol synthesis takes place over a copper zinc oxide catalyst in the temperature range 220-300 °C at pressures of 50-100 bar. The ideal molar ratio of H₂:CO:CO₂ is 11:4:1. Starting with methanol, there are Methanol To Olefines (MTO) technologies which lead to a whole panoply of downstream petrochemicals (polyethylene, polypropylene, ethylene oxide, glycols, surfactants etc). There are also processes for converting syngas into higher alcohols, with synthesis taking place at higher temperatures (up to 425 °C) and higher pressures (up to 300 bar). It is also possible to convert syngas into ethanol in a suitable fermentation process at less extreme process conditions (20-40 °C and atmospheric pressure) [13].

Alternatively, syngas can be converted into SNG (Substitute Natural Gas, or Synthetic Natural Gas) via a methanation process [22], which opens up a whole new set of options using the natural gas grid as a chemical feedstock transportation vehicle.

In the power generation sector, syngas production from coal gasification is also becoming more common. On Integrated Gasification Combined Cycle plants (IGCC), the idea is that coal is gasified to produce a syngas which can serve as a fuel for a highly efficient gas turbine in a combined gas/steam cycle [23, 6 page 286]. Where there are additional uses for syngas (such as those described above),
it becomes possible to keep the gasifier running steadily (and therefore reliably) whilst electricity demand fluctuates.

As CO₂ emission prices and CO₂ emission targets start to become a reality, there is growing interest in removing the CO₂. In the pre-combustion capture approach [23] the first step is the water gas shift reaction (see equation 5 above) in which CO is reacted with steam over a catalyst to produce additional hydrogen plus CO₂. A CO₂ separation step such as amine scrubbing follows, resulting in a gas which consists mainly of hydrogen [24,25]. A typical composition at that point would be: 90% hydrogen; 5% CO₂; 3% CO; 2% nitrogen [26]. Because most of the carbon has been removed from the syngas, if this hydrogen-rich gas is fed into a Combined Cycle Gas Turbine plant the emissions are about 90% carbon-free. Since the water gas shift reaction is an equilibrium reaction, it can be used instead to adjust the hydrogen to CO molar ratio to suit the intended end use. There is usually also a requirement to remove sulphur. For example, for an IGCC power plant subject to (say) a 5 ppmv SO₂ flue gas limit, the SO₂ level in the syngas downstream of the acid gas removal unit needs to be below 40 ppmv [6].

Syngas can also be used as a combustion fuel in a boiler for medium/high pressure steam production or a in a simple gas turbine for power generation. It has already been noted that the term “syngas” is used in many different ways. At one end of the spectrum, a low-grade gas can be used as a low-grade fuel. At the other end of the spectrum, a highly processed, decarbonised syngas (which is 90% hydrogen) can be used to reduce CO₂ emissions. In that case it should be noted that the decarbonised syngas has a lower energy density than natural gas and so a higher gas throughput is required. Gas turbines adapted to run in this mode have been found to produce power outputs that are 20-25% higher than normal due to the higher flow rate of hot combustion gases expanding through the turbine [26]. Where there is insufficient syngas available to supply all power generation needs on a large industrial site, there is the option of running some of the gas turbines on syngas and the rest on natural gas in order to reduce average CO₂ emissions. Syngas has also been used successfully in modified coal and oil fired burners on which new burners designed specifically for syngas have been retrofitted [26].

Where the intention is simply to use the syngas as a fuel, the most obvious comparator is natural gas which typically has a calorific value (CV) of around 40 MJ/Nm³. The equivalent figure for syngas – because of the wide range of possible compositions – is very variable. CVs in the range 10-15 MJ/Nm³ are not unusual with biomass-derived syngas [27]. With underground coal gasification, figures as high as 10 MJ/Nm³ have been reported [28]. More conventional coal gasification plants tend to produce syngas with CVs in the 10-12 MJ/Nm³ range [6]. Air-blown processes result in much lower CVs.

In the specific case where a hydrogen-rich syngas is to be used to replace natural gas in on-site combustion equipment, it should be noted that hydrogen has a higher flame speed and higher flame temperature than natural gas. It is therefore necessary to dilute it with water or nitrogen at the point of combustion to prevent damage to combustion systems [26]. In order to avoid damage to gas turbine components, the aim should be to keep the hot-gas-path parts at temperatures similar to when burning natural gas.
3.2. Syngas purification

Syngas produced via oxygen-blown gasification (rather than air-blown) consists principally of varying proportions of hydrogen, CO, CO₂ and methane. Other minor contaminants, even in small concentrations, can however cause serious problems. Particulates can lead to erosion, fouling and plugging; alkali metals can cause hot corrosion and catalyst poisoning; tars can lead to catalyst carbonisation and fouling; and many contaminants cause catalyst poisoning.

Where the raw syngas contains sulphur compounds such as H₂S or COS, the usual approach is to employ a physical absorption process followed by a Claus unit for conversion to elemental sulphur [26]. If the methane content is problematic (rather than desirable), it can be converted to hydrogen and CO via steam reforming.

Depending on the source of syngas, there is likely to be a requirement to remove entrained particulate matter, tars etc. The subject of removal of tars has attracted considerable research activity [29, 30]. Plasma gasifiers produce a very clean syngas, Entrained Flow gasifiers require a little more gas cleanup, and other gasifiers tend to require substantially more [13]. Gas cleanup technologies available range from cyclones, bag house filters, candle filters and packed bed filters through to wet scrubbers and electrostatic precipitators and on to specialist tar removal processes and activated carbon treatment [5].

The extent to which these various upgrading steps are necessary depends also on the intended end use for the syngas. Whilst raw syngas may be adequate for a gas boiler, a gas engine for power generation or CHP would have a tighter requirement, an even tighter requirement would apply for a gas turbine and a very tight specification indeed for a chemical synthesis feedstock [5]. Table 3 provides some illustrative examples of how final syngas composition constrains its utilisation.

Table 3: Maximum permissible impurity levels (against a selection of parameters) in treated syngas for various end-use applications compared with raw syngas (adapted from [5])

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum Permissible Levels (adapted from [5])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>130 mg/Nm³</td>
</tr>
<tr>
<td>HCl</td>
<td>150 mg/Nm³</td>
</tr>
<tr>
<td>H₂S</td>
<td>less than 25 mg/Nm³</td>
</tr>
<tr>
<td>COS, CS₂</td>
<td>2000 mg/Nm³</td>
</tr>
<tr>
<td>HCN, HBr</td>
<td>0.12% v/v</td>
</tr>
<tr>
<td>Dust, soot, ash</td>
<td>2200 mg/Nm³</td>
</tr>
</tbody>
</table>

An example would be the conversion of wood into a Fischer-Tropsch diesel. Using an air-blown circulating fluidised bed for gasification, the raw syngas was found to contain 0.12% v/v tars, 2200 mg/Nm³ of ammonia, 130 mg/Nm³ of HCl, 150 mg/Nm³ of H₂S, less than 25 mg/Nm³ of COS, CS₂, HCN and HBr (combined), and 2000 mg/Nm³ of dust, soot and ash [31]. The purification process required a cyclone for dust removal, an organic liquid washing process for removing, benzene, toluene and xylene (BTX), a wet scrubber to adsorb ammonia and HCl, an electrostatic precipitator (ESP) to remove fine dust and tar aerosols, and ZnO and active carbon filters to remove traces of inorganic impurities.

A different example would be the raw syngas from in-situ gasification of coal. In addition to the above contaminants it is likely to contain mercaptans and a great many metals eg K, Na, V, Zn, Mg, Ca, Cu, Cr, B, Al, Si, Fe, Mn, Ni, Pb, Hg, As, Cd, Se. Typical clean-up and conditioning steps would be: particulate removal using cyclones, filters, ESP and scrubbers; water scrubbers for removing water soluble materials eg HCl, ammonia and alkali salts; activated carbon and oil scrubbers for removal of
tars and BTX; activated and sulphided carbon to remove trace volatile metals and non-water-soluble contaminants; oxidative washes or acid gas removal for sulphur compounds; hydrolysis for COS conversion to H₂S; and a CO₂ removal process [32].

Because of the wide range of feedstocks that can be used to produce syngas, there is a vast number of contaminants that could potentially be present in the raw syngas – some of which are highly reactive and could seriously impact on both process performance and equipment life. It is important, therefore, to select or design a syngas treatment system that is appropriate to the circumstances. Whilst acknowledging that gas purification is a specialist subject, the broad requirements for a satisfactory approach include understanding the specific syngas purity requirements for the intended use, determining whether any minor components of the raw syngas might react adversely with any solvents used, ensuring the right level of selectivity in any gas separation process to avoid unnecessary downstream processing costs, avoiding corrosion, minimising solvent losses, avoiding excessive energy use throughout the purification process, and striking an appropriate balance between capital and operating costs [6, chapter 8.2].

4. Development of a versatile syngas network

In order to connect various sources of syngas (upgraded to the extent necessary) to potential users of syngas, some form of syngas network is required similar to the gas network depicted in Fig.1. There is considerable experience in the chemical industry of building hydrogen networks to connect users and suppliers of by-product hydrogen on nearby chemical sites [33]. There is also experience of building more extensive pipeline networks for moving petrochemical building blocks such as ethylene between petrochemical sites that are hundreds of miles apart. In one sense, national gas grids used to be syngas networks before they were converted in the 1970s to carry natural gas instead. Mini syngas networks exist in the vicinity of some chemical and petrochemical complexes with limited inter-plant connectivity in much the same way as exists for hydrogen [33]. To create a high-capacity system delivering (say) 40 te/hour at 20 bar pressure would cost about £1m per mile of pipeline plus about 70% of that amount on compressors [26].

Fig 1. Pipeline network linking site in foreground to site in background and another site on the other side of the river.

Many of the issues involved are similar to those which arise in considering the construction of a CO₂ network [24]. Some relate to the question of how best to size such a system when different suppliers and consumers of syngas are likely to make their investment decisions at different times over an extended time period. There is an up-front cost involved in over-sizing a capital asset in order to enable others to connect at a later date. There are then questions about who should own such a multi-user system that runs over land owned by multiple parties, and how they should determine the cost of access to the system in a way that is seen as being fair and equitable – especially if government assistance is sought in connection with investment costs or construction...
permits [34]. Most of these issues have received some consideration before in the context of CO₂ networks [24]. However, having noted that the term “syngas” is used to cover a wide range of gas mixtures, there is an important question about how best to determine entry specifications onto a syngas network – and this is more complex than for the CO₂ network analogue.

If such a network is to feature as part of a drive to reduce the carbon footprint of industrial facilities, there is a need to distinguish between CO₂ derived from fossil fuels and CO₂ from biomass which has grown recently. Legislation aims to reduce the former. A shared syngas network will carry CO which is derived in part from fossil fuels, but the extent can be monitored and potentially accounted for by tracking the C14 radioisotope content [35].

Buffer storage is an important element in a syngas network in which rates of supply and demand are subject to variation. One option, where they exist, is to use solution-mined salt caverns as practised in North East and North West England since the 1940s. For example, the cavities currently used to store 1000 te of hydrogen in North East England at depths of 300-400m could equally store 5000 te of syngas consisting of hydrogen and CO at a 2:1 molar ratio [33].

5. Analysis of carbon/energy reduction potential

Syngas is a highly flexible material since it can be produced in so many ways from so many feedstocks and converted into so many products, especially where an interconnecting network is available. The important question for this paper is: which of these many pathways represent a net energy saving or a net reduction in CO₂ emissions? There are several circumstances under which such a reduction can be expected to occur:

- The original source of the syngas is biomass which has been grown sustainably or would ordinarily be sent to landfill. Provided that the use of fossil fuels in cultivating, harvesting and processing that biomass is small, any CO₂ emissions arising from combustion of the biomass will be largely eliminated by the absorption of CO₂ during the growing phase of the next batch of biomass material.
- The original source of the syngas is waste oils, flared gases and other carbonaceous materials that would ordinarily be treated as industrial waste without any attempt at energy recovery. If these materials are converted to syngas and used for power generation or industrial heating, then there is a net energy saving even though no CO₂ saving can be claimed.
- The syngas is decarbonised as described in Section 3.1 and used to displace natural gas for power generation or fossil-derived hydrogen in any chemical process. Provided the CO₂ removed in the decarbonisation process is consigned to long-term geological storage, then there is a net CO₂ saving.
- Large volumes of CO₂ are generated, captured and stored during the process of syngas conversion. This can work with ammonia production, for example.
- The syngas is converted via one of the processes outlined in Section 3.1 into a long-life polymer. If those processes are low-carbon (for example, their utilities may be supplied by a CHP unit running on syngas derived from biomass), and if the polymer is not incinerated early in its life, then CO₂ is effectively locked up for the lifetime of the polymer.
Some combinations of the above offer a double benefit. For example, options involving sustainable biomass combined with carbon capture and storage can go beyond carbon-neutral to carbon-negative.

6. Conclusions

In a carbon-constrained world with a growing world population and rising aspirations for a developed-world lifestyle, the energy footprint and CO₂ emissions associated with the energy-intensive industries that underpin that lifestyle are causing increasing concern, leading to legislation and targets. Surplus resource (or waste) from industrial, domestic, urban and agricultural systems can often be converted into a very versatile material – syngas. There are a great many ways of converting syngas into power, industrial heat, fuels, chemical feedstocks and chemical products. Some of the processes involved provide an opportunity for cost-effective capture and storage of CO₂. There are therefore a number of pathways through this range of possibilities that enable a net reduction in energy footprint or in CO₂ emissions. Examples of these have been identified. Since those opportunities are likely to involve industrial facilities that are distributed spatially within a certain area, there is a case for building an interconnecting syngas network. The issues surrounding sizing the network, timing its growth, determining ownership and access arrangements, and planning/regulatory hurdles are similar to the analogous case of building an industrial CO₂ network, with the added complication that the term “syngas” tends to be used to cover a fairly wide range of gas compositions. If these issues can be addressed, there is a good case for building syngas networks to facilitate the reduction of industrial carbon footprints.

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