The role of natural gas in mega-cities up to 2050

A discussion paper

Prepared for: The International Gas Union

Contents

1.0 Introduction

This discussion paper addresses issues affecting the role of gas in cities up to 2050.

Predicting the future is notoriously problematic, especially for a timeline as long as 34 years. This is especially true in the realm of investment and economics. For this reason the paper does not attempt to speculate about the future of energy pricing or markets. Instead it refers to present trends in the areas of science, technology, policy and legislation, which are converging.

Section two looks at the context: the growing and urbanising global population; the science of climate change and global agreements to tackle it; the threat of rising sea levels; the energy trilemma; and concern about air pollution.

Section three makes a distinction between the effect these factors will have on new and existing urban developments respectively for natural gas.

Section four refers to the limitations of current projections for natural gas markets and the expansion of liquid natural gas (LNG), contrasting these with projections that take into account the need to keep global temperatures below 2°C.

Within this context it imperative to be aware of the life-cycle greenhouse gas emissions from natural gas, which are discussed in section five.

The following two sections look at the prospects for natural gas positioning itself as a transitional fuel to a low carbon economy, and possible substitutes for it in gas pipeline networks – biomethane and hydrogen.

A significant trend today is for cities to declare targets on the way to or including 100% renewable energy, and this is discussed in section eight, while section nine looks at six sample case studies for future urban energy policies.

We round up with an examination of the consequences of all of this for natural gas in different contexts within cities (section ten).

This is followed by an overall conclusion and a decision table for urban developments up 2050 (section eleven).

The short take-away is that gas is unlikely to act as a cost-effective 'bridge' to a decarbonised world except in the short term and in areas where a high proportion of electricity is generated by coal.

Two appendices examine selected examples of cities declaring renewable energy targets and the prospects for carbon capture and utilisation which could be interesting and the likeliest way to ensure the legal and economic viability of hydrogen production by steam methane reforming and electricity production using natural gas, in the not-too-distant future.

David Thorpe, August 2016
Email: hello@davidthorpe.info.

2.0 The context: urbanisation and the need to mitigate and adapt to climate change

2.1 The urbanising trend

- **Urban areas are currently responsible for 70-75% of energy related CO_2 emissions and 40-50% of global greenhouse gas emissions.**
- 54% of the world's population now lives in urban areas, expected to reach 66% by 2050[1].
- Together with overall population growth this could add another 2.5 billion people to urban areas by 2050.
- Around 90% of the increase will be in mega-cities in Asia and Africa.
- Between now and 2050 the amount of new infrastructure to be constructed in these cities is equivalent to 40% of that already existent in the world[2].
- Altogether, this will drive at least two-thirds of the anticipated growth in final global energy demand by 2050.

"Cities today are home to about half the global population but represent almost two-thirds of global energy demand and 70% of carbon emissions from the energy sector, so they must play a leading role if COP21 commitments are to be achieved."
– Fatih Birol, Executive Director, International Energy Agency.

2.2 Global policy drivers

- The **Paris Agreement** is for global temperature rise to be limited to a maximum of 2^{o}C above pre-industrial levels.
- This incorporates the **Fifth Assessment Report** of the International Panel on Climate Change (IPCC) which quantifies the global maximum CO_2 the world can still emit and have a likely chance of keeping global average temperature rise below 2°C above pre-industrial temperatures. These cumulative emissions must not exceed 1 trillion tonnes of carbon. From 2015 onwards, to meet the 2°C target, the world need to emit no more than 450 GtC by the time carbon emissions end.
- In addition, many developing countries support a reduction in the target to keep global average temperature increases below 1.5°C above pre-industrial levels.
- All countries that ratify the Paris Agreement must have strategies (Intended Nationally Determined Contributions or INDCs) to decarbonise their economies so that global emissions in 2050 are 80% of 1990 levels.
- But these strategies do not yet supply anywhere near the required level of decarbonisation.

"Countries have submitted Intended Nationally Determined Contributions (INDCs) outlining their post-2020 climate action. The INDCs ... imply a median warming of 2.6–3.1 degrees Celsius by 2100."
– article in Nature journal[3].

- The **U.N.'s Sustainable Development Goal 11**[4] is to make cities inclusive, safe, resilient and sustainable, and mitigate and adapt to climate change.

- The **New Urban Agenda**[5], a 20-year urbanization strategy, is to be agreed at the U.N.'s Habitat III conference in October 2016. It aims to reduce pollution and make cities places of opportunities for all, with access to renewable energy, sustainable transportation and more.

2.3 Climate change and cities

Action taken by cities is considered to be one of the most cost-effective ways of attaining the goals of the Paris Agreement by the International Energy Agency[6].

> **"Cities and mayors are now a central part of the solution to climate change. City governments have demonstrated an ability to get to grips with climate change where others have failed."**
> ***– Eduardo Paes, Mayor, Rio de Janeiro, Chair, C40 Cities[7]***

Most mega-cities are and will be constructed in developing countries.

2.4 The threat of rapid sea level rise

2.4.1 Coastal cities are under threat from rising sea levels.

- Limiting a global temperature rise to 2°C could still lock in up to six metres of global average sea level rise (SLR) as soon as 2200, leaving over a quarter of the populations of Shanghai, Hong Kong and Mumbai below the water line[8].
- Lord Krebs, President of the British Science Association and chair of the Adaptation Sub-Committee of the UK Climate Change Committee, agrees with the *Nature* analysis that the Paris Agreement will be lucky to limit the global rise to 3°C. He says we should be preparing around the world for a 4°C rise[9].
- This will lead to a global mean SLR of 0.45m to 0.82m by 2080, rising much more in the subsequent century.
- As this is a mean SLR, hotspots can result in 3-4 times this amount[10]. Land would submerge that is now inhabited by half or more of today's population in Shanghai and Shantou, China; Haora, Calcutta and Mumbai, India; Hanoi, Viet Nam; and Khulna, Bangladesh.
- Thousands of other coastal settlements will be affected: global megacities with the top-10 largest threatened populations include Shanghai, Hong Kong, Calcutta, Mumbai, Dhaka, Jakarta, and Hanoi. Three non-Asian cities with a high proportion of population at risk are Rio de Janeiro, New York, and Buenos Aires.
- Limiting warming to 2°C would cut the threat by more than half in 13 megacities, but this cannot be guaranteed.

2.4.2 The consequences for Natural Gas

- All ports and docks are threatened by sea level rise. This has implications for the transportation of LNG and LPG by ship. If docks are flooded, fuel cannot be unloaded.
- Any city or region relying on this source of fuel for energy would find itself without power.
- Coastal gas-fired electricity power stations and substations at risk will be knocked out or relocated.
- Underground pipe networks in submerged areas will be less accessible for maintenance.
- City authorities planning for climate resilience and adaptation are anticipating these scenarios. The avoidance of dependence on gas will be on their agendas.

2.5 The Energy Trilemma

Decisions upon energy policy are now increasingly determined with reference to the need to balance the challenges of energy security, affordability and sustainability in a given context. This is called the Energy Trilemma.

> **"The trilemma means that policy should never focus on one single aspect. You have to look at the three challenges in a balanced way."**
> ***– Christoph Frei, Secretary General of the World Energy Council.***

2.6 The impact of air pollution legislation

Concern over air pollution favours gas over coal and oil.

In general, natural gas-fired plants emit fewer air pollutants than coal and oil-fired power plants, so are favoured by clean air legislation. In 2015, gas-fired generation emitted close to 20% of NO_X from power generation but barely any SO2 or PM2.5. Natural gas with sulphur has its sulphur content removed.

Air quality is improved by switching from coal-to-gas in power generation or industry, from heavy fuel oil to liquefied natural gas (LNG) in maritime transport, or from solid biomass to liquefied petroleum gas (LPG) for cooking in developing countries, and from diesel to electric commercial vehicles and natural gas buses.

However in each case there are cleaner zero-emission low carbon alternatives that will compete with gas.

3.0 Decarbonising cities

The strategy for decarbonising urban areas will depend upon whether the area already exists or is yet to be built, which has a radically different impact upon the future of gas use in that context.

New urban developments can be designed to be low or zero carbon by 2050. Existing urban areas require adaptation. The challenges for gas are to contribute to efforts to decarbonise electricity, heat supply, cooling and transport **within the overall national and global 80% reduction target**, which also includes agriculture, air travel, shipping, etc. Each country and region will have its own strategies, starting from a different place.

3.1 The design of new urban developments

A 60% reduction of energy use can be achieved in new urban developments by a different approach to planning – a compact city design that eliminates the need for long and frequent private car journeys.

This requires highly insulated buildings and neighbourhood plans that encourage the use of public transport, walking and cycling. Neighbourhoods or individual buildings can also generate their own renewable energy. If all cities adopt all of these tactics, the IEA report says, they will help reduce global greenhouse gas emissions by 15% – about 8 giga-tonnes – by 2050.

The IEA believes that this approach has other benefits:

- it can increase access to modern energy services for inhabitants of developing economies;
- it can improve their living standards;
- it avoids the "locking-in" of carbon-intensive infrastructure by not copying the urban sprawl designs of developed nations.

3.2 Decarbonising existing urban areas

In existing cities, electricity supply, heating services, gas for cooking, and transport must be decarbonised. Some projections see natural gas as a bridge to this decarbonised future. Others do not.

According to sustainable construction consultants Arup[11], lower-carbon energy solutions such as wind, solar, geothermal, hydro, heat pumps, hydrogen, biogas, marine and nuclear power, zero net energy schemes, microgrids and district heating all have a part to play. They do not explicitly consider natural gas to be part of the solution.

However, other case studies Arup have compiled for the UK's Catapult Future Cities programme refer to natural gas-fired combustion turbine combined heat and power (CHP) district networks for heating and electricity supply. CHP is an affordable and more sustainable use of gas than for electricity alone, as a system typically uses 75% rather than 33% of the energy content of the fuel[12].

All studies which see gas continuing to have a role to play require some form of carbon capture and storage or carbon capture and utilisation.

"If we change the way we power our cities we will change the way we power the world and in the process we will save it. America and China recognise that."
– US Secretary of State John Kerry at the Second China-U.S. Climate-Smart Low-Carbon Cities Summit in Beijing.

4.0 Existing projections for NG markets

Several organisations have in recent months published projections for the future evolution of natural gas (NG) markets. However, only some of these fully take on board the implications of the above policy drivers. Therefore those which do not should be discounted. This is especially important in the time frame up to 2050.

To illustrate this we contrast two such projections: one by the U.S. Energy Information Administration and one by the International Energy Agency. But first, where are we now?

4.1 The present picture

In 2014, global primary energy use lay at 570 EJ, having risen 20% since 2004, and comprised oil (31%), coal (29%), natural gas (21%), biofuels (10%), nuclear (5%) and other renewables (4%).

Final energy demand totalled about 390 EJ in 2014, with oil being the dominant vector in final uses (39%), followed by electricity (18%), coal (15%), natural gas (15%), biofuels (11%) and heat (3%)[13].

70% of NG is used in large-scale stationary sources in industry and power generation, compared to almost 95% for coal.

The proportion of NG used in different applications not only varies around the world but will change dynamically over the next 25 years. How it will change depends on many factors: price, economic growth, international politics and climate change policies to name but four.

4.2 The International Energy Outlook 2016 (IEO2016)

This is the U.S. Energy Information Administration (EIA)'s outlook for international energy markets through 2040 and contains projections for the growth of NG – but it must be interpreted with caution for these reasons:

1. It uses a standard Reference case based on expected growth paths for economic activity.
2. It does not include the effects of recent climate change policies such as the Clean Power Plan (CPP) regulations in the United States.
3. It assumes only known technologies and technological and demographic trends, current policies, and does not anticipate new policies already under discussion but not adopted. For example, only some of the Intended Nationally Determined Contributions (INDCs) submitted to COP21 last year, such as renewable energy goals, are included in the modelling.

Therefore it cannot be regarded as a prediction of what will happen, on the basis of which investments should be made by players in the gas market.

Key points of this report:

- The Reference case projects natural gas consumption worldwide to rise from 120 trillion cubic feet (Tcf) in 2012 to 203 Tcf in 2040 with producers increasing supplies by nearly 69%.
- Demand in non-OECD nations is seen as increasing more than twice as fast as in the OECD.
- The largest increases in production occur in non-OECD Asia (18.7 Tcf), the Middle East (16.6 Tcf), and the OECD Americas.
- World LNG trade more than doubles, from about 12 Tcf in 2012 to 29 Tcf in 2040.
- There is a large increase in shale gas production (fracking).
- In the Middle East gas will continue to be largely for industrial purposes.
- In Europe buildings will continue to dominate.
- In Japan electricity generation will increase in proportion.
- One assumed factor in this rise is the use of NG to displace more carbon-intensive coal and liquid fuels (see more below on gas as a 'transitional' fuel).

4.3 IEA 5-year outlook

The five year outlook for NG has been examined by the International Energy Agency (IEA)[14]. By contrast, it sees demand growth for gas in some major markets currently weakening, not growing.

Cheaper coal and continued strong renewables growth are seen as blocking gas from expanding more rapidly in the power sector.

Global demand up to 2021 is seen as rising by 1.5% per year compared with 2% projected in the 2015 IEA annual gas report.

Within fossil fuels, gas is increasingly displacing oil and coal. Fossils' collective share in global energy consumption has remained static at 81% between 1989 and 2014 but oil use has declined from 37% to 31%, while natural gas rose from 19% to 21%.

This trend is seen as increasing due to the impact of the Paris Agreement and air pollution control legislation. But what happens beyond five years?

4.4 IEA 35 year outlook

This is addressed by the IEA's *Energy Technology Perspectives 2016 Towards Sustainable Urban Energy Systems*[15]. This uses three scenarios: the 6˚C scenario (6DS), the 4˚C Scenario (4DS) and the 2˚C scenario (2DS).

The 6DS assumes no greenhouse gas (GHG) mitigation efforts beyond policy measures already implemented, leading to a 60% rise in annual energy- and process-related emissions by 2050 and primary energy demand reaching 940 EJ.

In the 2DS they fall to less than half the current value.

The 2DS is the main focus of *ETP 2016*. It is the one that is in line with the policy drivers listed above in section 2. Key features are:

- A one-third rise in global energy demand is met one-third by wind, solar, hydro and nuclear power with another 30% from natural gas.
- The impact of the Paris Agreement and air pollution control legislation, particularly in urban zones, will favour low carbon fuel sources.
- Therefore by 2050, primary energy demand totals 663 EJ, satisfied by renewables (44%), fossil fuels (45% with gas at 17% – less than now in relative and absolute terms), and nuclear (11%).
- Electricity surpasses oil in the role of most important carrier, with a share of 28% and increasing by 80% from 2014.
- Oil (25%), natural gas (16%), biofuels and waste (15%), and coal (11%) make up the remainder of final energy demand.
- Some NG is only seen as possible with carbon capture and storage (CCS).

4.5 LNG expansion

Some industry modellers expect global liquefied natural gas (LNG) exports to increase substantially, mostly from the United States and Australia[16].

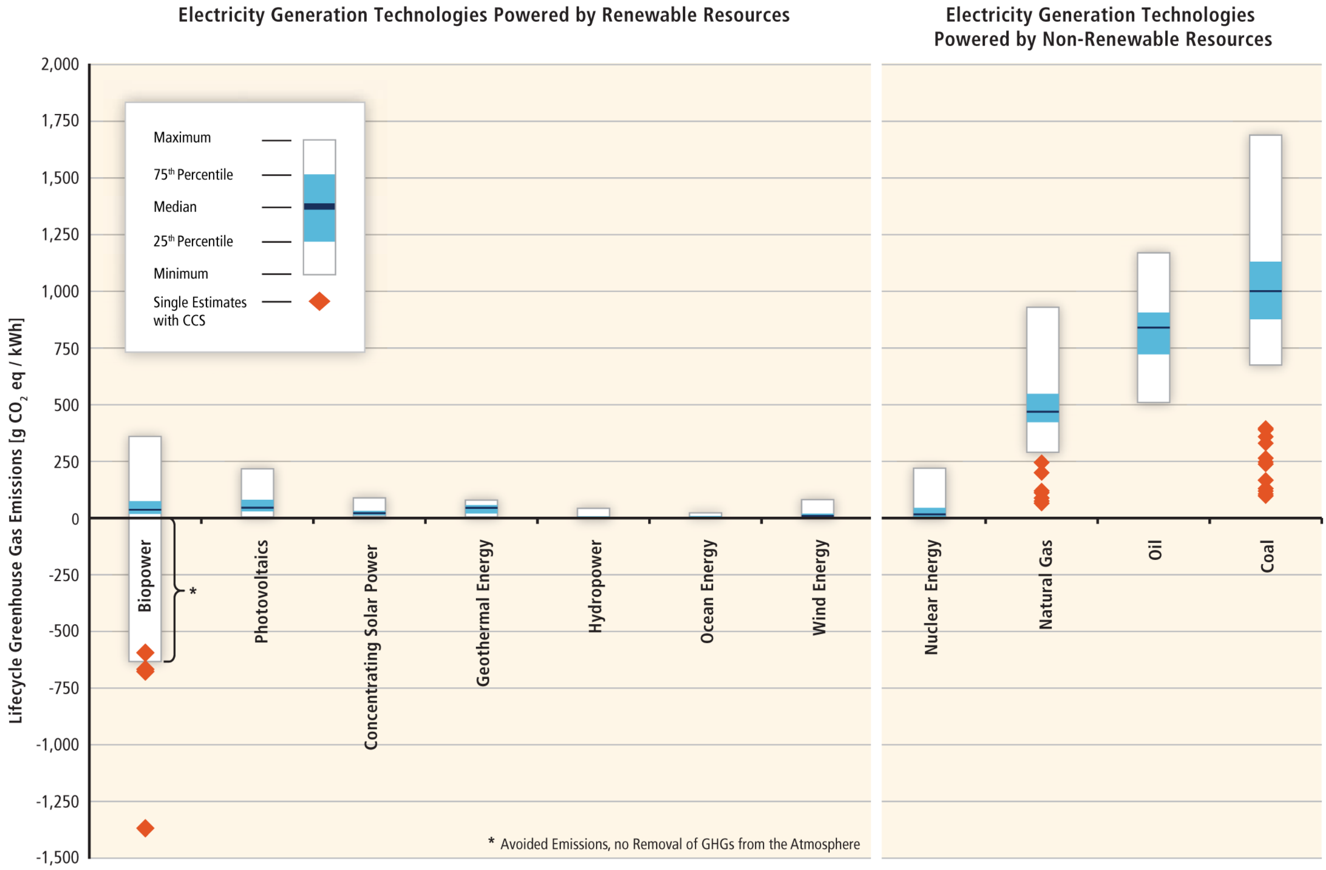
By 2021, Australia is expected to rival Qatar as the world's largest LNG exporter with the US not far behind. These new suppliers will allegedly find buyers in China, India and ASEAN countries with the US helped by the newly expanded Panama Canal, now able to accommodate 90% of the world's current LNG tankers, reducing travel time and transportation costs for shipments from the Gulf Coast to Asia and providing further access to previously regionalized LNG markets.

However, the longer term picture becomes less rosy for LNG shipment if the impact of likely sea level rise on the validity of port infrastructure, with associated insurance costs, are taken into account.

5.0 Lifecycle greenhouse gas emissions of natural gas

Natural gas is a fossil fuel that is generally less polluting than oil or coal. But to determine its effect on climate change – and therefore the part it can play in the future energy scenario – it is necessary to quantify all emissions from the specific drilling, processing, transportation and use of each supply: not all natural gas is equal.

The U.N.'s International Panel on Climate Change (IPCC) puts the range of carbon emissions for **electricity generation** at between **400 and 550 g/kWh**[17]**.**



	Biopower	Photovoltaics	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure SPM.8 | Estimates of lifecycle GHG emissions (g CO_2eq/kWh) for broad categories of electricity generation technologies, plus some technologies integrated with CCS. Land use-related net changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) and land management impacts are excluded; negative estimates[10] for biopower are based on assumptions about avoided emissions from residues and wastes in landfill disposals and co-products. References and methods for the review are reported in Annex II. The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions. [Figure 9.8, 9.3.4.1]

The latest UK government estimated LCA CO_2 emission figures for NG combustion for **heating** are 184.45 g/kWh plus 24.83 g/kWh emitted by the supply system, totalling **209.28 g/kWh**.

But this depends on the gas source: e.g., liquefying natural gas in Qatar, transporting it in refrigerated ships, transporting it in special depots, reclassifying and compressing it into the transmission system can add around another 20 g/kWh, totalling **230 g/kWh**[18].

The Sustainable Gas institute recommends that **total supply chain emissions** for NG should lie within the range of 2.7–32.8g CO_2 eq./MJ HHV (higher heating value) with a central estimate of 13.4g CO_2 eq./MJ HHV, if modern equipment with appropriate operation and maintenance regimes is used."[19]

5.1 Gas replacing coal for electricity generation

Gas emits less carbon than coal when used to generate electricity.

For every 1GW of coal-fired plants replaced by combined cycle gas turbines (CCGTs) operating at a 40% load factor, emissions are reduced by 2.6667 Mt CO_2-eq per year[20], to which supply chain emissions should be added.

The Sustainable Gas Institute says: "Allowing for power plant emissions of 400 g CO_2 eq./ kWh, total GHG emissions would be 419–636 g CO_2 eq./ kWh electricity generated, with a central estimate of 496 g CO_2 eq./ kWh: this is well below typical GHG estimates of coal generated electricity of around 1,000 g CO_2 eq./ kWh. However, the supply chain emissions still represent a significant contribution to life cycle emissions: **4–34% for electricity generation**."

This has led to natural gas being championed as a transitional fuel towards a low or zero carbon world. But how realistic is this?

6.0 Natural gas positioning itself as a transitional fuel

Because it emits less carbon dioxide than coal and oil natural gas (NG) is positioning itself as a transitional fuel to a decarbonised world.

This is why, for example, Eurogas, a trade association representing 43 companies and associations engaged in gas wholesale, retail and distribution in Europe, in July 2016 joined the Covenant of Mayors for Climate & Energy. This body's members aim to reach an EU 40% greenhouse gas reduction target by 2030 and work together to mitigate and adapt to climate change. Eurogas' stated reasons for joining are partly to "highlight the vital role that gas can play in helping local and regional communities accelerate their efforts to reduce carbon dioxide emissions, while maintaining a secure, sustainable and affordable energy supply."

> **"Replacing 30 GW of coal-fired plants with combined cycle gas turbines (CCGTs), operating at the 40% load factor that was the average for such power stations over 2010-2014, could reduce emissions by over 80 Mt CO_2-eq per year (not counting supply chain emissions).[21]"**
> ***– The future role of natural gas in the UK, UK Energy Research Centre (UKERC).***

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80 Mt CO_2-eq per year is equivalent to the emissions from 7,360 average homes.

Yet there are two objections to this strategy.

1. Building new NG infrastructure locks in a level of emissions for at least 30 years. Emissions would be lower if instead renewable and other low/zero carbon options were deployed.
2. The higher emissions from shale gas exploitation.

6.1 Shale gas and global warming

The expansion of shale gas is predicted by models assuming that markets will develop along present supply-and-demand lines. But this is incompatible with keeping global temperatures down to below 2^{o}C in keeping with the science of climate change.

Hydraulic fracturing, or 'fracking' is the technology used to obtain NG from shale wells, tight sands and coal bed methane wells. Projections such as WEC's World Energy Outlook foresee that production of gas from such sources will increase greatly in the future. The U.S. is already switching from coal to gas-fired generation and many new plants are near shale operations.

Will this trend make NG more or less suitable as a transitional fuel from coal or oil to a low or zero carbon world? The most comprehensive study on greenhouse gas emissions from natural gas has been made by the Sustainable Gas Institute (SGI)[22]. This paper reviews the body of evidence on the magnitude of methane and CO_2 emissions in the natural gas supply chain. Its key findings are:

1. The range of estimated greenhouse gas emissions across the supply chain is vast: from 2 to 42g CO_2 eq./MJ HHV (Higher Heating Value) assuming a global warming potential of 34 for methane. But there are sources outside this range and emissions estimates vary greatly due to methodological differences in measurement.
2. There is a lack of data, particularly outside of the U.S.
3. A key challenge is to improve and standardise measurement techniques in order for the industry's claims to be taken seriously.
4. Total supply chain emissions should lie within the range of 2.7–32.8g CO_2 eq./MJ HHV with a central estimate of 13.4g CO_2 eq./MJ HHV, if modern equipment with appropriate operation and maintenance regimes were used. However, there is significant potential for further reductions.

How does this compare with other sources? This is a very complicated question. Different studies have reached differing conclusions[23]:

1. Howarth and colleagues at Cornell University found that natural gas may be worse than coal in terms of global warming potential.
2. A series of other US studies found that significant variability.
3. Life cycle assessments have suggested that combined carbon dioxide and methane emissions remain below those of coal, but not insignificant.

These different conclusions make it difficult for policymakers to make assessments.

Based partly on these findings, the UK Climate Change Commission recommendation to the government on whether shale gas should be exploited in the context of the country's climate change goal is that **fracking on a significant scale is not compatible with UK climate targets unless three tests are met**:

1. Emissions from well development, production and decommissioning must be strictly limited, tightly regulated and closely monitored to ensure rapid action in the event of leaks.
2. Gas consumption must remain in line with carbon budgets and requirements.
3. Shale gas production emissions must be accommodated within overall carbon budgets.

Similar tests could be applied in every country that has signed up to the Paris Agreement, since the UK's climate target of an 80% reduction in emissions by 2050 from 1990 is compatible with the IEA's 2DC scenario and the Paris Agreement. They could be considered the world standard moving forward.

Michael Bradshaw, Professor of Global Energy at Warwick Business School and co-author of a report on the *Future Role of Natural Gas in the UK* for UKERC observes that tests 2 and 3 relate to the overall role of natural gas in any future energy mix, not just shale. He adds that in the 2020s-30s the decarbonisation of domestic heat presents the greatest challenge to the carbon budget in the UK (and by extension Europe).

A further serious constraint on shale gas exploitation that will apply worldwide is noted by the World Energy Council[24]: the limited availability of water for thirsty shale gas production, since, by 2050, the world will require most available fresh water for its population's direct needs.

New U.S. regulations aim to cut industrial methane emissions from the US oil and gas industry by 45% below 2012 levels by 2025[25]. The new U.S. Clean Power Plan also sets a national limit on carbon pollution produced from power plants but not the supply chain, and is facilitating a switch to gas-powered generation from coal.

This is underlined by the IPCC's models. The Working Group III recommendation to policymakers states:

> **" In gas distribution grids, injecting biomethane, or in the future, RE-derived hydrogen and synthetic natural gas, can be achieved for a range of applications but successful integration requires that appropriate gas quality standards are met and pipelines upgraded where necessary."**
> ***– Summary for Policymakers, The Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation***

The conclusion from this discussion is that any expansion of all gas production worldwide is likely to face increasing legislative constraints within overall carbon budgets.

It is likely, then, discounting the influence of price, that, in general:

- **gas will be phased out for electricity generation after coal and oil, in favour of renewable sources**
- **countries heavily dependent upon coal are more likely to convert to gas as a transitional method, depending upon the availability of renewable energy resources compared to demand**
- **natural gas may continue longer in areas where it is used for heating and cooking, while substitute gas fuels are developed.**

7.0 Substitutes for natural gas

If gas networks are not to be used in the future to carry natural gas, what should happen to them? Studies show that preserving and adapting the gas supply networks and infrastructure, where it already exists, would be less socially and economically disruptive and costly than abandoning it for an all-electric future[26].

There are a number of candidates for an alternative gas to natural gas that can ensure this continuity. Each has pros and cons. Their sustainability, including their impact on the climate, needs very careful scrutiny. In the past grave errors have been made, e.g. about the impacts of first and second generation biofuels which turned out to be less sustainable than the fossil fuel they replaced.

7.1 Biomethane or biogas	Biogas (biomethane, CH4, usually with some CO_2 and hydrogen sulphide present) can be produced through anaerobic digestion (AD) of organic farm or catering/food waste, animal manure and sewage sludge, or dedicated crops such as maize, grass and crop wheat. The term also covers gas collected from emissions from landfill and sewage works. AD is proven technology. An advantage is that it also solves a waste problem. Other valuable outputs are: compost (liquid and solid), CO_2 (as feedstock). All of these provide additional income streams. Potential is high but limited locally by availability of year-round feedstock supply. The gas is used locally and, once treated, can be injected into the gas grid or used as fuel in natural gas vehicles, the numbers of which are growing rapidly. Using biogas to generate electricity is common but a much less efficient use due to conversion losses.	**Life-cycle carbon emissions** Analysis of an anaerobic digestion plant using energy crops and crop waste in Hungary found that it produced 33.39 g CO_2/kWh[27] – an astonishing 93.7% less than that from regular Hungarian energy production. The result was heavily influenced by the distance the feedstock had to travel to the plant and the use of artificial fertilisers. **For optimum results these should be minimised to under 10km and zero respectively.** Biogas production and use in electricity and heat production also leads to GHG reductions compared to **composting** of feedstock but reductions are not as high[28]. A further study[29] has concluded: "The reduction of direct methane emissions (from the decay of waste organic matter) together with the efficient utilization of the heat from cogeneration and the use of animal waste as input material can improve the GHG balance substantially." The use of biogas for **transportation** leads to reductions of GHG emissions from 49% to 84% compared to fossil fuels.

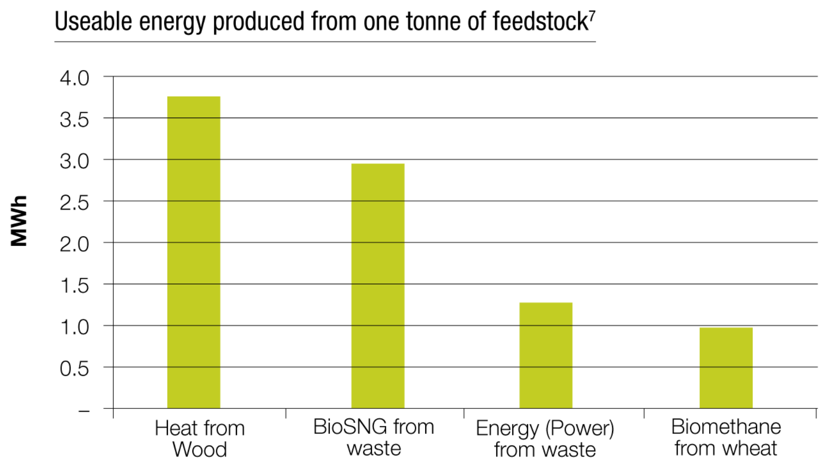
7.2 Biopropane	An alternative to liquid petroleum gas (LPG) that is made from biomass, including used vegetable oil. Biopropane can be used to 'spike' biomethane for injection into the natural gas grid. The current cost is around three times that of LPG, but as a co-product of HVO biodiesel production in practice the cost is lower[30].	**Life-cycle carbon emissions** From 10-50 g of CO_2 equivalent per MJ, or a 43-88% carbon saving on the benchmark fossil-fuel it displaces[31].

7.3 **Bio-synthetic gas (bio-syngas or bio-SNG)**	Bio-SNG is processed from biomass or waste organic matter using gasification, which produces a mixture of gases. To produce biomethane the bio-SNG must be cleaned, filtered and processed further, using advanced catalytic and chemical processing techniques to combine the hydrogen and carbon monoxide in the gas to form methane. This is an intensive process and not amenable to small scale production. A typical bioSNG plant is around half the size of a household waste incinerator for the same volume of waste disposal. Its emissions are cleaner. It provides for more jobs than landfilling. Syngas may also be converted into liquid advanced biodiesel, bioethanol or other fuels. Studies by the UK National Grid suggest between a third and half of UK domestic demand for gas can be met from bioSNG – around 100TWh/annum by 2050. Growing crops for energy and not food, using marginal arable land or grassland, could provide a valuable source of feedstock for bioSNG plants. Potential is huge. The UK Climate Change Committee and relevant government departments have agreed biogas will play an important role in the UK's low carbon energy future and that **it is wrong to use it to generate electricity since only 40% to 65% ends up as electrical energy.** Biogas will be used directly, in the national grid or locally. **It is two to three times more efficient to use organic waste for bioSNG than burn it for electricity.** Currently NG delivers 120 TWh a year in the UK to almost half the population. It has been calculated this can be completely replaced by biogas from the following sources:	**Life-cycle carbon emissions** On the whole, it's advised that crops are not used as a feedstock. A 2010 EU analysis found biodiesel made from N. American soybeans to have a footprint four times higher than standard diesel[32]. A more recent comparative study[33] concluded: "The overall life cycle impacts for diesel, biodiesel, petrol, ethanol, natural gas, and biogas from grass are very close and roughly a factor 2 higher than for the other natural gas options assessed... **Biogas based on waste is the best option**". If crops are to be used as a feedstock, emissions can be reduced in five ways: 1. growing dedicated energy crops that do not require prime agricultural land 2. no use of fertiliser and other inputs 3. growing crops which need less intensive or energy-hungry processing 4. growing crops that help increase soil carbon sequestration on marginal land 5. developing more integrated production systems for food and fuel, such as through agro-forestry and the greater use of co-products. There is yet no standardised methodology for assessing the greenhouse gas emissions of all biofuels. For biogas, the choice of the time horizon in lifecycle carbon assessment is crucial and needs a strong justification.

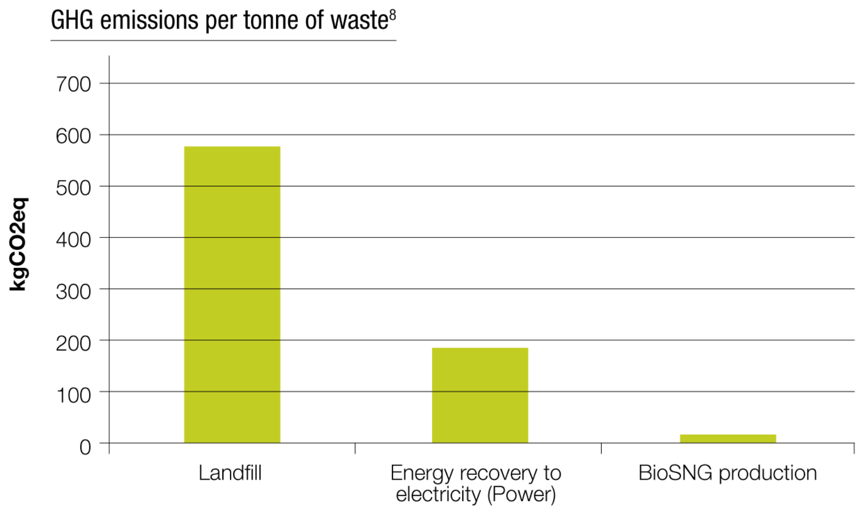
Crop	emissions (CO_2/MJ)	notes
Corn, wheat, rape seed oil	c. 23-28g (28-34% of the emissions from conventional fuels)	principal cause is use of fertilisers and emissions from the soil.
Oil palm, sugarcane	12-14g	need less fertiliser
Sugar beet	12g	
New crops e.g. carmeline & jatropha	c.10g	at an early stage of development; require even less fertiliser.

Biomass source	Percentage
Energy crops	5
Wood	16
Manures	14
Agricultural residues (straw)	17
Waste	47

A team at Oak Ridge National Laboratory, USA, has developed a set of key indicators of bioenergy sustainability and proposed a method for their application to a bioenergy supply chain from feedstock production through energy product consumption[34]. Thirty-five indicators under 12 categories are used to indicate the environmental and socioeconomic values that should be assessed across the entire supply chain. Important are: potential risks to biodiversity, soil fertility and productivity, and water quality and quantity.



BioSNG from waste produces nearly as much energy from one tonne of feedstock as burning wood and nearly three times more than using straw and burning waste. Source: UK National Grid.



Using waste for BioSNG greatly reduces greenhouse gas emissions compared to landfill and energy recovery. Source: UK National Grid.

7.3.1 Advantages of renewable biogas from waste

- **Waste has a negative cost but can produce gas at a cost similar to that of fossil fuels.**
- **New BioSNG plants could support 100 jobs during construction and 50 when up and running.**
- **BioSNG requires no changes to network infrastructure or appliances.**
- **BioSNG ensures the long term future of the gas grid – avoiding decommissioning costs.**
- **Waste from a city could produce enough gas to meet one quarter of domestic demand.**
- **Waste to BioSNG is two or three times as efficient as waste to electricity.**
- **The technologies to support AD and BioSNG are tried and tested and low risk.**
- **BioSNG is a local solution, producing minimal waste emissions. A plant can be located close to the communities it serves.**
- **It is two to three times more efficient to use organic waste for bioSNG than burn it for electricity.**

"Biomethane is in its infancy and green gases in general are perhaps like solar was 10 to 15 years ago […] at that stage of development".
– Chris Clarke, Director of Asset Management at Wales and West Utilities[35].

7.4 Hydrogen

First element in the periodic table and constituent of water (H_2O), where most of it in the lithosphere is found, bonded to oxygen. Also found in methane (CH_4), which is 7.857 times more dense than hydrogen. Natural gas carries 41.7% less energy per unit of weight, so just over three (3.277) times as much volume of uncompressed hydrogen is needed to obtain the same amount of energy. Therefore the gas needs to be delivered at a higher pressure to compensate. Customers' appliances will need adapting or upgrading to cope.

Fuel	Energy content (kWh/kg)
Hydrogen	33.33
Natural gas (82-93% methane)	10.6-13.1
Petrol	12.0
Methane	13.9

Over 90% of today's hydrogen is mainly produced by steam reforming. This process uses fossil fuels – natural gas, oil or coal – as a source of the hydrogen. The carbon dioxide is removed and vented to the atmosphere. Hydrogen produced from NG this way is two to three times the cost of the original fuel. The claimed energy efficiency for natural gas reforming is 75%[36], in other words a quarter of the energy is lost in conversion.

Life-cycle carbon emissions of hydrogen production using SMR plus CCS

The carbon footprint of SMR+CCS has been evaluated as 269 g/kWh using the lowest 184.45g/kWh figure from page 9[37], and assuming an efficiency for the process of 68.4%.

But applying this to the more accurate lifecycle figure for NG of 230 g/kWh obtains 336.26 g/kWh.

If 90% of the carbon dioxide emitted by combustion is captured by CCS or CCU this still leaves [184.45/0.687] x 0.1 + 20 + 24.83 g/kWh = 71.68g/kWh emissions of carbon dioxide equivalent gases – a not insignificant amount.

H21Leeds puts the figure higher, at 85.83g/kWh – Hardly zero carbon.

[Note: 1kWh = 3.6MJ]

If the gas is produced from renewable electricity, then it is more likely to have a much lower carbon footprint. However, presently, this is around eight times more costly.

Benefits of hydrogen	Disadvantages of hydrogen
Once decarbonised it is zero carbon.	Requires the presently unknown provision and cost of carbon capture and storage or utilisation.
Gas production is a proven technology.	Requires changes in pressure to the grid delivery network and polyethylene pipes.
Can be transported through a polyethylene pipe network.	If produced by SMR+CCS/CCU is still not zero carbon, but produces c.85.83gCO_2e/kWh
Offers a familiar service level to customers although existing gas appliances must be modified.	
Can be produced by proton exchange membrane electrolysis from renewable electricity generators as energy storage and used when required.	
Can be injected already into the gas grid up to a certain percentage to 'top up' natural gas	

We are currently selling high purity hydrogen at our refuelling stations for fuel cell cars at £10 /kg of hydrogen. Each kg contains 39.4kWh of energy, so that's about 25 pence/kWh or $0.33/kWh. The ambition is to decrease the $/kWh value as more stations are manufactured and more fuel cell cars are in circulation.

7.4.2 Power-to-gas

Power-to-gas (P2G) uses hydrogen as a form of gas storage and has been proven in real conditions in Germany by a consortium led by ITM, to supply power to the electricity grid and to the gas grid when required as a form of grid balancing[38].

"P2G is particularly advantageous in each of these respects:

- **ability to respond to an instruction from the grid operator to charge up or absorb electricity**
- **ability to hold on to the stored energy for a significant period without incurring energy losses**
- **ability to discharge energy on demand at a desired rate**
- **ability to be scaled up in number or capacity as we head towards a much more renewable electricity system.**

Clearly the economics of P2G are a function of such balancing services payments from the grid operator and the electricity tariff, but in addition P2G offers a greening agent to the gas grid operator in the form of injecting hydrogen at low concentrations into natural gas. So the economics are also a function of the value placed on greening up the gas grid. By analogy we have seen in recent years in France, Germany and the UK feed-in tariffs for injecting bio-methane into the gas grid as a greening agent and these have been up to four times the value of a kWh of natural gas. The economic case therefore depends on a combination of value propositions and costs (providing services to the electricity grid, the electricity tariff paid, the value of green gas for the gas grid and the capital cost of the plant)."

– Prof. Marcus Newborough, Development Director at ITM Power[39]

7.5 Adapting existing gas networks

At least five recent studies have explored the option of using the existing gas network in the UK for biomethane or hydrogen[40]. All regard conversion as a realistic, least-cost option.

Biomethane cannot be produced insufficient quantities to satisfy total demand but is the best option for satisfying demand local to a production facility (anaerobic digestion, landfill gas, etc.). It will likely be used in combination with other sources such as SNG.

For **hydrogen**, there are many hurdles, the most serious of which is the need to use carbon capture and storage or carbon capture and utilisation to produce the hydrogen from the steam reforming of methane, unless it is generated by electrolysis using renewable electricity, which is currently very expensive.

This topic is explored more fully in section 9.6.

Carbon capture and utilisation holds more potential for the gas industry than carbon capture and storage, since it allows local initiatives to proceed – with potential income streams for the CO_2 – without waiting for national governments to support an expensive CCS programme. This topic is explored in Appendix 2.

> **"The most likely use for biomethane will be with hybrid heat pumps, using renewable electricity when available in the heat pump and using a mix of green gases, topped up at peak with natural gas when renewable generation is unavailable."**
> ***– Chris Clarke, Director of Asset Management, Safety & Environment, Wales & West Utilities***

7.6 Hybrid heat pumps

A hybrid heat pump can help reduce carbon emissions and may replace boilers using only mains gas and LPG as there's no need to replace existing radiators and pipework.

It is most suited to properties with heat loads from 12kW-20kW, but can cover heat loads up to 27kW. By monitoring external temperatures and internal heat and hot water demand, and the relative cost of gas and electricity, smart controls identify the most economical operating mode to maximise the use of an air-source heat pump when it is more cost-efficient than using the gas boiler. It can run in four modes:

- **Heat pump only:** during mild temperatures when capacity and efficiency are sufficient to satisfy total demand;
- **First hybrid mode**: when outdoor temperature drops the heat pump efficiency falls but continues to operate and the boiler provides any required additional heat;
- **Second hybrid mode**: when outdoor temperature drops further the variable speed pump is made to slow the flow rate, raising efficiency for as long as possible before switching completely to boiler mode;
- **Boiler only**: When the outdoor temperature is very low only the boiler operates.

However, hybrid heat pumps are not highly efficient (with an energy efficiency rating label of only D or C) and can be expensive. The pumps will need to be powered by renewable electricity to be low carbon.

8.0 The 100% Renewable Energy City movement

A growing numbers of cities, communities and regions are proving that meeting all of their energy demand with renewable energy is viable[41].

Furthermore, 608 cities, towns and regions from 62 countries, representing 553 million people – 8% of the world population – now have targets to reduce their greenhouse gas emissions. These areas are registered with the carbonn® Climate Registry (cCR)[42]. This was launched at the World Mayors Summit on Climate in Mexico City on 21 November 2010 and has grown rapidly.

8.1 Examples of cities with targets

Some examples of cities with these targets are below, and more are listed in Appendix 1.

- **Amsterdam** committed to total decarbonisation of its district heating system in 2015 and set an immediate goal of increasing connections to a total of 230,000 houses by 2040 (a 70% increase)[43].
- **Tshwane, South Africa,** is preparing the transition to renewable energy in the transport sector, including biogas recovery from waste to fuel the city-operated bus fleet running on compressed natural gas[44]. It has a target to reach 50% renewable energy at community-scale by 2030, and a clear political interest in aiming for 100% renewable energy.
- **Jeju Province, South Korea**, has committed to reach 100% renewable electricity and transport by 2030 as part of its "Carbon Free Island by 2030" strategy, and is connecting renewable energy to electric vehicles using smart grids to power both buildings and transport, using a battery-based energy storage system and fuel cell power plants[45].
- **Graz, Austria**, has committed to increasing the share of solar thermal in its district heating network by 20% through the installation of up to 500 MWth of new solar collectors. Bärbel Epp, "Austria: Up to 500 MWth for district heating in Graz," [Solar Thermal World, 7 August 2015, at http://bit.ly/2a0wfeQ.]
- **Münster, Germany**, the first German city to divest from fossil fuels invested in hot water storage tanks in 2015 to utilise surplus grid electricity to generate heat for injection into the city's district heat network as part of a plan to increase renewable energy penetration[46].

Numerous other cities around the world have committed to going 100% renewable. Many already have achieved their goals, including the US cities of **Burlington** (Vermont), **Aspen** (Colorado) and **Greensburg** (Kansas), which all reached 100% renewable electricity during 2015.

8.2 Other initiatives

Further initiatives demonstrate the strength of this movement:

- **The Climate Summit for Local Leaders**, held in parallel with COP21, issued a declaration in support of a transition to 100% renewable energy by 2050[47]. It was signed by nearly 1,000 mayors from around the world. This non-binding commitment builds on examples of leading cities such as Copenhagen, Frankfurt, San Francisco, Sydney and Stockholm.
- **The Global 100% RE Campaign** published 12 criteria in 2015 to help define the concept of 100% renewable energy for local governments[48] and to guide policy makers in initiating their transition to 100% renewables.
- **The 100% RE Cities and Regions network**[49] was also launched by the Campaign in 2015, to enable peer-learning and exchange among municipalities.
- The Campaign works alongside **Europe's 100% RES Communities** and **RES Champions League**.

- In Germany, a pioneering country in this regard, 100% renewable energy has been a movement for several years. A national framework empowers cities to transform their energy systems. 140 regions, hosting one quarter of the population, have set targets of one type or another. E.g., The Fraunhofer Institute has modelled that it is feasible for Frankfurt to achieve 95% RE in power heating, cooling, local mobility from its hinterland, with the rest coming from outside the region.

8.2 Developing countries

Cities in developed countries are leading the way. There are different realities in developing countries.

These cities are advised to link their 100% renewable energy strategy to their development strategy, i.e. making it a tool for development to enable access to international funding sources. This is India's approach. It's not necessarily only a technology transfer issue but a means for new investment sources to come in. There is the additional advantage of securing energy security and developing new business models for local jobs.

Furthermore, the value of the energy produced stays within the city area. With the traditional model, this capital leaves the city to flow to the utilities, to pay for fossil fuels, having contaminated the city and contributed to climate change. Instead, distributed production can be implemented and citizens rewarded with a competitive structure. It's an important way of reducing energy poverty too, by implementing a plan for offering renewable energy to families affected by this issue.

The World Future Council and the ICLEI are two organisations which are active in this field, helping with integrating the strategies into a national economic development plan for a country or region to help create jobs and train young people in learning the skills required.

9.0 Some case studies

9.1 Mexico City

A mega-city with a population of over 20 million, Mexico City is a founder party to the new International Standard for sustainable cities, ISO 37120: Standard Sustainable Development of Communities: Indicators for City Services and Quality of Life[50]. This is being developed and adopted by hundreds of cities, including Shanghai and others in China and India.

Mexico City has adopted a goal to halve carbon dioxide (CO_2) emissions from 2000 levels by 2050. Mexico as a whole is aiming for 40% of electricity to come from wind power alone by 2040. Policies for Mexico City[51] are being developed to encourage lower-emission vehicles (partly with a switch to biofuels) and public transportation, distributed renewable energy networks, build more energy efficient buildings, implement smart grid technologies, retrofit existing buildings and enforce building codes to support energy saving.

9.2 India's "Development of Solar Cities" programme

India's 'Ministry in the Urban Sector' has a "Development of Solar Cities" programme to support/encourage Urban Local Bodies to prepare a Road Map to guide their cities in becoming 'renewable energy cities' or 'solar cities'.

Initiatives include promoting solar water heating systems in homes, hotels, hostels, hospitals and industry; deployment of pilot PV systems/devices; establishment of 'Akshya Urja Shops'; design of Solar Buildings and promoting urban and industrial waste/ biomass to energy projects. The solar city programme aims to consolidate all the efforts of the and address the energy problem of the urban areas in a holistic manner.

The initial aim was a minimum 10% reduction in projected demand of conventional energy within five years. Past solar targets in India have been rapidly exceeded[52]. Already there is a new target for green townships of 25% reduction within five years[53].

9.3 A heat pump-driven district heat network in Dramman

Heat pumps represent a significant competitor to NG for space heating and cooling. (They are sometimes known as geothermal energy, but strictly this applies to energy from deep boreholes that tap into hot rocks.)

The same system can be used to either remove heat from a space (cooling) or add heat to it, i.e. heat pumps can work forwards for heating space and backwards for cooling. They can be installed in individual buildings or clusters and drive heat mains. The energy in/energy out ratio of an efficient system is in the range of two to four times. Electricity (preferably renewable) drives the pump. The heat or cooling source is free. For heating, this renewable source may derive from ground, air, water or waste industrial heat.

Water source heat pumps are particularly useful when developments are near bodies of water. A hotel complex in Greater London, for example, uses the River Thames as a heat source, while the town of Drammen in Norway heats most of its buildings from water with a source temperature of just 8^oC.

The 45MW Drammen district heating system serves over 200 large buildings. The heat was originally supplied from fossil fuel and biomass. Now a large heat pump is the primary source. This draws 75% of the network heat from ammonia heat pumps with 15% from biomass and 10% from gas/oil. The fjord water is used to heat ammonia, at four times atmospheric pressure, till it evaporates (at 2^oC). The pressure is then increased to 50 times atmospheric pressure (50 bar), bringing the gas to

120°C. The heat is transferred via a heat exchanger to the water in the heating system, which (returning from the district heat main at 60°C) is heated back up to 90°C and sent round again. The ammonia returns to a liquid state and begins its own cycle over again. The pumps are driven by electricity, but the whole system produces three times more energy than is put in. If the electricity comes from a renewable source then the system is zero carbon. The Dramman system has paid for itself very quickly and now saves the town around €2m and 1.5m tonnes of carbon emissions a year.

Elsewhere in the world, ground source heat pumps are a most economic option. Switzerland, for example, already boasts over 25,000 such systems. Swiss public utilities use energy contracting to incentivise their adoption by paying for the installation and operation of systems then charging the property owner for the cooling or heating service.

9.4 Commercial BioSNG Demonstration Plant, Swindon, UK

The UK's National Grid is constructing a BioSNG Demonstration Plant using gasification of residual household waste. The aim is to encourage commercialisation of the technology required to produce significant quantities of renewable gas. It will be capable of heating 1600 homes or of fuelling 75 heavy goods vehicles.

The contractual, financing, commercial and engineering issues relating to the construction and operation of such facilities, the off-take of the fuel it produces and the supply of the waste feedstock are all being investigated by this pilot study. It will begin operation in January 2018.

9.5 Ontario's heat networks plan

Ontario's five year Climate Change Action Plan adopted in 2016 aims to make the region "one of the easiest and most affordable in North America for homeowners and businesses to install or retrofit clean-energy systems like solar, battery storage, advanced insulation and heat pumps."

Over four years the government will spend over $7 billion. It decided to make a switch from natural gas to heat pumps because it was calculated that the $200 million subsidy demanded for installation of NG pipelines into 68 communities translated to an average of $25,600 for each connection, not including the cost of the furnace/boiler, hot water tank, or installation.

Heat pump networks have similar set-up costs to natural gas – for new equipment and putting the pipework in the ground – but the ongoing running cost is reduced by 50 to 80%. Heat pumps were seen as cheaper and, if powered by renewable electricity, zero carbon. The government therefore opted to phase out natural gas. By 2030, the building code for residential and small buildings will eliminate combustion heating, and by 2050 combustion heating will be outlawed in all buildings.

9.6 New York City's 80x50 program

New York City's 80X50 program aims, like the UK's, for an 80% reduction in emissions by 2050. In January 2016 the city passed a law on requiring all government buildings to switch to heat pumps in all new construction and retrofits when it is shown that doing so would be cost-effective. Hundreds of buildings in the city have already done so. The city goal is for over 900,000 of its 1.1 million buildings make the switch by 2050. Heat pumps also eliminate the cooling towers needed by non-geothermal cooling technologies, making buildings more storm and disease resistant.

Factors to be taken into account when comparing conventional heating and cooling technologies with heat pumps include: greenhouse gas emissions, air pollution concentrations, annual electricity consumption and peak demand reduction, a possible revenue stream due to the peak demand reduction, fuel and power costs, net present value of all alternatives based on a 20-year life expectancy and capital costs, operations and maintenance, fuel costs, available federal, state and other non-city governmental funding assistance, and the social cost of carbon.

The New York State Public Service Commission (PSC) has begun a dialogue with NG utilities asking them to switch their pipelines from NG to heat pumps, along with other options, such as using the city's water-mains for heat pumps.

Other cities are expected to follow suit[54].

9.7 Adapting the existing gas network

Consultants KPMG have examined the effects of four different energy scenarios on the UK gas networks for the use of energy demand by domestic and commercial customers up to 2054[55].

They particularly compared one where gas remains the main heating fuel for the majority of customers and one where services are all electric [In the UK 23 million or 84% of homes are connected to the gas network. About two-thirds of residential and commercial energy consumption is met by natural gas]. They did not consider the role of gas in electricity generation or a scenario where there is significant improvement in the energy performance of buildings.

They found that the cheapest option was one where the gas network is kept but evolves by conversion to alternative gases such as hydrogen and biogas. This option was less than half the cost of a fully electric future for heating and cooking, and was even more attractive compared to options where there was a significant hurdle for customers in accepting new ways of providing for their heating and cooking. But even in this option there is no extension of the gas network going forward for new urban developments because there are energy supply alternatives.

The most significant challenge for decarbonisation of heat is to meet the winter peak heating demand by alternative means. There were some significant caveats however associated with continuing with the gas network:

1. It is necessary to find a way to render harmless the carbon dioxide removed from methane by steam reforming (either by carbon capture and storage or carbon capture and utilisation – see Appendix 2).

2. Electricity supply and transport (accounting for approximately 40% of energy demand in the typical developed economy) would need to be completely decarbonised by 2050.

3. They assumed no decarbonising of other sectors of the economy such as agriculture, refineries etc.

4. The cost includes the costs of installing steam methane reformers to produce hydrogen from methane, and the costs of installing CO_2 pipes to carry the CO_2 bi-product to storage facilities, but not the CO2 storage facilities themselves.

Failure to do both of these would put carbon emissions too high to meet the target of the UK producing no more than 20% of 1990 CO_2 emissions.

Modelling has been done on the relative costs of different options, comparing biomethane to storage and overgeneration capacity to meet peak demand[56].

Option	Consumer Cost per Annum	Cost/Tonne CO_2 abated
Base Case (Gas Boiler)	£1,308	N/A
Low Carbon Option A (Storage)	£75,363	£17,117
Low Carbon Option B (Over Generation)	£115,930	£26,494
Green Gases mix	£2,183	£271

However there would not be sufficient supply of biomethane from energy crops and waste to meet all demand.

Meanwhile, in Germany, ITM Power and Thuga Group have been injecting gas into the Frankfurt distribution grid for two years using a 300kW pilot unit. A second project has begun with RWE.

10.0 The consequences for NG in cities

Looking ahead to 2050 bearing all of the above in mind, and in particular reference to the IEA's 2DS scenario, we can make the following assumptions about the implications for the differing applications of NG in cities.

10.1 Coastal cities

Especially vulnerable to sea level rise, these are liable to lead the way in adapting to climate change and have more stringent climate policies that will favour renewables over fossil fuels, even NG. Docks and ports are vulnerable, and this has implications for the shipping of LNG and a reluctance among markets to be dependent upon this supply mode.

10.2 New urban developments

These would require new infrastructure, and as time goes on, authorities are more likely to favour renewable sources of electricity and energy, and not rely on new gas pipeline networks or generation. Heat pumps and renewable energy district heat and power networks will become the norm. A regulatory investment framework for district heating is required in most areas.

10.3 Existing urban developments

These will find new uses for existing NG infrastructure or replace it with electricity-powered alternatives. Owners of pipe networks have a vested interest in finding new applications beyond NG. These will include hydrogen either produced by electrolysis using intermittent renewable energy, or from methane with CCS or CCU if available, and biomethane/bioSNG, initially topped up with natural gas at times of high demand. Hybrid heat pumps are also a contender.

10.4 Electricity supply

The power sector will be almost completely decarbonised by 2050, with only some natural gas required for generation and no coal or oil-fired generation.

Around 5,100 gigawatts (GW) of new capacity is needed globally. Much will be renewable and locally supplied within or close to cities. Electricity storage will be widespread to meet demand at all times. The technologies used for storage will vary but include hydrogen as power-to-gas. Disruptive technologies may well have appeared in regard to storage and renewable energy generation. One such on the horizon is third generation photovoltaics known as perovskite solar cells.

There will be some gas-fired CHP networks, and non-CHP gas-powered generation may well have to have CCS attached, or the use of CO_2 as a feedstock for fuels, chemistry and polymers (CCU). Without this, gas consumption will fall by 2050 to only about 12% of the 2010 level, to balance intermittent renewables and in industry. Under current assumptions, most of this fall will happen after 2030[57], indicating the limit of gas as a transitional fuel, but these assumptions are subject to rapid change, post-COP21.

10.5 Transport

Compressed and liquefied natural gas will replace diesel in road freight applications in certain markets, provided that certain issues (e.g. "methane slip") are addressed[58]. Otherwise most transport will be electric, biofuel or hydrogen fuel cell.

10.6 Industry

Energy efficiency will become increasingly important but decarbonisation will be more gradual than in other sectors. Globally the industrial sector is responsible for around one-quarter of total energy consumption and gas is widely used. Often, industry is concentrated in a small number of urban areas. This makes it relatively easy to identify the big energy consuming enterprises. Therefore, improving energy efficiency in the industrial sector is being prioritised in many countries[59].

Over coming decades, as plant is replaced and new plant installed, this will reduce energy demand and improve energy intensity (GDP per unit of energy consumed). In combination with a switch to renewable energy, the industrial sector will be gradually decarbonised. Even so, gas use will still increase in petrochemicals and chemicals, iron and steel and aluminium sectors and grow slightly in the cement sector. Only in the pulp and paper sector is a decline foreseen.

10.7 Buildings

According to the IEA's 2DS scenario, NG consumption falls by 15% and electricity demand falls 33% due to energy efficiency in the mid-term, saving an estimated 57 exajoules (EJ). There is projected a 250% increase in the use of heat pumps.

In the mid-term, commercial heat (district heating) fuel demand remains roughly constant, despite significant improvements in building envelopes, as additional buildings are able to join existing networks without having to increase heat production capacity. Solar thermal use, in particular for water heating, increases by 850% over 2013 levels.

Space heating (accounting now for over one-third of energy use in buildings around the world) will still be the largest consumer of energy in buildings. Energy for space cooling (roughly 5% of energy use in buildings today) is fast-growing (up to tenfold in some hot, rapidly emerging economies) and needs to be supplied sustainably – most likely by reversible heat pumps.

Climate-appropriate design of urban developments and the use of passive solar architectural design principles will reduce both heating and cooling requirements. This will occur faster in commercial and other services buildings, where turnover and demolition rates are faster than for residential stock.

20% of cumulative energy savings are due to efficient equipment, through minimum or mandatory energy performance standards (e.g. mandatory condensing boilers) and strong uptake of high efficiency technologies (e.g. heat pumps).

15% of savings are in the developing world and come from switching from traditional biomass to solar technology and high-efficiency pellet stoves and from inefficient use of fossil fuels (e.g. to mandatory condensing or instantaneous gas boilers or mini- or micro-CHP).

11.0 Overall conclusion

Gas is unlikely to act as a cost-effective 'bridge' to a decarbonised world except in the short term and in areas where a high proportion of electricity is generated by coal.

Gas demand will likely rise up to 2020 to 2025 (depending on the country) before declining. This timescale will vary in different parts of the world, dependent upon many local factors. Gas is more likely to provide a short-term stop-gap until low- or zero-carbon energy sources can come on stream, but existing gas networks may be adapted to take biogas or hydrogen gas with CCS/CCU.

The decision table below is provided to assist in clarifying the principles involved.

11.1 Decision table for urban developments up to 2050

In order to help devise a gas implementation strategy for a given location, it may be useful to proceed through answering the questions below.

Abbreviations are explained on the next page.

Has the host country an INDC? and/or: Has the city a climate change mitigation and adaptation strategy?	NO	Devise NG or L/ZC policies in keeping with another global 2DS, e.g. the IEA's
	YES	Harmonise NG decisions with INDC/strategy
Is the urban development existing or new?	NEW	Will probably not opt for NG but L/ZC options, e.g. heat pumps. If mixed use with strong anchor clients: district heating
	EXISTING	Proceed to next question
Does the area already have a gas network for heating/cooking?	YES	Adapt it for biogas or H2 + CCS/CCU
	NO	Will probably opt for L/ZC options OR if for NG then CHP and perhaps district heat networks
Is the settlement low or high density?	LOW	Probably best for heat pumps.
	HIGH	High rise: electric heating and cooling where gas-fired boilers cannot be used and space heating requirements are low.
Does country have coal-fired generation?	YES	Can transition to 2DS via gas CCGT + CHP
	NO	Will probably opt for L/ZC options OR if NG then CHP and perhaps district heat networks
Is city endangered by sea level rise?	YES	NG not appropriate
	NO	Will probably opt for L/ZC options OR if for NG then CHP and perhaps district heat networks
Does country have existing NG reserves or a pipeline connection for import?	YES	It may continue to exploit or adapt network for biogas or H_2 + CCS/CCU
Does country currently import NG by sea?	YES	May opt for L/ZC options because of sea level rise threatening ports OR opt for L/ZC options
Are sufficient 365 days/year supplies of nearby organic waste/sustainable energy crops available?	YES	Use AD or bioSNG
	NO	Use other L/ZC options
Is CCS or CCU available at an economic scale?	YES	Adapt or create network for H2
	NO	Use other L/ZC options.

11.2 Abbreviations

INDC	Intended Nationally Determined Contribution: the decarbonising strategy a country must prepare under the Paris Agreement
L/ZC	Low/Zero Carbon: energy efficiency, solar, wind, water, marine, bio- energy and heat pumps, sustainable transport and land use, etc.
2DS	Two-degree strategy: a plan involving the use of L/ZC solutions to move towards a world where there is no more than a 2^{o}C global temperature rise above pre-industrial levels
IEA	International Energy Agency
H2	Hydrogen gas
CCS	Carbon Capture and Storage, typically underground in a geologically safe place
CCU	Carbon Capture and Utilisation as a feedstock for other product manufacturing
CCGT	Combined Cycle Gas Turbine electricity power plant
CHP	Combined Heat and Power or cogeneration
NG	Natural gas
AD	Anaerobic Digestion: the composting of organic waste matter under special conditions without the presence of oxygen to produce biogas and fertiliser.
BioSNG	Bio-synthetic natural gas: chemically equivalent to natural gas and made from organic waste matter or energy crops

12.0 Appendix 1: City and Local Renewable Energy Targets: Selected Examples

Cities are increasingly setting targets for up to 100% renewable energy. Here are some examples[60].

Targets for 100% of total energy or electricity from renewables

City	Target date for 100% total energy	Target date for 100% electricity
Aspen, Colorado, USA		2015
Burlington, Vermont, USA		Achieved in 2014
Byron Shire County, Australia	2025	
Coffs Harbour, Australia		2030
Copenhagen, Denmark	2050	
Frankfurt, Germany	2050	
Fukushima Prefecture, Japan	2040	
Greensburg, Kansas, USA		Achieved in 2015
Hamburg, Germany	2050	
Jeju Self Governing Province, Republic of Korea		2030
Lancaster, California, USA		2020
Malmö, Sweden		2030
Munich, Germany		2025
Osnabrück, Germany		2030
Oxford County, Canada	2050	
Palo Alto, California, USA		(no date given)
Rochester, Minnesota, USA		2031
San Diego, California, USA		2035
San Francisco, California, USA		2020
San Jose, California, USA		2022
Seattle, Washington, USA		(no date given)
Skellefteå, Sweden		2020
Sønderborg, Denmark	2029	
Sydney, Australia	2030	
Ulm, Germany		2025
Uralla, Australia	(no date given)	
Vancouver, Canada	2050	
Växjö, Sweden	2030	

NB: This is not an exclusive list. 73 more are on a list provided by Anna Leidreiter of the the World Future Council. Of these the following table shows those that have already achieved 100%:

Cities that have achieved 100% renewable energy[61]

City	Country	Continent	Administrative unit	Sectors (Electricity, Transport, Heat)
Columbia, Maryland	US	North America	city	Electricity, Transport, Heat
Dardesheim	Germany	Europe	town	Electricity, Transport, Heat
Dobbiaco	Italy	Europe	city	Electricity, Heat
Feldheim	Germany	Europe	town	Electricity, Heat
Flecken Steyerberg	Germany	Europe	village	Electricity, Transport, Heat
Kasese	Uganda	Africa	region	Electricity, Heat
Knežice	Czech-Republic	Europe	village	Electricity, Heat
Linköping	Sweden	Europe	city	Transport
Mureck/Steiermark	Austria	Europe	region	Electricity, Heat
Odenwald District	Germany	Europe	region	Electricity, Heat
Perpignan Méditerranée	France	Europe	region	Electricity, Heat
Saerbeck	Germany	Europe	village	Electricity
Saint-Julien-Montdenis	France	Europe	village	Electricity, Heat
Schleswig-Holstein	Germany	Europe	region	Electricity
Thisted	Denmark	Europe	town	Electricity
Wallonie Picarde	Belgium	Europe	region	Electricity, Transport, Heat
Wildpoldsried	Germany	Europe	village	Electricity, Transport, Heat
Wilhelmsburg (Hamburg)	Germany	Europe	city district	Electricity, Heat
Wolfhagen	Germany	Europe	city	Electricity

Targets for renewable share of total energy, all consumers

City	Target
Austin, Texas, USA	65% by 2025
Boulder, Colorado, USA	30% by 2020
Calgary, Alberta, Canada	30% by 2036
Cape Town, South Africa	10% by 2020
Howrah, India	10% by 2018
Nagano Prefecture, Japan	70% by 2050
Oaxaca, Mexico	5% by 2017
Paris, France	25% by 2020
Skellefteå, Sweden	Net exporter of biomass, hydro or wind energy by 2020

Targets for renewable share of electricity, all consumers

City	Target
Amsterdam, Netherlands	25% by 2025; 50% by 2040
Austin, Texas, USA	35% by 2020
Canberra, Australian Capital Territory, Australia	90% by 2020
Cape Town, South Africa	15% by 2020
Nagano Prefecture, Japan	10% by 2020; 20% by 2030; 30% by 2050
Taipei City, Taipei, China	12% by 2020
Tokyo, Japan	24% by 2024 [20% by 2024]
Wellington, New Zealand	78–90% by 2020

Heat-related mandates and targets

City	Target
Amsterdam, Netherlands	District heating for at least 200,000 houses by 2040 (using biogas, woody biomass and waste heat)
Chandigarh, India	Mandatory use of solar water heating in industries, hotels, hospitals, prisons, canteens, housing complexes, and government and residential buildings (as of 2013) and 100 MW of rooftop solar PV by 2022
Helsingborg, Sweden	100% renewable energy district heating (community-scale) by 2035
Loures, Portugal	Solar thermal systems mandated as of 2013 in all sports facilities and schools that have good sun exposure
Munich, Germany	80% reduction of heat demand by 2058 (base year 2009) through passive solar design (includes heat, process heat and water heating)
Nantes, France	Extend the district heating system to source heat from biomass boilers for half of city inhabitants by 2017
Osnabrück, Germany	100% renewable heat by 2050
Täby, Sweden	100% renewable heat in local government operations by 2020
Vienna, Austria	50% of total heat demand with solar thermal energy by 2050

Targets for government self-generation / own-use purchases of renewable energy

City	Target
Belo Horizonte, Brazil	30% of electricity from solar PV by 2030
Cockburn, Australia	20% of final energy in city buildings by 2020
Ghent, Belgium	50% of final energy by 2020
Hepburn Shire, Australia	100% of final energy in public buildings; 8% of electricity for public lighting
Kristianstad, Sweden	100% of final energy by 2020
Malmö, Sweden	100% of final energy by 2020
Portland, Oregon, USA	100% of final energy by 2030
Sydney, Australia	100% of electricity in buildings; 20% for street lamps

Target for renewable electric capacity or generation

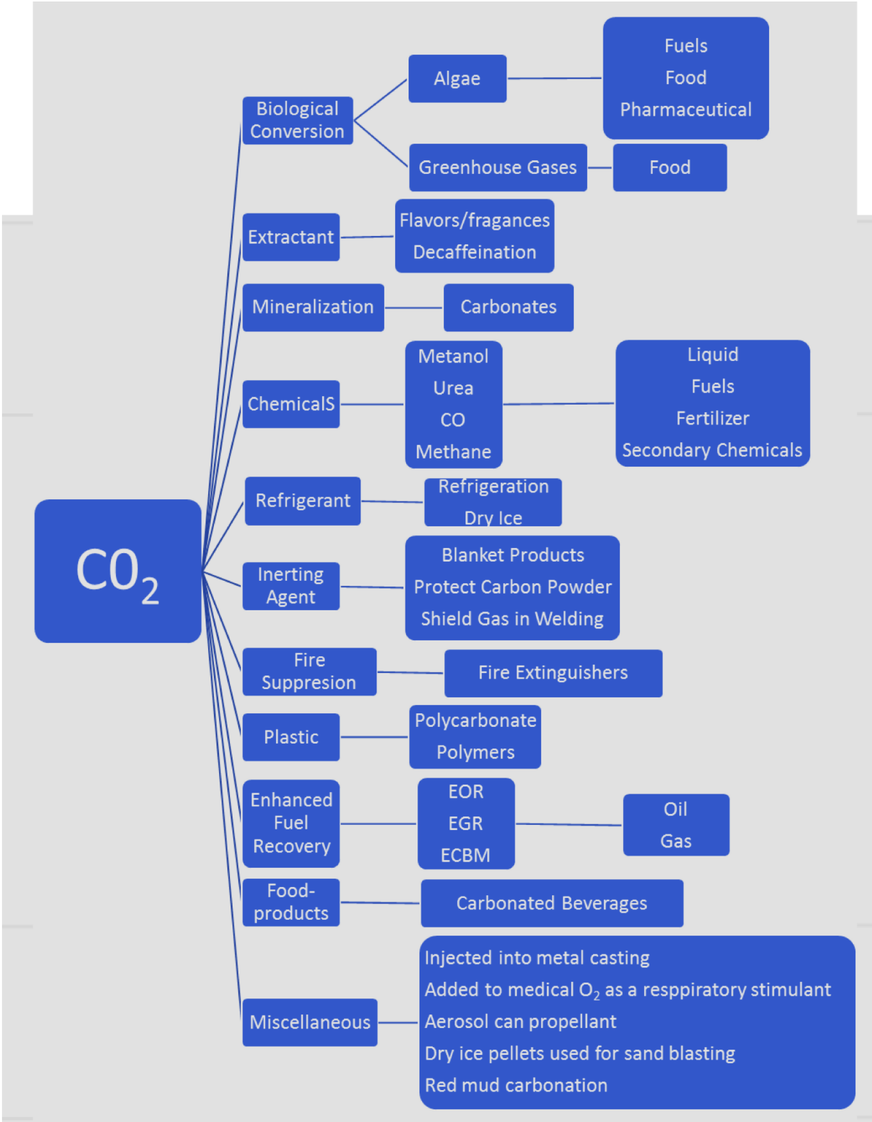
City	Target
Adelaide, Australia	2 MW of solar PV on residential and commercial buildings by 2020
Esklistuna, Sweden	48 GWh from wind power, 9.5 GWh from solar PV by 2020
Gothenburg, Sweden	500 GWh by 2030
Los Angeles, California, USA	1.3 GW of solar PV by 2020
New York, New York, USA	350 MW of solar PV by 2024
San Francisco, California, USA	100% of peak demand (950 MW) by 2020

13.0 Appendix 2: Carbon Capture and Utilisation

Carbon dioxide utilisation for the production of fuels, chemicals and materials has emerged as a possible but as yet little known alternative to CO_2 storage. This is relevant if hydrogen is to be made by steam reforming of methane for gas networks, or for addition to gas-fired electricity generation plants, to keep them within agreed greenhouse gas emission limits.

"CCS is basically a non-profit technology, where every step is costly. CCU however has the potential to produce value-added products that have a market and can generate a profit."
– Dr Lothar Mennicken, German Federal Ministry of Education and Research[62]

Right: The potential for CCU[63].



The report *CCU in the Green Economy* from The Centre for Low Carbon Futures[64] shows that CCU can be profitable, with short payback times on investment. It says: "Although only a partial solution to the CO_2 problem, under some conditions using CO_2 for CCU rather than storing it underground can add value as well as offsetting some of the CCS costs."

The Carbon Storage Program of the NETL (National Energy Technology Laboratory) of US Department of Energy supports four main CO_2 utilisation research areas:

- cement
- polycarbonate plastic
- mineralisation
- enhanced hydrocarbon recovery.

The first three represent a large potential market for CO_2 storage in materials, especially building materials.

"If the European chemical industry were to meet its entire carbon needs from CO_2 rather than fossil sources such as oil, gas and coal, it would use or recycle 5.5% of Europe's total CO_2 emissions, despite being responsible for just under 2% of Europe's CO_2 emissions."
– Michael Carus, managing director of nova-Institute GmbH[65].

14.0 About the author

David Thorpe is an energy and sustainability consultant and journalist, and the author of over 10 books on energy efficiency and renewable energy, including :

- *Best Practices and Case Studies for Industrial Energy Efficiency Improvement* (with Oung, K. and Fawkes, S. UNEP, 2016)
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- *Earthscan Expert Guide to Energy Management in Industry* (Earthscan, 2013)
- *Investors' Guide to Photovoltaics* (Do Sustainability e-short, 2012)
- *Investors' Guide to Low Carbon Vehicle Fuels* (Do Sustainability e-short, 2012)
- *Earthscan Expert Guide to Solar Technology* (Earthscan, 2011)
- *Earthscan Expert Guide to Sustainable Home Refurbishment* (Earthscan, 2010)

Twitter: @DavidKThorpe
LinkedIn: http://bit.ly/1GFS13x
Email: hello@davidthorpe.info

15.0 NOTES and further reading

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