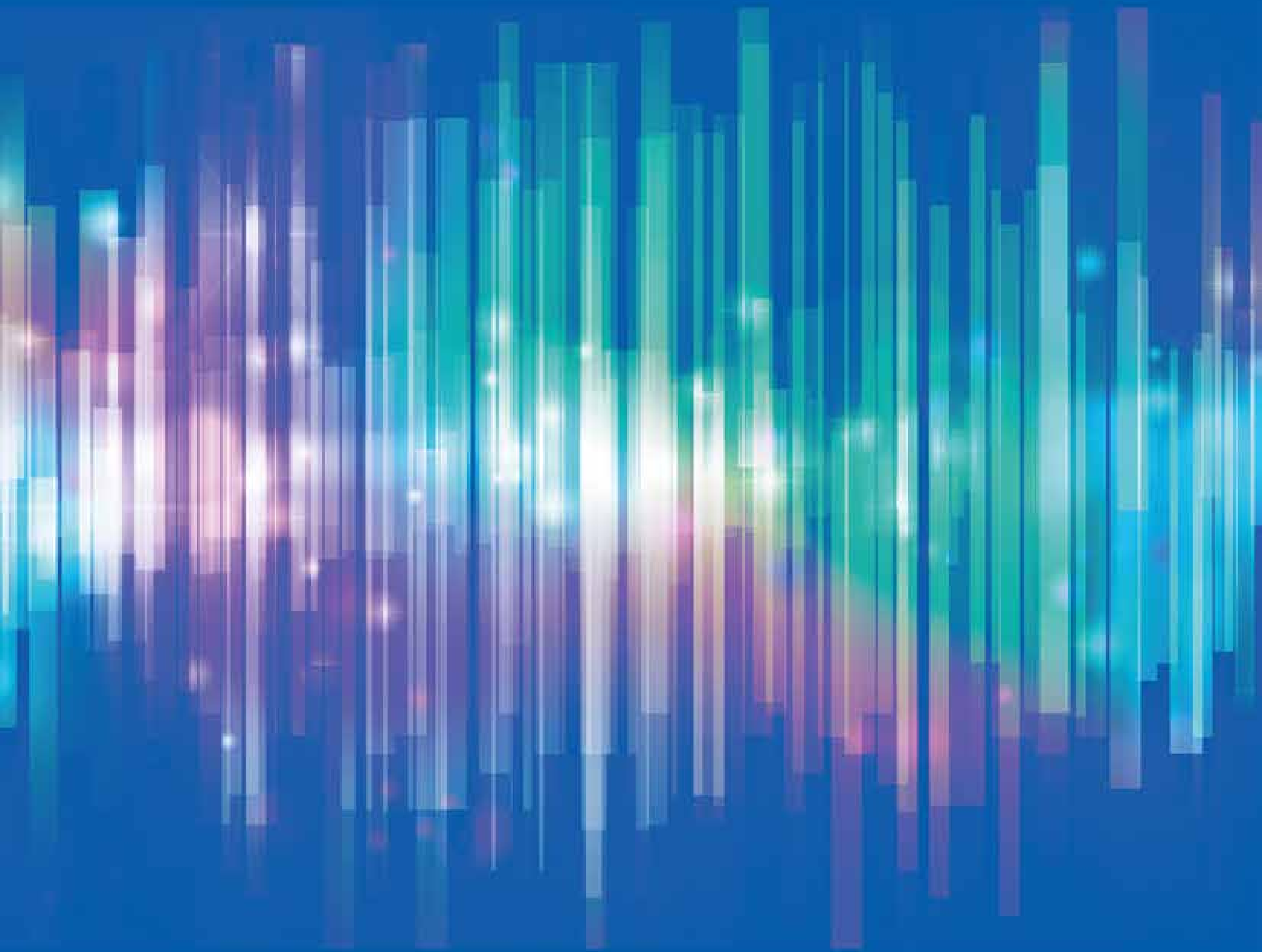
Gas Technology and Innovation for a Sustainable Future



IGU
INTERNATIONAL GAS UNION
UNION INTERNATIONALE DU GAZ

BCG

Disclaimer

The report is an independent study, conducted by Boston Consulting Group and commissioned by the IGU, Snam, and BP International Limited ("BP") (together "the funders"). The report does not necessarily reflect the views or positions of all of the funders and no warranty is given to readers concerning the completeness or accuracy of the information included. Readers will need to make their own evaluation of the information provided. Neither Boston Consulting Group nor any of the funders can accept any liability for any inaccuracies or omissions (other than for fraudulent misrepresentation) in the Report and any decisions you make based on information contained in this website are your sole responsibility.

Foreword

Joe M. Kang

President
International Gas Union

Alan Thomson

Global Leader
BCG Energy Practice

We are pleased to present this analysis, which quantifies the contribution that gas technologies can make to the success of the global energy transition, helping to build sustainable cities and communities, and to provide access to affordable and clean energy[1].

The analysis and modelling completed for this report show that deploying gas technologies to their economic potential for fuel-switching from coal and oil, continuing to develop distributed energy solutions, enabling access, improving efficiency, and scaling up renewable and low-carbon gas technologies including renewable gas, hydrogen, and CCUS, could deliver a reduction in GHG emissions of up to 12 GT by 2040. That is equivalent to nearly a third of global energy sector GHG emissions in 2019.

While gas technologies cannot address the gap to achieving the Paris Agreement goal in its entirety and other clean tech solutions such as renewable power and energy efficiency will also be essential, the potential for progress is too large to ignore, especially given the ease of implementation from the economic deployment of these technologies.

Gas technologies also accelerate the world's sustainable development agenda, offering a way to improve people's lives and provide access to clean and modern energy. For example, gas could provide access to clean cooking for 1 billion additional people, reducing the number of people who currently lack this access by more than a third. This would immensely improve human health around the world and reduce premature mortality from lung and heart diseases.

From the time when we started this research and worked on the analysis, to when we were finalizing the report, the global situation has dramatically changed. In a matter of months, the world has gone from business as usual, to a global health and economic crisis by the first quarter of 2020. The first half of 2020 saw entire economies slam on the brakes. This resulted in a nearly four percent reduction in global energy demand by the start of second quarter, and the IEA expects an eight percent drop in CO_2 emissions this year – which would take them to the lowest level in a decade[2].

Unfortunately, this positive emissions outcome resulted from a crisis and comes at a great cost of loss of lives and livelihoods. It was not a result of structural changes that could be easily preserved after economies begin to restart and recover.

As the world plans how to recover, we believe that it has an opportunity to align to a path toward achieving the needed reductions in air pollutants and emissions, consistent with the Paris Agreement, and to deliver on the Sustainable Development Goals. These two critical global commitments will more than ever have to be united, because the poorest and the most vulnerable will suffer the most from the current crisis, as well as from failure meet environmental commitments. The gap on sustainable development is also likely to widen, as a result of the economic downturn from this crisis.

The findings presented in this report are urgent and relevant. They demonstrate that there is a huge untapped potential offered by gas technology and innovation, highlighting contribution that a selection of gas technologies can make to meeting the world's most pressing challenge of restoring growth, while reducing emissions, cleaning up local environments, and supporting fair development.

The challenge that the world is facing to accelerate energy transitions while rebuilding economies, is immense, yet we are convinced that human ingenuity is greater still; and with focus on the common purpose, political and business will, and the right policy and management tools, it can be solved.

We hope you will find this report helpful.

We invite you to read this report and learn how gas technologies and innovations can support the reduction of energy sector emissions.

1 Natural gas can play an enabling role in other ways, but these three goals are the core focus of this report.
2 IEA, 2020, Global Energy Review.

Contents

Executive summary

The global economy is in distress, due to the novel coronavirus global health crisis. Measures to contain the infection resulted in an unprecedented drop in energy demand[1] and emissions.

Unfortunately, this was the result of a vast economic slowdown, and came at great human cost. As the world recovers from the health crisis, the pressure to restore growth and prosperity will be great. At the same time, the urgent need to address the global climate and air quality challenges will remain. That means that the post-pandemic global energy supply will grow, while the environmental impacts from its production and use have to diminish. In order to meet this double challenge, the energy system as we know it today will need to evolve in leaps and bounds, and that will only be possible if energy innovation becomes society's urgent priority.

Technologies and innovation in the gas sector have a transformative potential impact on the global energy systems.

In fact, there is a vast array of gas technologies, ranging from highly mature to nascent, and their deployment has the potential to economically reduce up to one third of emissions from the energy sector by 2040. This report demonstrates that technology developments and innovation in natural gas are of great importance.

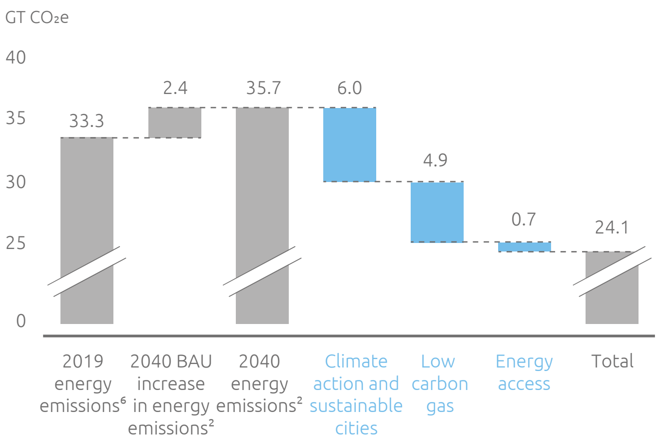
It does so by analyzing the economic potential of 12 technology applications, across gas networks and end-uses (see Exhibit below).

GAS TECHNOLOGIES CAN ABATE UP TO 30% OF GLOBAL ENERGY SECTOR GHG EMISSIONS

GHG reduction potential by 2040[1] (GT CO_2)

	Technology	Base case[2]	Potential[3]
Climate action and sustainable cities	Power switching	0.6	3.3
	Industry switching	0.6	2.0
	Industrial efficiency	0	0.1
	Enabling renewable power	*Enables renewables[4]*	
	Road transport	0.1	0.4
	LNG bunkering	<0.1	0.2
Low carbon gas	Renewable gas Hydrogen	0	0.9
	CCUS	0.1	4.0
Energy access	Building adoptions	0.2	0.5
	Distributed generation	0.1	0.2
	SSLNG	*Enables fuel switching[5]*	

Global GHG emissions maximum reduction potential[3] from gas technologies by 2040



1. Estimated on the basis of gas demand growth multiplied by the average emissions benefit of switching from coal and or oil to natural gas or low carbon gas; 2. Base case is aligned with IEA 2019 Stated Policies Scenario; 3. Potential is based on the economic potential as defined in Chapter 1; 4. Emissions benefit achieved from the adoption of renewable power were not evaluated, as part of this analysis; 5. Emissions benefit accounted for in other categories; 6. Based on IEA data; Source: IEA, EIA, BP 2019 Energy Outlook, NGVA Europe, IPCC, BCG analysis

1 The IEA assessed that global energy demand dropped by 3.8% in the first quarter of 2020, estimating that it could be down by up to 6% in the rest of the year, depending on the depth of the resulting economic recession. (IEA, 2020).

The results highlight that gas technologies are already playing a key role in facilitating a sustainable energy transition, and further innovation in the sector can significantly enhance benefits for the global environment and human development in three ways:

- **In the near-term**, switching to natural gas from coal or oil products would immediately reduce emissions, both in the form of GHG emissions and localized air pollutants. At the same time, gas technologies can improve global access to clean, modern energy, including for the world's poorest.

- **In the medium-term**, gas technologies can promote structural transitions in the way energy is delivered and used, by enabling distributed energy systems and increasing efficiency of energy consumption. Through the continued development and deployment of low-cost and highly efficient technologies, natural gas can facilitate renewable power integration, while further reducing both the emissions and costs

- **Progressively over the longer term**, low- and zero-carbon gas technologies–including renewable gas, hydrogen, and carbon capture, utilization, and storage (CCUS) provide an efficient and cost-effective pathway to dramatically reduce GHG emissions. These technologies are particularly relevant for sectors where emissions are difficult or very costly to abate through other means. They can also capitalize on the use of existing gas infrastructure to minimize capital investment.

Key enablers

It is pivotal to recognize that these benefits can be achieved by the deployment of gas technologies in a market environment. But that doesn't mean that this will happen by itself, substantial private and public efforts will be required to enable them.

Fostering sustainable development and achieving environmental benefits will require further research and development, as well as investment in testing and deployment, and removing barriers to adoption, such as a lack of infrastructure, access to upfront capital requirements, or even cultural and organizational obstacles to changing existing practices. These key actions can be summarized by the three enablers below, required to unlock the full value of gas technologies.

1. **Government policy** is critical to ensure that the value of reduced emissions benefits enabled by gas technologies is fairly reflected in the market, through carbon and pollution pricing, or regulation.

2. **Infrastructure investment** is required for enabling gas-fired power generation and access to gas in the near term, while also scaling up low-carbon gas technologies for the future. At the same time, it provides an important assurance of energy security.

3. **Industry innovation** is needed from the sector, where incumbent industry participants step up their support for innovation and the continued development and deployment of new technologies, as well as develop new business models to commercialize them.

Report structure and method

This report provides a comprehensive review of the status of new and emerging technologies within the scope of delivery and consumption of natural gas. In doing so, it focuses on demonstrating how, and under what circumstances, natural gas can contribute cleantech solutions in different value chains, across regions and sectors.

The analysis underpinning this report takes an unconstrained view of the economic potential for gas technologies to meet the challenges of the UN Sustainable Development Goals and the Paris Agreement. It focuses on 12 key categories of gas technologies, covering the full breadth of natural gas consumption, as well as key innovations in the means of delivering natural gas to customers.

A common methodology was deployed across each of the technology categories, employing the following principles:

- First, the analysis is rooted in a review of each of the technologies, assessing past developments, as well as forward-looking trends. Particular focus was directed to emerging innovations that have the potential to increase the efficiency of operations, reduce capital costs, and improve the flexibility of gas technologies. The current scale and breadth of technology adoption was also assessed.
- Second, the economic potential of the technologies was assessed to identify what role they could play in the future. Critically, this was done relative to other fuels and technologies, identifying where gas technologies offer economic advantages. As a basis for this analysis, academic and industry assessments of technologies were employed along with base assumptions from the IEA on more general energy supply, demand, and commodity prices[2].
- Third, case studies were developed across the technology categories to identify both cases of successful adoption, and the cases where technology adoption has been limited. The aim is to extract lessons about key enablers to maximize gas technology impact.

The report is structured around the three distinct ways that gas technologies can help to achieve the Sustainable Development Goals. Firstly, through near term action on climate change and promoting sustainable cities and communities, via fuel switching, industrial efficiency, enabling renewables integration, the use of natural gas in transport, and LNG for bunkering. Secondly, through climate change action via the deployment of low-carbon gas technologies including renewable gas, hydrogen, and CCUS. And thirdly, by enabling access to affordable and clean energy through greater gas adoption of gas in buildings, distributed energy, and small-scale LNG.

The methodology is aligned with the long term Paris goal of keeping a global temperature rise "well below 2° degrees". While the modeling in this report is only done to 2040, it incorporates a social cost of carbon in line with achieving net zero emissions in mid-century. The report therefore captures the emissions reduction potential from fuel switching and the adoption of low carbon gas technologies through 2040, while beyond 2040 net zero is achievement by further scaling of low carbon gas technologies that utilize gas infrastructure along with negative emissions levers.

As a starting point, Chapter 1 provides an overview of the key findings across the 12 technology categories assessed and outlines an action plan to maximize the impact from gas technologies.

2 IEA Stated Policy Scenario assumptions are used throughout while the economic potential for adoption is defined using Sustainable Development Scenario assumptions on carbon pricing to identify the competitiveness of gas relative to coal and oil particularly a rapid shift in policy toward climate action.

Findings highlights

Chapter 1. An action plan for gas technology and innovation

- Technology development trends indicate that significant opportunity still exists to further increase the operational efficiency of gas technologies, reduce capital deployment costs, and to improve their flexibility to support greater cost competitiveness and more widespread adoption over time.
- The economic potential for gas adoption is substantial: investing in technologies could increase the size of the global gas market by up to 2.5 times by 2040, while also enabling emissions reductions equivalent to one-third of the current total global energy sector emissions.
- Achieving the full potential of natural gas will require sustained action on three fronts: government policy, infrastructure investment, and industry innovation.
- Based on experience to date, government policy can be particularly effective in promoting gas technology adoption when it takes a full technology cycle approach and places appropriate focus on early-stage R&D, while also taking steps to support commercialization and deployment of most promising technologies – particularly when it comes to new markets, and efficient adoption measures (such as carbon pricing or local pollution controls).
- Up to $820 billion of infrastructure investment total per year through 2040 would be required to achieve the economic potential of gas by enabling access, developing capacity for end consumption, and supplying low-carbon gas; this is a substantial increase over the less than $200 billion invested annually in mid and downstream gas value chains.
- Industry innovation will also be critical to achieve the fuel's full potential, through privately funded R&D, early-stage deployment of technologies, and the development of new business models that provide more efficient ways to use gas technologies.
- In established gas combustion applications in the power, industry, and buildings sectors, technology developments are improving efficiency of gas consumption by up to 20%, while reducing the capital costs of gas equipment by 10% or more[3].
- The development of new processes and new applications, such as distributed generation and small-scale LNG, show potential to reduce upfront capital costs for accessing gas by 50% or more[4].
- New developments are making existing gas technologies more flexible, enabling them to support renewable power development through improvements in plant ramp times of 40% or more and by providing easily scalable capacity[5].
- Beyond existing uses of natural gas, developments in low-carbon gas technologies, including for the production of renewable gas, hydrogen, and the deployment of CCUS, demonstrate the potential to reduce costs significantly going forward. The development of new processes show potential to improve the operating efficiency of these technologies by more than 50%[6].
- Meanwhile, breakthrough innovations, as well as experience and scale effects, could reduce the upfront capital costs of new technologies by up to 65% in renewable gas and as much as 90% in specific CCUS applications[7].

3 Summary based on BCG review of gas technologies; see subsequent chapters for detailed analysis and citations. Examples here include energy efficiency applications in industrial heat and reductions in boiler capex discussed in Chapter 2.
4 Ibid. Example here includes small scale LNG disused in chapter 5.
5 Ibid. Examples here include CCGT ramp time improvements and the use of gas reciprocating internal combustion engines discussed in Chapter 2.
6 Based on an example of thermochemical applications in solvent-based post-combustion capture discussed in Chapter 3.
7 Based on industry studies for renewable gas and CCUS demonstration examples discussed in Chapter 3.

Chapter 2. Action on climate change and sustainable cities and communities - enabling immediate GHG emissions reductions and improvements in air quality

- Gas technologies can significantly contribute to GHG emissions reductions in the near-term, through fuel switching from coal and oil, efficiency improvements in industrial processes, by enabling the greater deployment of renewables, and through the adoption of natural gas in the transport sector.
- Developments in gas turbine and boiler efficiencies and design are reducing upfront capital costs and recurring operational expenditures by up to 20%, resulting in improved cost competitiveness.
- Gas technologies in power generation have become more flexible and cost efficient, enabling gas to complement and enable greater penetration of intermittent renewable energy sources; for example, CCGT ramp times have improved by up to 44%, while capital costs have fallen by up to 25%.
- Technology developments in the digitalization of energy system management, heat recovery, and industrial process redesign are emerging as key enablers of emissions reductions in the industrial sector.
- In ground transport, gas engine and storage technologies are improving the economics of gas adoption, but the scaling up of supply chains for vehicles and refueling are needed in most markets for gas to be even more cost-competitive relative to oil products.
- Innovations in LNG bunkering technology are improving its cost competitiveness versus other technologies through improvements in engine power output (by up to 25%) and reducing space requirements for storage on ships (by up to 60%).

Chapter 3. Action on climate change – deployment of low-carbon gas technologies

- Low-carbon gas technologies – including renewable gas, hydrogen, and CCUS – all have the potential to substantially reduce the GHG emissions of existing natural gas systems, and can even achieve net negative emissions when bio-energy is paired with CCUS.
- Deployment of these technologies is limited today, but low-carbon gas technologies show substantial potential to reduce GHG emissions going forward (up to 5GT by 2040) given their competitiveness vs. alternative electricity-based technologies.
- Renewable gas has the potential to be a highly flexible for reducing emissions in existing natural gas networks. However, production will need to be scaled up from a negligible global amount today to realize potential scale and learning effects.
- Parts of the hydrogen value chains are already established, but emerging low-carbon technologies – including electrolysis, gas reforming with CCUS, and methane cracking – must be further developed and deployed at scale to achieve potential emissions impacts.
- While CCUS capacity has been slow to develop in the past, new enabling policies are set to support near-term growth, particularly in the US, Europe, and China. Technology innovation combined with deployment at scale shows significant potential to reduce costs of carbon capture by 50% or more.

Chapter 4. Access to clean energy – more widespread and affordable access to natural gas

- Access to clean cooking fuels remains a major international development challenge with 2.7 billion people lacking access; natural gas shows the economic potential to enable access to up to 1 billion people by 2040.
- Technology and business model innovations are enabling significantly lower cost access to gas in buildings within non-OECD market costs; in India for example, residential gas connection costs have been reduced to less than 10% of those in the US.
- Developments in microturbine and solid oxide fuel cell technologies have made gas viable in microgrid or other distributed energy systems.
- Efficiency improvements in gas boilers and the use of CHP systems in buildings has demonstrated potential to improve energy efficiency by 20% or more
- Small scale LNG supply chains have emerged as a new means of enabling access to natural gas where existing pipeline infrastructure is not present, speeding time to enable access and reducing capital costs by 80% or more relative to conventional pipeline development

Introduction

Global economy is in distress, due to the novel coronavirus global health crisis. Global infection containment measures came with vast economic slowdown that in turn resulted in an unprecedented drop in energy demand[8] and emissions. Unfortunately, it also came with a great human cost. As the world recovers from the health crisis, the pressure to restore growth and prosperity will be great. At the same time, the urgent need to address the global climate and air quality challenges will remain. That means that the post-pandemic global energy supply must grow, while the environmental impacts from its production and use have to diminish at the same time. In order to meet this double challenge, the energy system as we know it today will need to evolve by leaps and bounds, and that will only be possible if energy innovation becomes society's urgent priority. In fact, this global crisis provides businesses and governments around the world with an opportunity to "rebuild better".

This report focuses on the critical role that gas technologies and innovation can play in helping the world reach a sustainable future in the shortest possible timeframe. It starts from the premise that a wide variety of technologies, applied across all sectors and fuels, will be necessary to achieve the required transition, including gas technologies. It then seeks to fill a gap in discourse about energy innovation, which often overlooks the important role that natural gas can play in accelerating global energy transition. This report takes a close look at some of the most promising gas technologies and assesses how they can interact with other cleantech solutions to deliver efficient and sustainable energy systems of the future – namely to achieve significant global emissions reductions and to do so economically.

The report focuses on the developments in the mid- and downstream segments of the natural gas value chain, as well as the production of low-carbon gas, for two reasons. First, this segment lies at the heart of solving the double challenge, as it directly links energy and society. Second, innovations and opportunities in this segment are highly impactful, yet often overlooked[9].

Gas technologies are already playing a key role in facilitating a sustainable energy transition, and further innovation in the sector can significantly enhance benefits for the global environment and human development in three ways:

- **In the near-term**, switching to natural gas from coal or oil products would immediately reduce emissions, both in the form of GHG emissions and localized air pollutants. At the same time, gas technologies can improve global access to clean modern energy, particularly for the world's poorest.
- **In the medium-term**, gas technologies can promote structural transitions in the way energy is delivered and used, by enabling distributed energy systems and increasing efficiency of energy consumption. Through the continued development and deployment of low-cost and highly efficient technologies, natural gas can facilitate renewable power integration, while further reducing both the emissions and costs.
- **Progressively over the longer term**, low- and zero-carbon gas technologies– including renewable gas, hydrogen, and carbon capture, utilization, and storage (CCUS) provide an efficient and cost-effective pathway to dramatically reducing GHG emissions. These technologies are particularly relevant for sectors where emissions are difficult or very costly to abate through other means.

8 The IEA assessed that global energy demand dropped by 3.8% in the first quarter of 2020, estimating that it could be down by up to 6% in the rest of the year, depending on the depth of the resulting economic recession. (IEA, 2020).

9 Upstream activities in natural gas are not covered in this report. While there has been significant technological progress and innovation in that space, it has been covered widely in other publications.

The sections of this report assess the steps by which gas technologies can pave the way to a sustainable energy future. Its conclusions and analysis are based on a comprehensive review of existing technologies, recent developments, and emerging trends in 12 areas, covering the delivery and consumption of natural gas. Importantly, in addition to the assessment of core technological developments, the report also applies an economic lens to determine where and how these technologies will be competitive, especially relative to other cleantech solutions.

Thus, it focuses heavily on recent and potential improvements in the efficiency, costs, and flexibility of gas technologies.

Beyond quantifying the potential value of gas technologies and innovation, this report provides a roadmap to achieve that potential. It also provides a recommended action plan covering investment, government policy, and evolution of the industry's culture, needed to get there.

Natural gas and sustainable development

In 2015, the international community agreed to two important and closely related accords: the 2030 UN Sustainable Development Agenda and the Paris Agreement. The first accord, lays out 17 sustainable development goals (SDG's), which became the blueprint for achieving a better and more sustainable future for all. The SDG's are also referred to by the UN, as "a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030[10]." In parallel, the Paris Agreement commits its 197 signatories to common but differentiated ambitions, with the goal to limit global warming to "well below 2° Celsius" by the end of the century.

Together, the Paris Agreement and the 2030 Agenda are the world's ambitious commitment to solving this century's biggest double challenge: fair development and climate change. Today, the world is not on track to solve it.

Gas technologies can play a decisive role in support of the two agreements, by enabling action on climate change, by promoting sustainable cities and communities, and by providing access to affordable and clean energy[11].

10 UN Sustainable Development Goals: www.undp.org/content/undp/en/home/sustainable-development-goals.html.
11 Natural gas can play an enabling role in other ways, but these three goals are the core focus of this report.

Enabling action on climate change (SDG #13) & Implementing the Paris Agreement

Despite government commitments to the Paris Agreement, policy pledges since 2015 have failed to deliver what is needed to limit warming to well below 2° C. International Energy Agency (IEA) analysis demonstrates that current policy commitments will help to avoid more than 6 gigatons (GT) of CO_2 emissions through 2040, which is still 18 GT short of the level required to meet the below 2° target[12].

Closing this gap will be very challenging, even with the use of every policy and technology tool possible, including natural gas. However, data modeling indicates that deploying gas technologies to their full economic potential for fuel switching from coal and oil, while also scaling up low-carbon gas technologies, could enable a reduction in GHG emissions of up to 12 GT by 2040[13] (see Exhibit 1). This is equivalent to nearly 30% of global energy sector GHG emissions in 2019[14]. While gas technologies cannot address the gap in its entirety, the potential for progress is substantial.

Importantly, emissions reductions from gas adoption can be achieve immediately and at scale, particularly those achieved by replacing more carbon-intensive coal and oil products. The technologies that enable fuel-switching to natural gas across different sectors are already highly efficient, mature, and cost-effective. Moreover, these technologies are continuing to evolve, further improving efficiency and costs. In some cases, emerging innovations demonstrate the potential for an additional 30% or more reduction in overall costs.

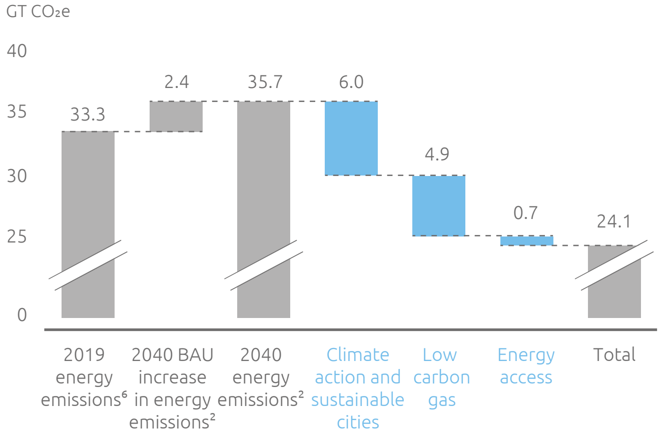
Looking to the next decade and beyond, natural gas and its infrastructure can be a direct pathway to deeper GHG reductions, via low-carbon gas technologies[15]. For example, gas technologies are more efficient in delivering energy for heat, than electricity and can also provide greater scale than renewable sources in power generation and industrial consumption. Importantly, using natural gas as a low-carbon pathway utilizes existing infrastructure—such as pipelines, boilers, and appliances—and therefore is a cost-effective way to reduce GHG emissions compared to alternatives, reducing the cost of transition.

Exhibit 1 - GAS TECHNOLOGIES CAN ABATE UP TO 30% OF GLOBAL ENERGY SECTOR GHG EMISSIONS

GHG reduction potential by 2040[1] ($GT\ CO_2$)

	Technology	Base case[2]	Potential[3]
Climate action and sustainable cities	Power switching	0.6	3.3
	Industry switching	0.6	2.0
	Industrial efficiency	0	0.1
	Enabling renewable power	*Enables renewables[4]*	
	Road transport	0.1	0.4
	LNG bunkering	<0.1	0.2
Low carbon gas	Renewable gas Hydrogen	0	0.9
	CCUS	0.1	4.0
Energy access	Building adoptions	0.2	0.5
	Distributed generation	0.1	0.2
	SSLNG	*Enables fuel switching[5]*	

Global GHG emissions maximum reduction potential[3] from gas technologies by 2040



1. Estimated on the basis of gas demand growth multiplied by the average emissions benefit of switching from coal and or oil to natural gas or low carbon gas; 2. Base case is aligned with IEA 2019 Stated Policies Scenario; 3. Potential is based on the economic potential as defined in Chapter 1; 4. Emissions benefit achieved from the adoption of renewable power were not evaluated, as part of this analysis; 5. Emissions benefit accounted for in other categories; 6. Based on IEA data; Source: IEA, EIA, BP 2019 Energy Outlook, NGVA Europe, IPCC, BCG analysis

12 IEA, 2018 World Energy Outlook.
13 For this report energy system modeling was only run to 2040, but extending it beyond 2040 would result in greater potential GHG emissions reductions as the cost of carbon increases further and technologies continue to develop.
14 Global scenario analysis assessing the economically viable share of natural gas (including low-carbon gas) based on technology trends assessed in this report.
15 While low-carbon technologies have been deployed before, the economic conditions required under a 2 degree scenario would likely not necessitate a much more rapid increase in their deployment until at least the 2030s.

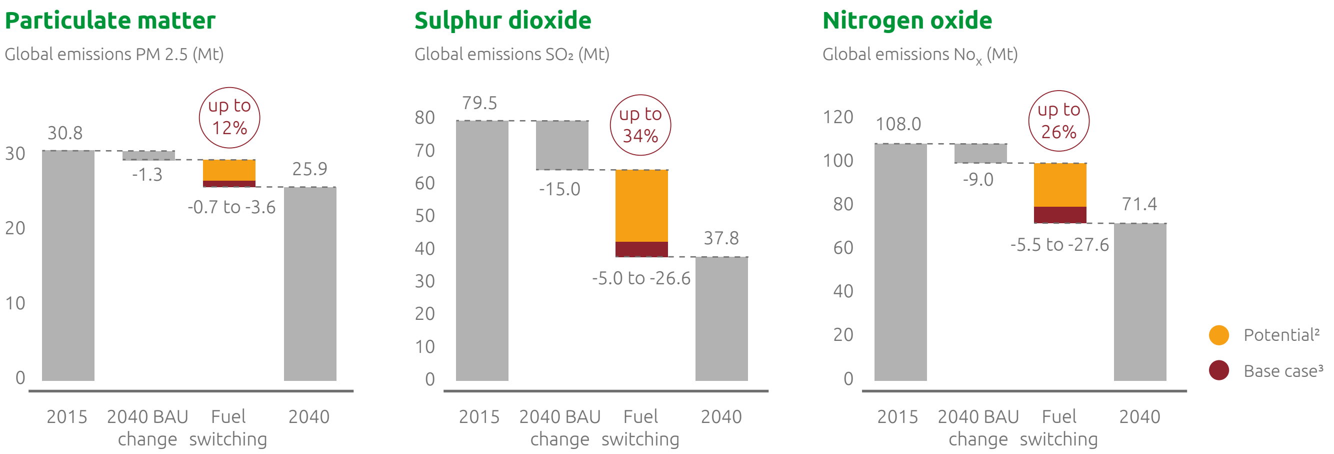
Promoting sustainable cities and communities (SDG #11)

Another way natural gas can play a key role in achieving the SDGs is by reducing air pollution, particularly in cities. The World Health Organization has described air pollution as "the world's largest environmental health threat" and has estimated that ambient outdoor air pollution causes 4.2 million premature deaths annually, while the indoor pollution causes another 3.8 million deaths[16]. Natural gas combustion produces almost no emissions of particulate matter (PM), sulfur dioxide, and nitrogen oxide. Thus, when switching from coal or diesel to natural gas, or when gas adoption displaces the use of traditional biomass, emissions of localized pollutants can be reduced drastically and immediately. A growing number of cases have shown that focused switching to gas from higher polluting fuels results in significant air quality improvements. In China, for example, recent measures to switch from coal to gas have reduced particulate emissions in the Beijing region by half, helping to add an estimated two years to the average lifespan in the region[17]. Global modeling of the economic potential of natural gas suggests that it can play a significant role in reducing emissions of key air pollutants around the world. With technology adoption aligned with the economic potential for gas, fuel switching could reduce global average PM2.5 emissions by up to 12%, nitrogen oxide emissions by up to 25%, and sulfur dioxide emissions by up to 34% by 2040[18] (see Exhibit 2). Local impacts in areas where the switching is highest are much more pronounced, with reductions of pollutants amounting to 70% or more from fuel switching. This was seen in an industrial case from the Gujarat region in India, where a switch from coal to gas dramatically reduced major pollutant emissions by over 70 percent in a major ceramic producing city of Morbi[19].

Developments in gas technologies are making this level of fuel switching increasingly feasible. Improvements in the efficiency and capital costs of technologies across the power, industry, and buildings sectors are helping to make natural gas more cost-competitive, in turn enabling more rapid adoption. Meanwhile, new technology developments in the supply and use of natural gas in the transportation sector are increasing the potential for greater fuel switching from diesel and fuel oil, which are key contributors to urban air pollution.

Exhibit 2 - NATURAL GAS ADOPTION WOULD SIGNIFICANTLY REDUCE GLOBAL EMISSIONS OF KEY AIR QUALITY POLLUTANTS

Potential 2040 annual local emissions reduction from gas adoption¹



1. Calculated as potential emissions benefit relative to business as usual 2040 emissions using Current Policies Scenarios from IEA 2016 WEO report;
2. Base case is aligned with IEA New Policies Scenario in prior WEO reports;
3. Potential is based on the economic potential as defined in Chapter 1.
Source: IEA, WHO, BCG analysis.

16 World Health Organisation, "Ambient air pollution: Health impacts", 2020.
17 IGU, 2018 Global Gas Report.
18 Global scenario analysis assessing the potential economic share of natural gas and low-carbon gas based on technology trends assessed in this report.
19 IGU, "2019 Case Studies in Urban Air Quality".

Providing access to affordable and clean energy (SDG #7)

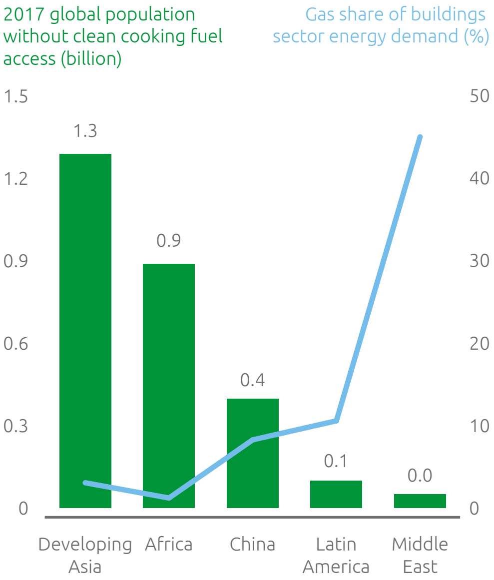
Globally, approximately 2.7 billion people still lack access to clean cooking fuels, almost all of them in Asia and sub-Saharan Africa[20]. This remains one of the greatest global development challenges. While access to electricity has improved rapidly (around 800 million people currently don't have access to electricity worldwide, down from 1.2 billion in 2010) universal access to clean cooking fuels has been harder to achieve[21]. Typically, communities that do not have access to clean cooking have used traditional biomass for their cooking needs. Traditional biomass for cooking, along with oil products for lighting, causes significant indoor air pollution, which is estimated to be responsible for 4.2 million premature deaths each year globally[22].

Gas technologies for cooking and heating / cooling in buildings in general are well established and highly efficient, costing about half of even the most efficient electric technologies (i.e. induction cooking)[23]. The greatest challenge remains providing access to natural gas. Technology innovations are improving the accessibility of gas through new methods of distribution and use, namely small-scale LNG (SSLNG) for distributing natural gas, as well as distributed generation technologies that enable off-grid uses.

With more extensive and deliberate investment in energy infrastructure, it is possible to achieve universal access to clean cooking by 2040[24], and the expansion of natural gas access can be a key contributor in that effort. Modeling suggests that, by 2040, gas could provide access to clean cooking for 1 billion additional people, making a substantial contribution to the improvement of human health around the world[25] (see Exhibit 3).

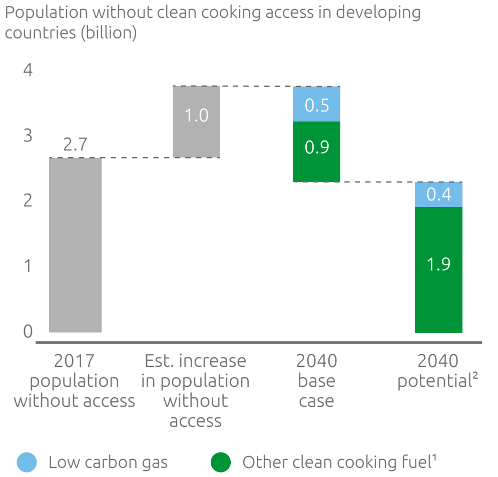
Exhibit 3 - NATURAL GAS CAN PROVIDE ACCESS TO CLEAN COOKING FUEL FOR UP TO 1 BILLION ADDITIONAL PEOPLE BY 2040

Population without access to clean cooking fuels relative to gas access



Source: IEA, UN, BCG analysis.

Access to clean cooking fuels by 2040



1. Other clean fuels consist of clean biomass, LPG, and solar.
2. Potential is based on the economic potential as defined in Chapter 1.
Source: IEA, UN, BCG analysis.

20 IEA, "SDG7: Data and projections", 2019.
21 World Bank, "Sustainable Energy for All Database", 2019.
22 WHO "Ambient air pollution: Health impacts", 2020.
23 Based on US average retail prices for gas and power and considering efficiency differences between gas and electric induction cooking.
24 IEA 2017 World Energy Outlook Sustainable Development Scenario.
25 Global scenario analysis assessing the economically potential share of natural gas and low carbon gas based on technology trends assessed in this report.

Key enablers

In order to foster the sustainable development and leverage on all gas technologies benefits, further research and development, as well as investment in testing and deployment, are required to bring down costs and improve their relative competitiveness, or enable market access. And even when economic incentives exist, adoption can be hindered by barriers, such as a lack of infrastructure, access to upfront capital requirements, or even cultural and organizational obstacles to changing existing practices.

Therefore, for gas technologies to realize their full potential, three sets of enablers are required: government policy, infrastructure investment, and innovation among industry participants in deploying new technologies.

1. **Government policy** is critical to ensure that the value of reduced emissions benefits enabled by gas technologies is fairly reflected in the market, through carbon and pollution pricing, or regulation.
2. **Infrastructure investment** is required for enabling gas-fired power generation and access to gas in the near term, while also scaling up low-carbon gas technologies for the future. At the same time, it provides an important assurance of energy security.
3. **Industry innovation** is needed from the sector, where incumbent industry participants step up their support for innovation and the continued development and deployment of new technologies, as well as develop new business models to commercialize them.

Chapter 1

An action plan for gas technology and innovation

Highlights

- Technology development trends indicate that significant opportunity still exists to further increase the operational efficiency of gas technologies, reduce capital deployment costs, and to improve their flexibility to support greater cost competitiveness and more widespread adoption over time.
- The economic potential for gas adoption is substantial: investing in technologies could increase the size of the global gas market by up to 2.5 times by 2040, while also enabling emissions reductions equivalent to one-third of global energy sector emissions.
- Achieving the full potential of natural gas will require sustained action on three fronts: government policy, infrastructure investment, and industry innovation.
- Based on experience to date, government policy can be particularly effective in promoting gas technology adoption when it takes a full technology cycle approach and places appropriate focus on early-stage R&D, while also taking steps to support commercialization and deployment of most promising technologies – particularly when it comes to new markets, and efficient adoption measures (such as carbon pricing or local pollution controls).
- Up to $815 billion of infrastructure investment total per year through 2040 would be required to achieve the economic potential of gas by enabling access, developing capacity for end consumption, and supplying low-carbon gas; this is a substantial increase over the less than $200 billion invested annually in mid and downstream gas value chains.
- Industry innovation will also be critical to achieve the fuel's full potential, through privately funded R&D, early-stage deployment of technologies, and the development of new business models that provide more efficient ways to use gas technologies.

Key technology trends

Significant innovations are taking place across gas technologies; innovations that are transforming how gas is used, improving the efficiency of gas consumption, reducing the capital costs of gas adoption, and improving its operational flexibility. In turn, these developments are also improving the competitiveness of natural gas compared to other fuels, while lowering the incremental costs of reducing GHG emissions from energy systems. Improvements in the flexibility of natural gas systems also support more effective deployment and grid integration of renewable power technologies.

Based on a comprehensive review of gas technologies in 12 different mid and downstream categories, the following key themes emerged from this study:

- In established gas combustion applications in the power, industry, and buildings sectors, technology developments are improving efficiency of gas consumption by up to 20%, while reducing the capital costs of gas equipment by up to 10% or more[26].
- The development of new processes and new applications, such as distributed generation and small-scale LNG, show potential to reduce upfront capital costs for accessing gas by 50% or more[27].
- New developments are making existing gas technologies more flexible, enabling them to support renewable power development through improvements in plant ramp times of 40% or more and by providing easily scalable capacity[28].
- Beyond existing uses of natural gas, developments in low-carbon gas technologies, including for the production of renewable gas, hydrogen, and the deployment of CCUS, demonstrate the potential to reduce costs significantly going forward. The development of new processes show potential to improve the operating efficiency of these technologies by more than 50%[29].
- Meanwhile, breakthrough innovations, as well as experience and scale effects, could reduce the upfront capital costs of new technologies by up to 65% in renewable gas and as much as 90% in specific CCUS applications[30].

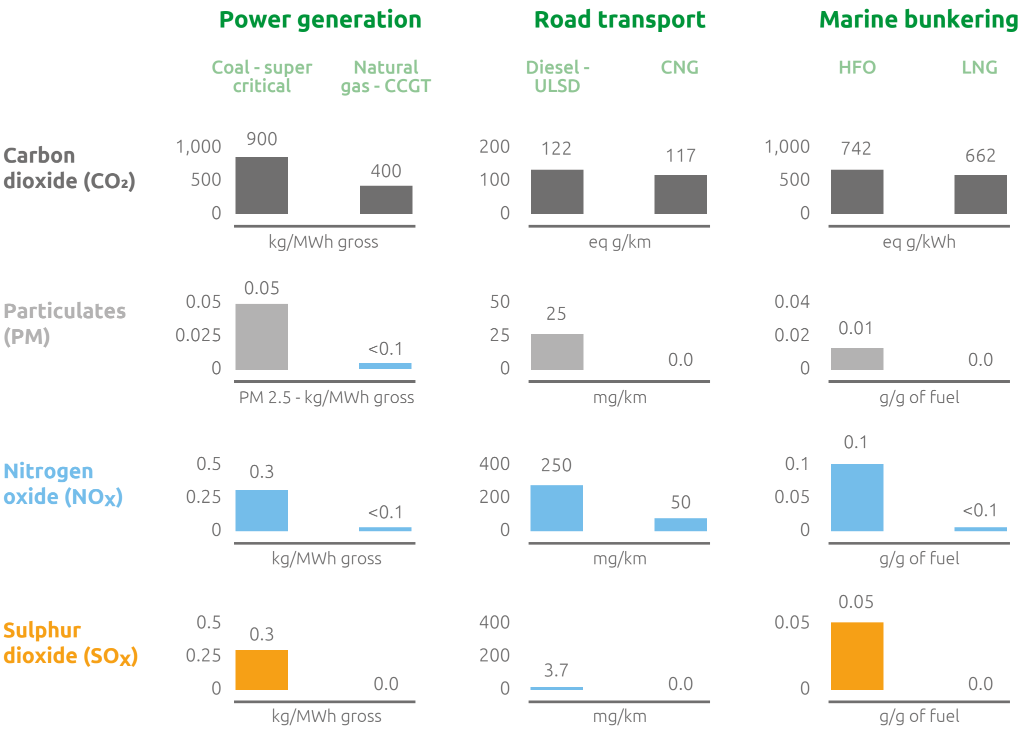
26 Summary based on BCG review of gas technologies; see subsequent chapters for detailed analysis and citations. Examples here include energy efficiency applications in industrial heat and reductions in boiler capex discussed in Chapter 2.
27 Ibid. Example here includes small scale LNG disused in chapter 5.
28 Ibid. Examples here include CCGT ramp time improvements and the use of gas reciprocating internal combustion engines discussed in Chapter 2.
29 Based on an example of thermochemical applications in solvent-based post-combustion capture discussed in Chapter 3.
30 Based on industry studies for renewable gas and CCUS demonstration examples discussed in Chapter 3.

The economic potential of gas

This report is based on a techno-economic assessment of gas technologies in the 12 different categories. It combines analysis of the fundamental costs and applications of the technologies with an assessment of the relative economics of gas compared with other energy sources. That economic analysis also incorporates environmental and social value of lower emissions from gas technologies. The result is an assessment of the economic potential for natural gas, specifically identifying where gas technologies are projected to have a cost advantage in the future. The economic potential of natural gas first reflects a rationale for sustained adoption of the fuel across sectors in the context of higher and more consistent carbon prices. The analysis of the economic potential for gas used in this report is anchored in an assumption of a global carbon price reaching $125 per metric ton by 2040, aligned with what is required to achieve a 2 degree pathway[31]. As gas use produces 50% fewer CO_2 emissions than coal and 25% fewer than oil,[32] on average, fuel switching to natural gas results in a significant reduction in GHG emissions. As such, in an environment of increasing carbon prices, gas becomes more competitive relative to other fossil fuels (see Exhibit 4).

Exhibit 4 - NATURAL GAS IS THE CLEANEST FOSSIL FUEL

Emissions factors for natural gas vs. coal and oil



Source: NETL, EEA, OIES, BCG analysis.

31 Assumptions are aligned with the IEA's 2019 Sustainable Development Scenario.
32 US EIA.

When considering the impact of the switch on local air pollution, the benefits of gas are even more substantial. In most uses, natural gas emits near zero levels of particulate matter, sulphur dioxide, and nitrogen oxide. Where large-scale fuel switching efforts have been undertaken, air quality has improved rapidly. In Beijing, for example, particulate matter pollution declined by approximately 50% between 2016 and 2017 as a result of switching from coal to gas.[33]

To assess the economic potential adoption of natural gas, these environmental benefits were incorporated along with an analysis of the relative economic competitiveness of natural gas as a source of energy. It is necessary to consider gas as an alternative to coal and oil in near-term fuel switching, as well as the role of gas compared with renewables in power generation and the electrification of energy consumption. Due to the differences in local energy systems, including the power generation mix, results differ considerably across sectors and regions.

Natural gas is typically one-half to one-third of the cost of oil, based on energy supplied[34]. This cost factor has provided a strong economic argument for fuel switching in the power, industrial, and buildings sectors.

While many opportunities to switch from oil to gas have been exploited, large gaps remain, due to limited access, social or regulatory barriers, or because of the upfront capital requirements. In the transport sector, for example, the higher upfront costs of natural gas vehicles partly offset the benefits of lower fuel costs, thereby limiting the economic potential of gas.

The difference in cost between gas and coal is more varied and depends more on regional factors. In many gas-producing markets, the cost of natural gas is typically lower than coal. In the U.S., for example, gas has rapidly displaced coal, largely because of the growth of unconventional gas production and the resulting drop in the market price. However, in gas-importing and coal-producing regions—such as Asia and Europe—coal is typically cheaper[35]. Part of the reason for this “cheapness” of coal is that a significant part of its cost is socialized, when appropriate carbon and pollutant emissions controls are lacking. Thus, putting a value on the social costs of emissions, through a carbon price or controls on emissions and air quality regulations, significantly improves the cost competitiveness of gas, and makes the cost of gas lower than coal in any geographic region[36].

33 World Bank, PM 2.5 air pollution data.
34 BCG, IGU, Snam, “2018 Global Gas Report”.
35 Ibid.
36 BCG analysis using LCOE data and social cost of pollution estimates.

This modeling exercise shows that the economic potential of natural gas is substantial. At the highest potential economic deployment, the global natural gas market consumption could be around 2.5 times bigger in 2040 than it is today[37]. The biggest growth potential is in the power and industry sectors where natural gas can displace coal. These two sectors account for about 70% of the economic potential of gas (see Exhibit 5).

This assessment of the economic potential of gas, along with the sustainable development benefits it offers, is not a forecast. It outlines a modelled potential role for natural gas in the energy mix, and depends on economic conditions where the environmental benefits of switching from oil and coal to natural gas are valued. In addition, it assumes a world where a sustainable development scenario is implemented and global energy policies adjust to meet climate goals, which would require that renewable power and gas technologies are quickly scaled up. That would allow for near-term emissions reductions through fuel switching and progressively also reductions from a transition to low-carbon gas technologies.

Exhibit 5 - ECONOMIC POTENTIAL FOR GAS DEFINED ON THE BASIS OF COMPETITIVENESS IN DIFERENT SEGMENTS OF USE

		ECONOMIC POTENTIAL[1]	
SECTOR	**DRIVERS OF MAXIMUM POTENTIAL OF GAS**	**DEMAND GROWTH BY 2040 (BCM)**	**GHG REDUCTION BY 2040[2] (GT CO_2)**
POWER	• Competitiveness of gas at a national level • Gas replacing coal and oil generation only at the end of average plant lifecycles	2,400	3.3
INDUSTRY	• Declining cost of gas technologies based on recent innovation trends • Average competitiveness of gas vs. coal in different industrial sub-segments	1,600	2.0
BUILDING	• Gas replacing all remaining coal and oil products used to fuel commercial and residential buildings	500	0.5
TRANSPORTATION	• Road transport: Impact of technology trends, applied by segment (e.g. heavy duty most viable for LNG) • Marine bunkering: Segment of marine consumption most exposed to action on air pollution	900	0.5

Note: In all cases, increasing cost of carbon assumed in line with requirements to limit warming to 2 degrees as included in the IEA SDS from the 2019 WEO; technology cost trends identified in the report are applied, otherwise economic assumption are generally aligned with IEA SPS from the 2019 WEO.
1. Potential is based on the economic potential as defined in Chapter 1;
2. Calculated as gas demand growth multiplied the emissions benefit of switching from coal and or oil to natural gas.
Source: IEA, EIA, BP 2019 Energy Outlook, NGVA Europe, IPCC, BCG analysis.

37 BCG analysis.

The role of gas technologies in a carbon constrained world

As well as considering the economic potential of natural gas, it is also necessary to assess the role that natural gas can play in minimizing the costs of meeting the Sustainable Development Goals. With regard to climate change action, gas technologies are critical for achieving the lowest-cost route to reducing the GHG intensity of the global energy supply.

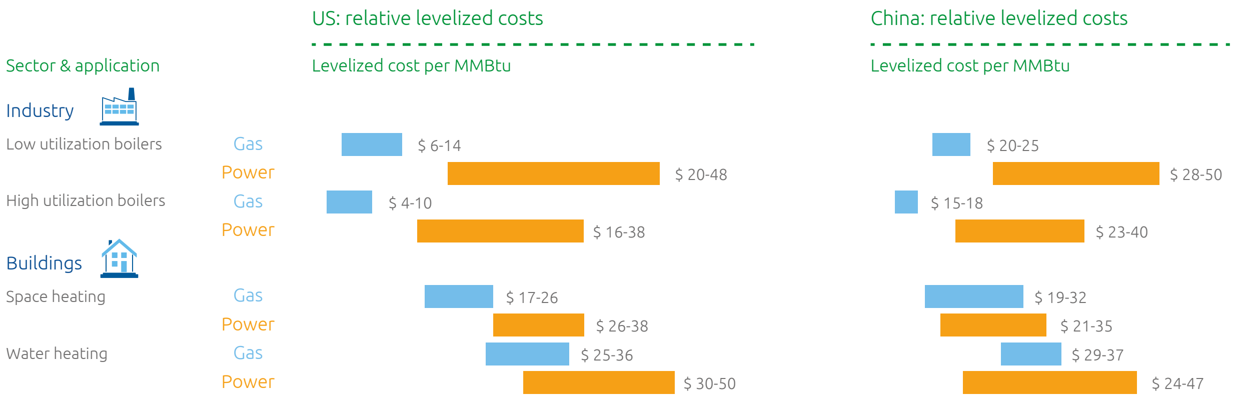
In the near-term, substituting gas for coal and oil can result in material GHG emissions reductions on a cost-effective basis. This is particularly true in Asia, which directly faces the dual challenges of rapidly growing energy demand and the dominance of coal as the main energy source in several countries. The rapid increase in renewable power generation is helping to offset part of the growth in coal demand, but constraints on the pace of capacity development and grid integration issues are limiting its role[38].

Natural gas provides a scalable and cost-effective means for offsetting the growth in coal-fired power generation, while helping to integrate growing shares of variable renewables into the grids. While coal's levelized cost of energy is still lower than gas in much of Asia, a carbon price of just $20 to $50 per metric ton would bring gas to achieve cost equivalence with coal[39].

In industrial and buildings applications, gas provides a highly efficient source of heat generation, typically at a lower cost than electrification options (see Exhibit 6).

In industrial applications, gas is the most efficient energy source for process heat generation, and it is the least-emitting feedstock for petrochemicals production (other than biofuel inputs, which face supply constraints). While efficient electrification technologies are emerging for industrial applications, they can cost up to five times more than gas on a levelized basis. Even in China, where the cost of electricity is relatively low, compared to gas, a carbon price of between $30-80 per metric ton would be required to equalize the cost of electrification options with gas[40]. In the buildings sector, gas and electricity are closer in levelized cost, though their relative competitiveness is highly dependent on local factors.

Exhibit 6 - GAS PROVIDES A LOWER LEVELIZED COST OF SERVICE THAN ELECTRICITY IN MOST CONTEXTS



Source: NREL, EIA, NDRC, BCG analysis.

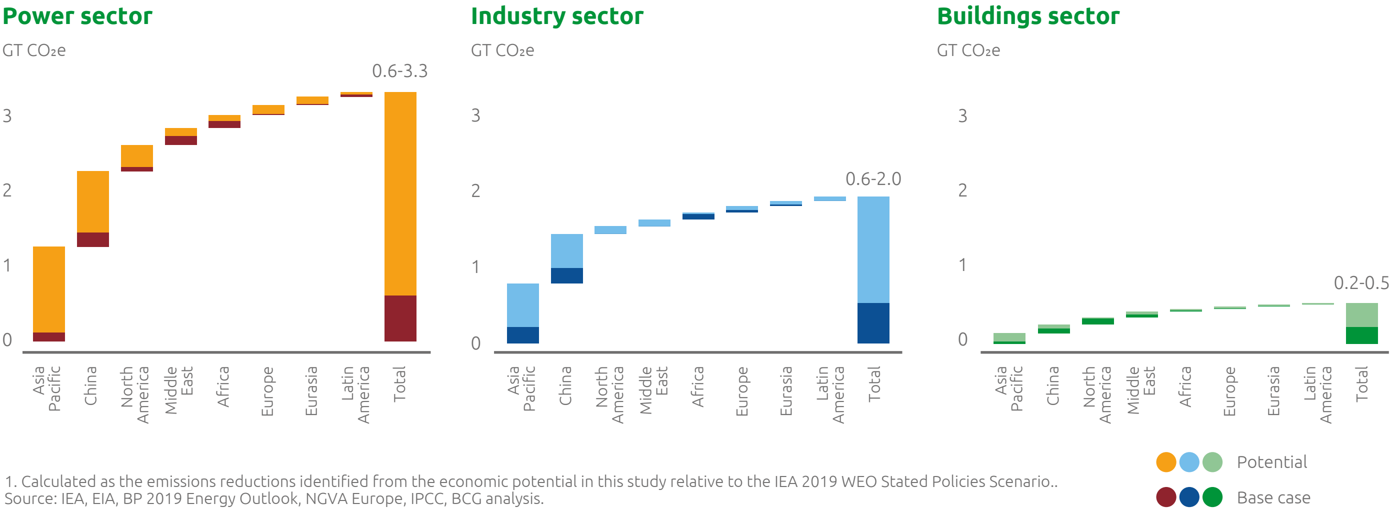
38 See for example recent challenges to scaling wind and solar development in India and China.
39 BCG analysis – example of China based on average of 2018-19 LNG import prices.
40 BCG Levelized Cost of Service analysis. Assumes that electricity supply is zero carbon at current power prices.

Given the cost competitiveness of gas as a means of reducing the GHG emissions intensity of energy, fuel switching can play a significant role in climate change mitigation. Switching to gas from other fossil fuels has already cut global emissions: since 2010, coal to gas switching has avoided 0.5 GT of emissions per year worldwide[41]. In the future, if gas were to displace coal and oil in to its full economic potential, up to 6.3 GT of emissions per year could be avoided by 2040[42]. The greatest potential for this form of emissions mitigation is in the power and industrial sectors in Asia, and especially China (see Exhibit 7).

Over the longer term, low-carbon gas technologies offer the most efficient means of significantly reducing emissions from high heat and energy-intensive applications. Consequently, they are best placed to help achieve a below 2°C scenario. In these so-called "hard to abate" sectors in industry and transport, low-carbon options, other than the use of renewable gas, hydrogen, or CCUS, are either extremely expensive or impractical[43]. Gas technologies, therefore, provide a critical pathway for reducing emissions in line with the Paris Agreement targets.

Exhibit 7 - POWER SECTOR FUEL SWITCHING PROVIDES THE GREATEST OPPORTUNITY FOR GHG EMISSIONS REDUCTIONS

Potential¹ annual emissions reduction from gas fuel switching by 2040



1. Calculated as the emissions reductions identified from the economic potential in this study relative to the IEA 2019 WEO Stated Policies Scenario..
Source: IEA, EIA, BP 2019 Energy Outlook, NGVA Europe, IPCC, BCG analysis.

41 IEA, "The Role of Gas in Today's Energy Transitions", 2019.
42 BCG analysis. Global energy scenario based on assessment of comparative economics of gas vs. alternative fuels across sectors and regions by 2040. Assumes renewables penetration aligned with IEA Sustainable Development Scenario.
43 See for example recent report Columbia Center on Global Energy Policy, "Low carbon heat solutions for heavy industry: Sources, options, and costs today", 2019.

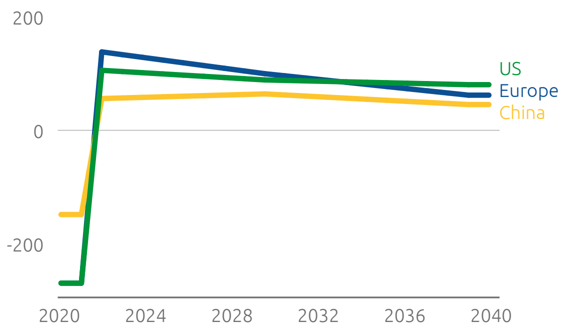
One argument often raised against investing in natural gas infrastructure is that these investments could become stranded, in the event of a rapid acceleration in climate change actions. To assess this possibility, an average cash flow from gas-fired power generation assets was constructed over their project life, assuming rising carbon prices aligned with achieving a below 2° Celsius scenario[44]. The resulting cash flows would remain positive throughout a 20-year lifecycle investment in these plants. Indeed, when considering the scale of incremental power generation capacity aligned with the economic potential of gas, substantial value would be created from investments in gas-fired generation: more than $40bn net present value (NPV) in both the US and Europe and $120bn NPV in China over the next two decades[45] (see Exhibit 8).

When assessing the long-term economic potential for gas pipeline infrastructure, positive economic value is also likely over the course of an asset lifespan under a below 2° Celsius scenario. In this case the value is to be derived from transitioning the use of the infrastructure over time to enable the transport and storage of renewable gas and hydrogen. In one study focusing on Europe, the total value of using natural gas networks in Europe for a low carbon transition was estimated to be €480 to €800 Billion by 2050 across eight western European countries[46].

Exhibit 8 - COAL-TO-GAS SWITCHING IS NPV POSITIVE, EVEN UNDER RAPIDLY RISING CARBON PRICES ALIGNED WITH A 2 DEGREE PATHWAY

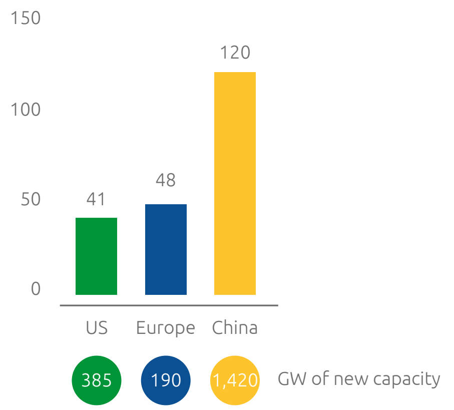
Example project cash flow in the US, EU and China for an average CCGT plant

Pre-tax cash flow of a standard US, European & Chinese CCGT¹ ($M)



Cumulative NPV of gas capacity additions aligned with maximum economic potential for gas

Estimated cumulative NPV of new CCGT investments 2020-2040 ($B)



1. Revenue calculated assuming realized prices consist of power plant capital recovery and O&M, fuel costs, and CO_2 price recovery as defined by the IEA 2019 WEO; Standard is defined as the averages used for Lazard's LCOE 13.0 study with a 25% discount for Chinese O&M costs; Carbon tax escalates to $140 per metric ton of CO_2e by 2040 in US and to $125 per metric ton of CO_2e by 2040 in China.
Source: Lazard, US EIA, IEA, BCG analysis.

44 An increase to at least $125 per metric ton on average globally by 2040, based on IEA 2019 World Energy outlook SDS assumptions.
45 BCG analysis based on IEA assumptions.
46 Frontier Economics, "The value of gas infrastructure in a climate-neutral Europe", 2019.

Recommended action plan

The ability to realize the full value of the most promising gas technologies and achieve emissions and economic benefits they deliver will depend on several interconnected actions, from both the public and private sectors.

1. **Government policy** which supports the development of new technologies and ensures their value is recognized, using widely accepted and efficient mechanisms such as carbon pricing and emissions regulations. Governments play a key role in reducing barriers to the development of new markets, particularly where there are strong social, economic and environmental drivers already in place.
2. **Continued investment in natural gas infrastructure** and in the development and deployment of new low-carbon gas technologies. This includes capex for the supply of natural gas, investments supporting its consumption in specific segments, and production capacity in the case of low-carbon renewable gas and hydrogen.
3. **Private-sector innovation** and commitments to deploy new technologies, as well as the development of new business models to maximize their adoption. It is thus incumbent on the industry to become the champion of innovation – developing and deploying it throughout operations to bring new products to market, add customer value, and make its contribution to the solution of sustainable development and energy challenge.

These requirements were identified by assessing each of the gas technology categories, and by taking a bottom-up approach to examine how and under what conditions technology impacts can be maximized. The following exhibit lists the key findings for each category in detail (see Exhibit 9) and provides the basis for the recommendations within this chapter.

Exhibit 9 - AN ACTION PLAN FOR GAS TECHNOLOGY AND INNOVATION

HIGH PRIORITY ACTIONS FOR GAS TECHNOLOGIES

	GOVERNMENT POLICY	INFRASTRUCTURE INVESTMENT	INDUSTRY INNOVATION
1. CLIMATE ACTION AND SUSTAINABLE CITIES	1. Sector based fuel switching measures – either mandate or market based 2. Carbon pricing (permits or tax) 3. Localized pollution control / air quality standards 4. Capacity mandates, markets valuing flexibility resources (for gas capacity), and steps to address barriers 5. Financial support for R&D and innovation	1. Accelerated equipment replacement/ adoption (policy or corporate driven) 2. Testing and deployment of higher efficiency processes (e.g. direct reduced iron) 3. Access to gas for cities – through transmission and LNG re-gasification investment 4. Gas peaking capacity development (via government and private investment) 5. Natural gas vehicle fueling & LNG bunkering infrastructure (via government and private investment)	1. Deploying of new high efficiency, cost-effective technologies 2. Business model innovation to facilitate efficiency improvement (e.g. ESCOs) 3. Development of modular, flexible capacity for peaking 4. Leasing models to reduce upfront capital commitments for gas in transport 5. Continued R&D to improve efficiency/cost competitiveness
2. LOW CARBON GAS	1. Financial support for R&D and innovation 2. Market based incentives to facilitate capacity deployment 3. Regulatory reforms to facilitate new technology deployment and to address barriers	1. Rapid scale up of capacity where there is already an economic case (e.g. low cost CCUS) 2. Development of demonstration/ early stage capacity for emerging technologies 3. Gas supply chain investment to enable future consumption	1. R&D investment in critical areas for innovation breakthroughs 2. Investment and risk pooling/sharing to lower deployment barriers 3. Low-carbon gas retail marketing
3. ENERGY ACCESS	1. Incentives for gas adoption and to address barriers (e.g. equipment conversion support) 2. Long-term system and infrastructure planning 3. Financial support for R&D and continued deployment of small scale/ distributed gas technologies	1. Gas network investment, including to enable fuel switching in buildings (via government and private investment) 2. Development of distributed generation and SSLNG supply chains	1. New business models to lower financial barriers to gas adoption 2. Continued innovation in SSLNG applications 3. Early stage testing and deployment of new technologies for gas access

Government actions

Industry actions

1. Government policy

Regardless of policy that provides market incentives for fuel switching and the adoption of gas technologies, in many markets access to natural gas remains limited (particularly non-OECD Asia). In these markets the successful promotion of fuel switching starts with providing adequate access to gas. To enable that investment a wide range of financial tools can be used. In the case of India for example, the regulated tariff structure provided for City Gas Distribution companies ensures attractive returns after an initial investment in expanding access, averaging 15% on capital employed[47]. In the US and some other markets, pipeline developers are often given tax-advantaged status. Industry participants also play an essential role in ensuring access to gas through mobilizing capital and pursuing the lowest cost development of gas infrastructure.

Government policy measures are essential for developing and deploying clean technologies. A wide range of specific mechanisms can be used, ranging from mandate-based to market-based (see Exhibit 10). However, three types of policies stand out as being particularly effective for both facilitating innovation and deploying new technologies at scale: R&D and early stage innovation support, market-based measures, and incentives for fuel switching as gas adoption.

R&D and early-stage innovation support:

Government research and development support is generally considered vital when developing new technologies that are very capital intensive and involve long lead times, and those with a high share of public (vs. appropriable) benefits[48,49]. While these conditions exist across the energy industry, they are especially acute in the natural gas sector because of the considerable infrastructure requirements for transporting and supplying natural gas and the breadth of potential use applications.

Government R&D support has already played a significant role in helping to develop and deploy new gas technologies. For example, US government funding in the 1990s was essential for the development of the first heavy duty compressed natural gas (CNG) engines for gas-powered vehicles. US federal investment, channeled through the Gas Research Institute, led to multiple new technologies which dramatically improved the efficiency of natural gas combustion devices and delivered more cost-efficient operations for natural gas systems. These, in turn, resulted in substantial reductions in consumption and consumption-related emissions.

Support for low-carbon gas technologies should be a key priority, given their strong potential for enabling low-carbon energy systems. Significant fundamental research into these technologies has been completed with government backing, but more is needed to continue making these technologies more cost-competitive and especially to facilitate early-stage deployment.

In this case, there are relevant lessons learned from the adoption of other cleantech solutions. The successful development of renewable power and battery technologies was made possible by significant government-supported R&D funding, followed by large deployment and market uptake incentives. The financing of early-stage deployment also helped to demonstrate the viability of these new technologies and kick-started the development of new markets.

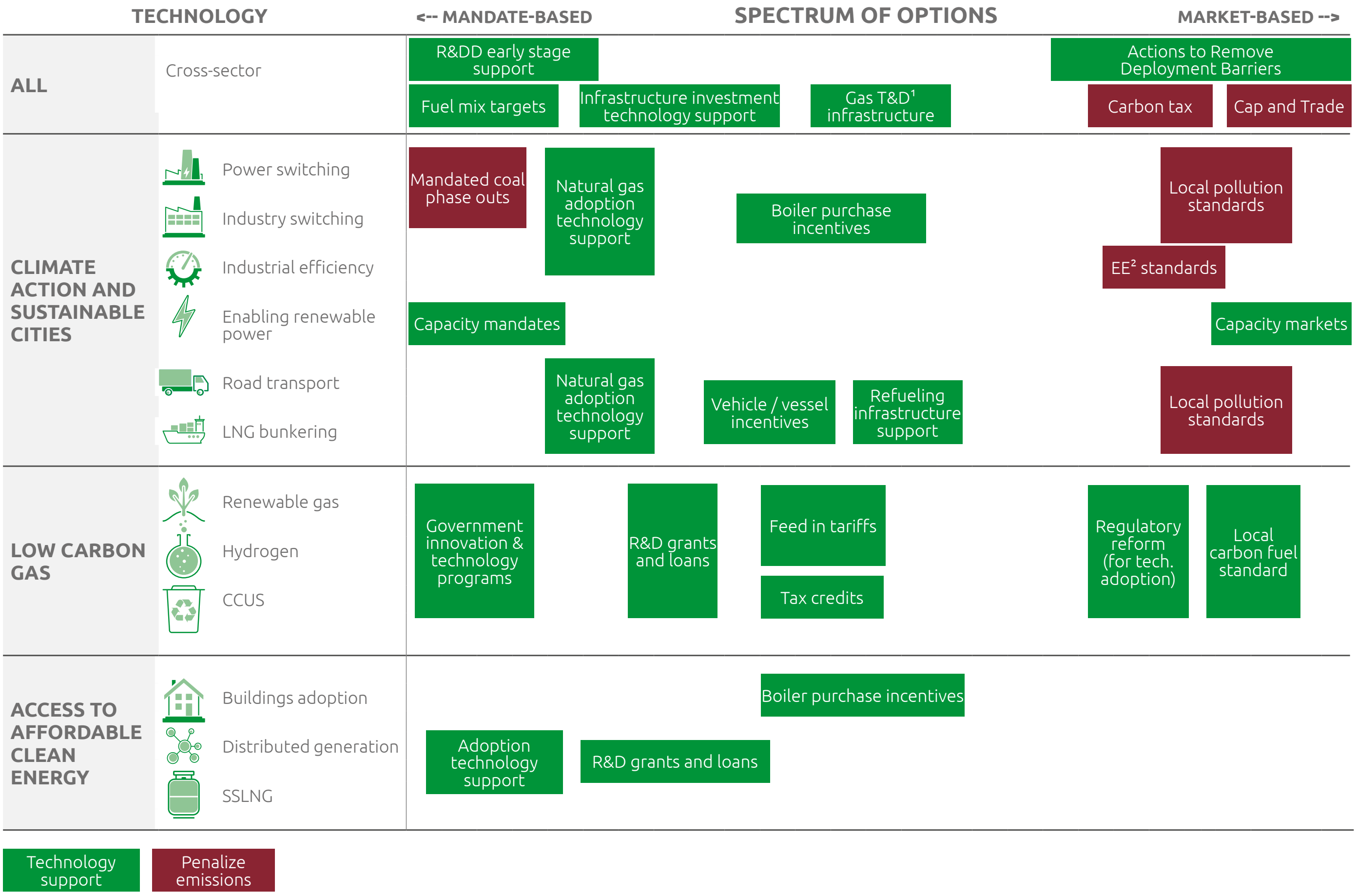
47 BCG analysis using publicly traded Indian CGD company reports.
48 For example, findings from American Energy Innovation Council, "Energy Innovation: Fueling America's Economic Engine", 2018.
49 For technologies that are not directly linked to profitability, such as end-use efficiency enhancements, the market incentive to invest does not apply, since the benefit will be socialized, rather than appropriated by the initial developer.

Market-based measures:

An extensive menu of cost-effective policy measures is already available to policymakers to provide market signals and to support clean technologies adoption. Each case must be treated individually and the specific policy toolkit will differ by region, sector, and technology, but Exhibit 10 provides an overview of the types of policy measures that can be used.

Enabling the adoption of gas technologies involves recognizing the core benefits they can deliver by reducing GHG emissions and improving air quality.

Exhibit 10 - WIDE RANGE OF POLICY OPTIONS AVAILABLE TO ENABLE GAS TECHNOLOGY DEVELOPMENT



Source: BCG analysis

On an economic or sector-specific level, policy can reflect these benefits by placing a value on environmental externalities. This can be achieved through carbon pricing mechanisms (such as tradeable permit schemes or pollution taxes) as well as localized pollution or air quality measures, and simple measures like fuel quality standards, which are still very uneven across the developed and developing world.

Government policy is also important in supporting the creation of new markets by setting standards and removing barriers to adoption. This is particularly relevant for distributed energy and energy efficiency technologies, where benefits often differ across multiple stakeholders or upfront barriers to adoption exist.

For the development of gas peaking capacity, the establishment of clear market rules reflecting the effective value of capacity are key. And, for small-scale LNG, lifting regulatory restrictions is essential to facilitate the transport of LNG by truck, rail or vessel.

Incentives for fuel switching and gas technology adoption:

Evidence from gas technology developments in the past suggests that broad policy mechanisms, such as carbon pricing, are necessary, but are often insufficient on their own for driving new technology adoption. For fuel switching in the power, industrial and buildings sectors, targeted mechanisms supporting natural gas infrastructure have proved to be effective, particularly when combined with specific fuel-switching policies.

To enable the adoption of the most efficient gas boilers in industry and buildings applications, efficiency mandates, combined with adoption incentives have proved successful. Meanwhile, for more nascent technologies in natural gas transport and bunkering, early-stage incentive programs for fuel adoption and infrastructure development can help to kick-start market development and initiate scale and experience benefits.

To facilitate the development of new markets for low- and zero-carbon gas technologies, policymakers should consider multiple complementary enabling policies. These include portfolio standards or low-carbon fuels standards that enable supply, as well as feed-in-tariffs or tax credits to enable demand. The sequencing of these policy measures is critical in promoting the development of a new industry while also creating the right conditions for cost reductions through scale and experience effects.

Realizing the Value of Fuel Switching

The potential contribution of fuel switching toward meeting global climate and development targets is not a given. In many cases, realizing this value will depend on addressing barriers to investment and fuel adoption through government policy. Past experience provides some lessons on what approaches and specific measures are required, specifically:

- Clear and consistent policy. Fuel switching typically requires significant capital investment, and to enable that investment, the future policy and market environment needs to be clear, to reduce risk.
- Value allocation. Policymakers have to assign value to the desired outcomes, and costs to the unwanted ones. For example, implementing carbon pricing is one of the easiest and most efficient means to facilitate fuel switching and the adoption of industrial efficiency measures, but it requires clearly valuing the social and environmental costs associated with GHG emissions.
- Capacity value. Capacity in electricity grids is supplied by flexible generators (or dispatchable resources), which can increase or decrease output, as needed, to fill the gaps between fluctuating demand and supply. This is a different function, than just supply of energy, or generation in that it is a can turn on and off, and up or down, for varying lengths of time, with relative ease. As the share of intermittent renewable generation grows, so does the need for grid balancing and flexibility to maintain reliable supply, increasing the value of capacity, while decreasing that of energy. This is often not reflected in the way that generators are remunerated, and it is critical for the growing relative value of capacity to be recognized to provide sufficient incentives for the needed investments in capacity. When this does not happen, and a system falls short on capacity, then reliability will be at risk.
- Prioritize Efficiency. Improving energy efficiency depends on sector-specific efficiency standards, as well as technology adoption incentives. For example, US data reveal that, despite the availability of high efficiency water heating boilers, only about 40% of residential customers purchase the most efficient option[50]. In cases like this, while the levelized cost of using gas can often be lower than alternatives over time, upfront capital costs are higher (see Exhibit 11).
- Invest in Prudent Infrastructure. Enabling natural gas use in new sectors, such as road transport and LNG bunkering requires upfront investment to both promote continued technology development (such as through further R&D), as well as to enable early stage adoption (such as fuel switching incentives and development of refueling infrastructure).
- Remove Barriers to Adoption. A combination of government policy and industry action can help overcome barriers to fuel switching in all sectors. Common approaches include specific mandates on fuel switching or efficiency standards, directed through policy or industry-specific agreements, and common operating standards. Additionally, measures that enable access to technologies or facilitate financing, either through government or industry support, can be effective in reducing upfront barriers.

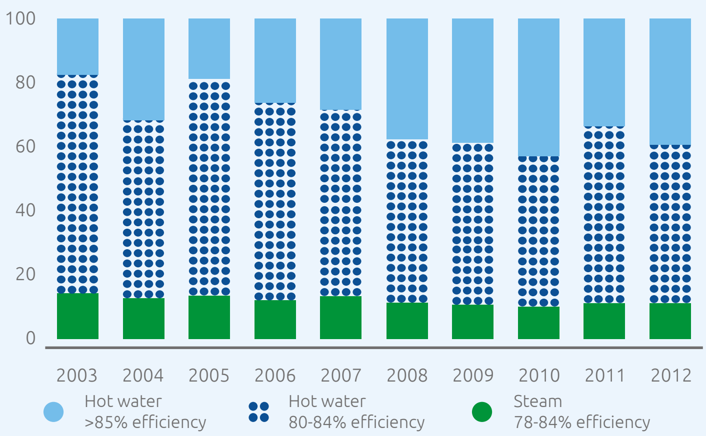
EXHIBIT 11 - THERMAL EFFICIENCY OF GAS COMBUSTION HAS NEARLY REACHED MAXIMUM, BUT RESIDENTIAL CONSUMERS STILL BUY LOWER EFFICIENCY UNITS

Gas combustion technology has significantly improved

	1950s-70s	1970s-90s	1990s onward
Efficiency	56-70%	80-83%	90-98.5%
Flue gas flows	Natural draft	Exhaust fan	Condensing unit & heat exchangers
Ignition	Continuous pilot light	Electronic ignition	Sealed combustion

Residential consumers still purchase lower efficiency units

US residential boiler sales by efficiency (%)



50 EIA, "Residential End Uses: Historical Efficiency Data and Incremental Installed Costs for Efficiency Upgrades", 2017.

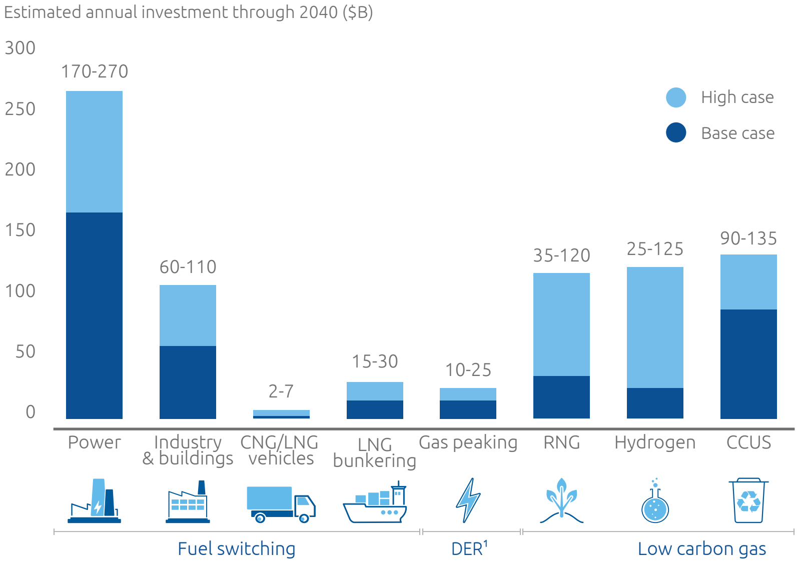
2. Infrastructure investment

For gas technologies to achieve their full potential, significant additional capital investment will be required to enable sufficient infrastructure expansion to meet demand (see Exhibit 12). To maximize the sustainable development benefit from gas, an estimated $415 billion to $820 billion of investment will be required annually through 2040[51 52].

The wide range of estimated required capital expenditure reflects the high level of uncertainty around future technology costs, with the low end of the range representing the potential for further cost-reducing innovation. Mobilizing capital from both public and private-sector sources in the near term will be critical for deploying these technologies, leading to greater competitiveness from scale and learning effects.

Exhibit 12 - SUBSTANTIAL INVESTMENT IS REQUIRED TO MAXIMIZE THE IMPACT OF GAS TECHNOLOGIES

Estimated required annual global investment to achieve full sustainable development impact



1. Distributed Energy Resources
Source: IEA, EIA, BP 2019 Energy Outlook, NGVA Europe, IPCC, Lazard, Navigant, Imperial College London, BCG analysis.

51 Investment requirements per year through 2040 to achieve the economic potential for gas. Includes the impact of potential improvements in gas technology efficiencies and capital costs, both for the modeling of the economic potential for gas and for the required capital.
52 IEA, "World Energy Investment", 2019.

Establishing access to gas:

To deliver the full benefits of fuel switching, a step change is also required in power generation, transmission and distribution infrastructure, as well as in vehicle and bunkering infrastructure.

Investment in gas power generation capacity has averaged $50 billion per year for the past three years[53]. But to achieve the sector's full potential to reduce global GHG emissions (by 3.3 GT of CO_2 by 2040), investment would need to total between $170 billion and $270 billion per year to 2040[54]. For transmission and distribution infrastructure, an estimated $60 billion to $110 billion per year would be required just to expand access to gas in new regions[55].

The most pressing need for gas infrastructure investment is in Asia, where access to gas is limited today. Across non-OECD Asian countries, gas contributes less than 10% of total energy supply while coal provides more than 50%[56]. This is due in large part to poor access: while the population of Asia is five times that of Europe, the total combined length of the region's gas pipelines is less than in Europe[57].

Beyond enabling near-term fuel switching, current natural gas infrastructure investments provide a pathway for low-carbon gas in the future. In power generation, existing policies and carbon pricing measures are not yet sufficient to warrant market-driven upfront investment in CCUS. However, given the availability of plant retrofits, it would be possible to add CCUS in future as the price of carbon increases. Similarly, for natural gas access in industry and buildings, the development of pipeline infrastructure now can enable renewable gas, as well as some hydrogen blending in the future.

The extensive pipeline network also plays an important role in supporting energy security, by providing an alternative and highly resilient energy delivery system.

Developing capacity for low- and zero-carbon gas:

Significant investment in renewable gas, hydrogen, and CCUS technologies will be required to develop entirely new value chains for the provision of low-carbon gas and deliver on the significant potential of natural gas to reduce the emissions intensity of energy systems. Of the total investment required through 2040 to maximize the sustainable development impacts of natural gas, and help meet the Paris climate goals, roughly half would need to be in low-carbon gas technologies.

The required investment in natural gas infrastructure is large in absolute terms, but it can deliver a high level of emissions reduction per dollar spent. Gas technologies have the potential to achieve emissions reductions totaling 12 GT per year by 2040. This would require a maximum of $820 billion per year of investment, thus making it roughly $68 per ton of reduction at the high end, and about half that on the low end of investment requirements. By comparison, the IEA, in its Sustainable Development Scenario, estimates that renewable power generation can achieve 7GT of emissions reductions per year through 2040, but this would require more than $1 trillion of annual investment in generation and transmission capacity[58] (roughly $142 per ton of reduction).

While the cost structures of renewable power and natural gas are very different (renewable power mainly involves upfront capital expenditures, whereas gas technologies require a mixture of capex and opex), the lower capital intensity of gas technologies and the lower integration costs are advantages, given competing demands for capital.

Targeted infrastructure to enable new technology adoption

Beyond broad-based infrastructure enabling access to gas in new geographies, targeted support is required to facilitate the adoption of new gas technologies for specific forms of consumption. This is critical in the transport and buildings sectors, for example, where consumers face adoption barriers in the form of upfront capital requirements. While the use of natural gas can lower operating costs over time, incremental capital costs can prevent adoption from the outset. To overcome this barrier, measures such as low-interest and on-bill financing could help to minimize any initial financial burden.

53 Ibid.
54 Investment requirements per year through 2040 to achieve economic potential for gas.
55 Ibid. Note this differs from annual global investment in T&D infrastructure as reported from other sources. This estimate only includes incremental access to natural gas, not infrastructure required to transport upstream production or maintenance capex on existing grids.
56 Based on IEA data.
57 IGU, "2018 Global Gas Report".
58 IEA, 2018 World Energy Outlook.

3. Industry innovation

The natural gas industry must play a central role in promoting innovation in gas technologies. Three opportunities to do so stand out, based on examples of existing gas technology adoption: through sustaining R&D and early-stage deployment investment, by developing smaller scale and more modular means of deploying technologies, and through the development of new business models.

Sustained R&D and early-stage deployment support:

Sustained private-sector R&D investment is essential to improve the efficiency, flexibility, and lower capital costs of gas technologies. This is true for all technologies, but is particularly important where technologies are more nascent. With low-carbon gas technologies, research is helping to make new processes commercially viable, such as biomethane conversion in renewable gas production or membrane-based carbon capture. In addition, fundamental research in the field of cryogenics has led to a range of new commercial applications for the transport and use of LNG.

Early deployment of emerging technologies is critical to the success of their development and time to full market readiness. Scale and experience effects gained through deploying new technologies early are key drivers of cost competitiveness. This has been demonstrated in the development of more energy efficient and flexible gas boiler and combined heat and power (CHP) technologies, as well as with gas peaking technologies. Similarly, the potential of low-carbon gas technologies is significant given their small scale today.

Early-stage investments in R&D and technology deployment do carry risks and involve a long-term commitment. Thus, companies and investors must have a long-term, holistic vision for the role natural gas can play in reducing GHG emissions and the competitive opportunities it offers. Early movers in the renewable power space have successfully captured significant market share in a large and rapidly growing industry. The same opportunity exists with natural gas, and particularly with low-carbon gas technologies.

This is where the key role for governments is to provide clear and consistent signals, in support of technological development, thus ensuring a stable private investment environment. Governments should resist the pressure to pick certain technology paths over others, while favouring technology agnostic, outcome-driven climate and energy policies. In short, it is essential to minimize political risk caused by changing policies, so that the industry can take long-term decisions that support innovation.

Smaller scale and more modular technology applications:

Re-thinking gas technologies in an emerging market context is essential for finding new avenues for growth, particularly in Asia where gas penetration is low today. Deploying new business models alongside new technologies can help to transform how gas is consumed. In India, for example, development of the country's low-cost City Gas Distribution model has resulted in widespread, rapid access to gas.

Small scale LNG (SSLNG) also offers significant opportunities for gas to leapfrog traditional centralized models of gas market development. SSLNG can lead to the development of natural gas value chains in months instead of years, while requiring 10% of the upfront capital. Despite this, the deployment of SSLNG has been limited to specific regions. For natural gas players, testing and learning by doing will be important to ensure broader deployment in the future.

New business models:

Beyond developing new technologies, companies and investors can make a significant impact by actively creating new business models for deployment. As has been shown in energy efficiency applications, successful adoption of new technologies involves more than simply being cost-effective. Business model innovation can overcome barriers preventing adoption or deliver greater scale. To date, business models related to energy efficiency have seen the greatest innovation: the development of service company models has helped to lower upfront costs while also enabling a wide range of groundbreaking technologies. Similar potential exists in other areas, particularly in leveraging new digital technologies.

Scale of support today vs. requirements for meeting the Sustainable Development Goals

Compared with what is required to achieve the economic potential of gas technologies, major gaps exist in policy and infrastructure investment. Current levels of policy support for clean energy R&D investments (which include gas technologies) are considered insufficient by the IEA[59]. The adoption of carbon pricing as a market incentive is growing. However, it is still limited globally and only covers about 20% of worldwide GHG emissions[60]. As demonstrated in this report, there are specific examples of support for technology rollouts, but on the whole, these are limited.

Infrastructure investment is also well below the level needed to achieve the full potential of gas, for established technologies and low-carbon gas technologies. In the power and industry sectors, total investment in 2018 was $175 billion. That compares with a requirement of close to $400 billion annually, which is the amount necessary to achieve the economic potential of natural gas adoption[61]. In low-carbon gas technologies, investment is negligible today, compared with what is required to achieve a below 2°Celsius scenario. For example, investment in CCUS over the past decade has averaged less than $100 million per year[62]. By comparison, total investment in renewable power generation totaled more than $260 billion in 2018[63].

Progress on industry innovations has been more significant, however. As the case studies in this report show, there have been advances in the development of business models facilitating the adoption of new gas technologies. While the deployment of some of the most promising technologies, such as SSLNG, remains limited, recent growth has been rapid.

Looking ahead, industry commitment to innovation is also likely to be critical to catalyze broader government and market forces. Ensuring that gas technologies help to achieve the global sustainability and development goals to their full potential will thus require a sustained collaborative effort from the private and public sectors, with an "all hands-on deck" approach to mission innovation in the energy sector. This is an approach that will be needed to get from the status quo to the desired state of a sustainable future, in line with key global commitments made to climate and development.

59 IEA, Tracking Clean Energy Progress, 2019.
60 World Bank, "State and Trends of Carbon Pricing", 2019.
61 IGU, Snam, BCG "2019 Global Gas Report".
62 Global CCS Institute.
63 UNEP & Bloomberg NEF, "Global trends in renewable energy investment", 2019.

Chapter 2

Action on climate change and sustainable cities and communities - enabling immediate GHG emissions reductions and improvements in air quality

Highlights

- Gas technologies can significantly contribute to GHG emissions reductions in the near-term, through fuel switching from coal and oil, efficiency improvements in industrial processes, by enabling the greater deployment of renewables, and through the adoption of natural gas in the transport sector.
- Natural gas adoption has already been demonstrated to be a highly cost-effective means of improving urban air quality when replacing coal and oil-based fuel consumption.
- Developments in gas turbine and improved boiler efficiencies and design are reducing upfront capital costs and lowering operational expenditures by up to 20%, strengthening the cost competitiveness for natural gas.
- In power generation, gas technologies have become more flexible and cost efficient, enabling greater deployment and integration of intermittent renewable energy sources; for example, CCGT ramp times have improved by up to 44%, while capital costs have fallen by up to 25%.
- Technology developments in the digitalization of energy system management, heat recovery, and industrial process redesign are also emerging and can be key enablers of emissions reductions in the industrial sector.
- In road transport, gas engine and storage technologies are improving the economics of gas fuel adoption, but the scaling up of supply chains for vehicles and refueling infrastructure are needed in most markets.
- Innovations in LNG bunkering technology are improving its cost competitiveness through improvements in engine power output (by up to 25%) and reducing space requirements for storage on ships (by up to 60%).

Introduction

Natural gas is already delivering significant climate change mitigation benefits through a combination of fuel switching, energy efficiency improvements, and by enabling large scale integration of renewable power generation. It also plays a clear role in reducing localized emissions that cause air pollution. Yet new technologies are further broadening the use of natural gas, enabling more widespread fuel switching and thus deeper reductions in GHG emissions and greater improvements in air quality. Innovation is helping to make fuel switching easier, by enhancing the efficiency of existing gas technologies, reducing capital costs for gas technology adoption, and by improving the flexibility of gas technologies (see Exhibit 13).

To enable more widespread fuel switching, operational efficiencies and lower capital costs are bringing down the cost of natural gas relative to other fuels. Developments in energy efficiency technologies and greater digitalization are also improving the GHG emissions performance of natural gas energy systems. Meanwhile, technology developments are making the use of natural gas in power generation more flexible and responsive. This has enabled gas to facilitate the integration of renewable power into energy systems through the management of intermittency.

New technologies are also enabling more widespread use of gas in the transport sector. In road transport, improvements in the combustion efficiency and capital costs of natural gas vehicles are increasing their competitiveness relative to diesel engines. Meanwhile, improvements in combustion efficiency combined with more efficient means of LNG transport and storage are increasing the commercial viability of LNG bunkering.

The sections below assess innovations across these different dimensions of fuel switching in power and industry sectors, energy efficiency, renewables integration, and use of gas in transport. The focus is to assess where innovations in gas technologies is supporting near-term reduction in GHG emissions and other pollution, as well as to identify the greater potential value that can be unlocked if barriers are removed and pricing signals align better with climate and sustainable development goals.

Exhibit 13 - NEAR TERM ACTION ON CLIMATE CHANGE: SUMMARY OF TECHNOLOGY TRENDS

TECHNOLOGY	RECENT TECHNOLOGY DEVELOPMENT	EMERGING TECHNOLOGY TRENDS	ILLUSTRATIVE POTENTIAL IMPROVEMENTS		
			EFFICIENCY	CAPEX	FLEXIBILITY
POWER SWITCHING	• CCGT thermal efficiency improvements • Ramp time reduction	• Improving heat retention during downtime • Equipment flexibility and resilience to better manage intermittency	CCGT thermal efficiency (up to 10%)	Up to 25% based on scale	Faster start times (1.5-2x)
INDUSTRY SWITCHING	• Combustion efficiency improvements • Declining capital and opex costs	• Improved boiler flexibility • Process efficiency improvements in petrochemical applications	Boiler efficiency (10-20%)		
INDUSTRIAL EFFICIENCY	• Energy management and process redesigning • Deployment of DRI steel production	• Digital applications for efficiency improvement • Heat upgrading technologies	Digital methods (10%)	Small DRI size & low req. capital (up to 75%)	
ENABLING RENEWABLES	• Gas peaking ramp time improvements and cost reduction in frame turbines	• Use of gas reciprocating engines to for modular and lower capex capacity		Lower capital intensity (10%)	Faster RICE ramp times (3-5x)
CNG/LNG VEHICLES	• Engine efficiency, torque, and emissions improvements • LNG storage and distribution	• New methods for engine efficiency • Improving control systems, combustion, and catalysts to further reduce emissions	Emissions reductions (15-70%)	Vehicle cost declines (up to 20%)	
LNG BUNKERING	• Engine scale and efficiency • Ship-to-ship LNG bunkering	• Port-scale distribution infrastructure • Development of smaller membrane fuel tanks	Engine power output (10-25%)	Scale & learning effects (up to 20%)	

Source: Power Engineering Magazine, Power Magazine, Lazard, BNEF, Lawrence Berkeley Laboratory, Colpier & Cornland, US EIA, US DOE, Power Magazine, BCG analysis.

Air quality improvements from fuel switching

As well as providing climate change mitigation benefits, gas technologies that enable fuel switching are also essential for reducing localized air pollutants including particulate matter, nitrogen oxide (NOx), sulfur dioxide, and ozone. Many case studies exist demonstrating significant air quality improvements in cities following dedicated fuel switching efforts[64]. Technology developments that are improving the competitiveness of natural gas and reducing barriers to adoption play a key role in facilitating fuel switching.

The region that offers the greatest opportunities for fuel switching and for natural gas to have a positive impact on improving air quality is non-OECD Asia (see Exhibit 14). Despite the rapid adoption of gas in some countries within Asia, its share in the overall energy mix remains low.

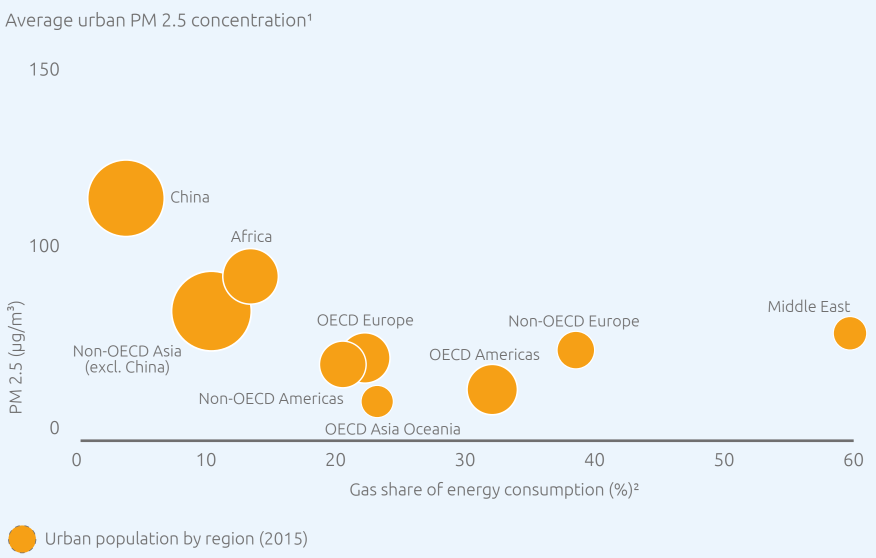
The greatest challenge for gas use in power generation and industrial applications today is the high cost of gas relative to coal, particularly in Asia. While the gap has been closing due to lower imported natural gas prices, coal is typically the lowest-cost source of energy generation across the region.

However, if a price were placed on carbon that was aligned with the Paris agreement's 2° Celsius trajectory (i.e. well above $50/t), gas would become competitive with coal in all regions[65]. Under these conditions, a combination of gas and renewable generation would become the most environmentally and economically viable option in the power sector, with gas providing baseload generation wherever renewables are not able to scale efficiently.

Policy measures that "internalize" the social costs of air pollution can be highly effective in transforming the relative economics of gas versus other fuel sources. For example, when comparing natural gas used in a CCGT plant in China relative to a sub-critical coal plant, where the value of localized pollutant externalities is incorporated into the levelized cost of energy, estimates indicate gas would achieve a lower LCOE than coal[66]. When combined with a carbon price of $40/t, incorporating the externality costs of localized emissions would raise the levelized cost of coal-fired generation to 30% more than gas in China[67].

64 See for example: IGU, "Case studies in improving urban air quality", 2015, 2016.
65 BCG LCOE analysis.
66 BCG LCOE analysis incorporating methodology from University of Texas "Full cost of electricity".
67 Ibid.

EXHIBIT 14 - GAS ADOPTION IS A KEY ENABLER OF IMPROVED URBAN AIR QUALITY



1. Based on cities in the WHO survey database
2. Includes weighted average of power generation, buildings, and industry sectors; based on 2015 data.
Source: IEA, World Health Organization, UN Population Division, BCG analysis.

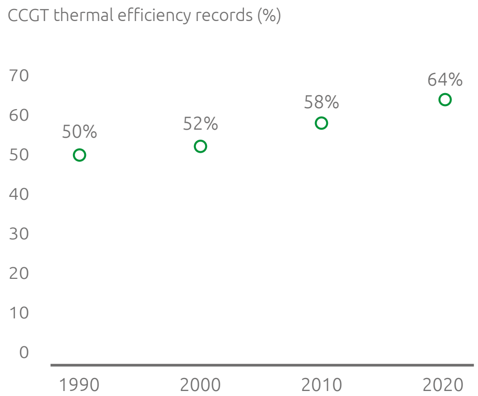
Fuel switching – power generation

Technology development has long played a critical role in advancing how natural gas can be used in power generation applications. The development of combined-cycle gas turbines (CCGTs) is one critical technology development that has enabled gas to play a central role in baseload power generation since the 1990s, particularly across OECD markets[68]. Since CCGTs have emerged though, the average thermal efficiency of CCGT plants has consistently improved, increasing from 50% in 1990 to 64% today[69].

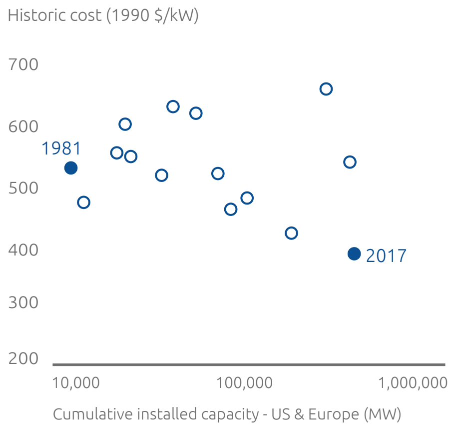
While the capital costs of CCGTs have largely remained stable and predictable over that period, some recent studies have identified scale benefits with newer turbines that can reduce unit capex costs by up to 25% with a doubling of plant size (see Exhibit 15). As a result of these trends, the average levelized cost of gas-powered CCGTs has declined over time, now reaching below $1,000 per KW of capacity in some instances[70].

Exhibit 15 - CCGT THERMAL EFFICIENCY HAVE IMPROVED WHILE CAPITAL COSTS HAVE BEEN GENERALLY STABLE

CCGT thermal efficiency improving



CCGT capital cost structure fairly stable



Source: Power Magazine, Power Engineering International, Lazard, Bloomberg new energy finance; Lawrence Berkeley laboratory; Colpier & Cornland; BCG analysis.

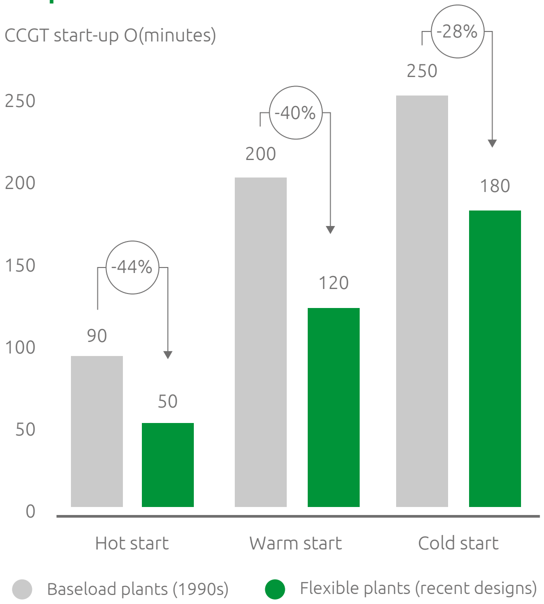
68 Mostly concentrated in Europe, North America, and the OECD Asia.
69 IEA; Power Magazine, "GE HA Turbine Snags Another World Record for CCGT Efficiency", 2018.
70 See for example: PJM, "PJM cost of new entry", 2018.

Recent innovations in CCGT technology have helped make power plants more flexible, enabling them to improve renewables grid integration, while also providing operators with the ability to better capture value from rapid shifts in spot power prices (where power markets enable that margin capture). The structure of the power market, and respective pricing tools available to meet the growing need for system flexibility, are important policy considerations. These tools are critical for enabling investments in technology, which would deliver the desired emissions reductions and reliability.

Start time is one measure of flexibility, and there has been a significant improvement in this area. Modern CCGT plants are able to ramp up between 28% and 44% faster than their predecessor plants were in the 1990s[71]. Additionally, a number of emerging technologies are set to further strengthen the flexibility of CCGTs. These technologies improve heat retention during downtimes, provide more effective control systems that minimize efficiency losses during partial loads, and offer better predictive-maintenance monitoring of equipment. The integration of batteries with existing gas plants (gas-battery hybrid) is another potential means of improving system flexibility, whereby batteries are used to further reduce or eliminate ramp times to provide a nearly instant grid response (see Exhibit 16).

Exhibit 16 - INNOVATION IN GAS POWER RAMP TIME WILL HELP INTEGRATE CCGTS WITH INTERMITTENT RENEWABLES

Design improvements have reduced CCGT ramp times



Source: Power Engineering Magazine, BCG analysis.

Further developments will improve CCGT flexibility

1. Improving heat retention during downtimes
   - Minimizing heat loss while the plant is not operating reduces stress on the overall system, reduces the ramp time, and costs.
2. Upgrading control systems
   - New control systems allow operators improve emissions compliance and minimize efficiency loss at partial load.
3. Employing condition monitoring
   - Frequent switching on and off imposes significant stress on plants.
   - Installing the latest monitoring devices enables timely preventative maintenance.
4. Gas-battery hybrid plant integration
   - Further reduces or eliminates ramp time and can provide nearly instant grid response.

75 Power Engineering Magazine, “Fast start combined cycles”, 2017.

Fuel switching - industry

As in power generation, technology innovation that can reduce the cost or maximize the flexibility of natural gas consumption in the industry sector will be critical for reducing the levelized cost of service of gas. Lowering costs or reducing barriers in turn will improve the prospects for fuel switching, particularly in Asia where gas adoption is still hampered by a structural cost disadvantage relative to coal. Within industrial gas technologies, innovation is occurring in both combustion boiler applications and feedstock processes to improve cost competitiveness.

Combustion Boilers

In the industry sector, gas combustion technologies have achieved very high levels of thermal efficiency, making gas combustion highly cost-effective in industrial uses. Since the 1990s, gas boilers have combined water-tube designs, which improve efficiency under pressure, with heat exchangers and condensing units to recycle heat from flue gas. This has resulted in near-maximum levels of efficiency in gas combustion, with up to 98% efficiency in some instances[72].

Beyond already high thermal efficiency, new developments today are reducing both capital and operating costs for gas industrial boilers. The adoption of smaller units that are easier to install and can be scaled to specific heat requirements has led to lower capital costs. Meanwhile, operational flexibility has improved through the ability to vary flow levels in condensing boilers. Boilers are lasting longer, in part due to breakthroughs in materials, such as more flexible fire tubes in heat exchangers which reduces the stress on boiler systems[73].

Feedstock Processes

As well as thermal combustion, natural gas is used in the industrial sector as a feedstock in petrochemical applications. This is mainly in the production of methanol and ammonia through steam reforming, as well as chemical conversion to ethylene. In these applications, incremental enhancements to process efficiencies and capex requirements have made gas more competitive, though such improvements have now largely leveled off. However, new technologies are emerging that use new, more efficient chemical processes[74]. These technologies have the potential to improve the relative costs of gas in petrochemical applications, leading to more widespread adoption.

Industrial efficiency

Efficiency improvements in the consumption of natural gas help to enable fuel switching by lowering the relative cost of gas to other fuels, but they are also critical drivers of GHG emissions reduction in their own right. Three categories of gas technology innovations in particular are enabling material improvements in the efficiency of natural gas use: greater use of waste heat in industrial applications, the application of digital tools to improve the efficiency of industrial processes, and industrial process redesign to reduce emissions intensity.

72 US EIA, 2019 Energy Outlook.
73 Facility Executive Magazine, “Breakthroughs in boiler technology”, 2019.
74 In ethylene production, this includes catalytic oxydehydrogenation, or oxidative coupling of methane, which aims to reduce the number of steps in petrochemical processes and thereby make the use of energy and catalysts more efficient. In methanol production, single-step methods are being developed that reduce energy input requirements (US DOE Industrial Technologies Program).

Waste heat from natural gas combustion has long been used to boost overall system efficiency through the use of combined heat and power (CHP) applications. CHP systems enable the utilization waste heat for power generation (topping cycle) or channel surplus heat from power generation to other industrial applications (bottoming cycle). Of the two approaches, topping cycle applications are most common and have demonstrated the ability to boost energy efficiency by more than 30%[75]. While CHP systems have been widely adopted in large scale industrial applications, adoption has been limited in smaller scale applications below 5MW. Recent innovations in CHP have largely focused in these applications, prioritizing system redesign and integration steps that enable easier adoption of CHP in small scale systems[76].

Innovation is also enabling new forms of energy efficiency in heat recovery. Technologies are improving the quality of recovered heat, providing industrial customers with more options and greater value from the use of recovered heat. Improvements have occurred in the use, transport, and storage of waste heat, for example:

- Waste heat is being used for air preheating, which increases the thermal efficiency of combustion in industrial boilers by up to 40%[77].
- Heat exchangers or heat pumps are upgrading waste heat from below 200° Celsius to make it more useable in industrial processes, boosting fuel savings by between 5% and 10%[78].
- Heat is being stored using water- or steam-based technologies - although new possibilities are emerging that use rock and molten salt. Solid materials can be heated to very high temperatures and so store more heat.

A second area where innovation is improving the efficiency of industrial processes is in the application of digital tools to improve energy system performance. The use of remote sensing, data analytics, artificial intelligence, and greater automation can all help to identify inefficiencies in the use of energy and optimize operations. When combined, these new digital technologies and methods can help to achieve a further improvement of 10% or more in the overall energy efficiency of operations[79].

While the benefits of digital technologies are compelling, their implementation can be slow, due to operational and organizational barriers within companies. New business models are beginning to emerge, however, to address these challenges. For example, new integrated energy management service providers can quickly deploy new technologies and support organizations with analytical capabilities. Energy service companies (ESCOs) are also increasingly used in industrial contexts to finance and install new equipment that improves energy efficiency, thereby reducing the financial and organizational burden for their industrial customers.

A third area of innovation is in the redesign of industrial processes to improve the efficiency of energy use, as well as to reduce GHG emissions. In some cases, these new processes can facilitate fuel switching to natural gas to obtain greater efficiency and lower emissions. Direct reduced iron (DRI) is one example. This process employs a chemical reaction to remove oxygen from iron ore, producing iron. DRI depends upon a reducing gas comprised of hydrogen and carbon monoxide (which is most commonly produced using natural gas). DRI can reduce CO_2 emissions by 30% compared with the traditional method of iron production that uses a blast furnace and coal[80]. Global gas-based DRI production has grown by 30% since 2015 and is concentrated in regions with low natural gas production costs[81].

75 US DOE, "Energy savings potential and R&D opportunities", 2017.
76 Distributed Energy Magazine, "CHP: Innovations and applications", 2019.
77 US DOE, "Quadrennial Technology Review", 2015.
78 Ibid.
79 BCG project experience.
80 Midrex, "World direct reduction statistics", 2018.
81 World Steel Association, Steel statistics database, 2019.

In the future, DRI production may become more widespread as a result of more extensive carbon pricing or other climate policies (see Exhibit 17).

To increase the adoption of energy-efficient technologies in industrial processes, governments can deploy a range of policies, from market-based measures that put a price on carbon to direct mandates of efficiency standards.

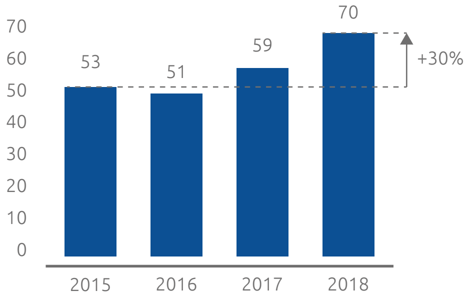
So far, direct mandates have been shown to be most effective. China has achieved the greatest energy efficiency improvement in its economy, reducing energy intensity per unit of GDP by 18% from 2005 to 2015[82]. This was largely achieved through policy measures tailored to specific applications, mandating efficiency levels and shutting down inefficient plants. Energy efficiency mandates have also proved effective in other countries, including Japan and India[83].

Exhibit 17 - DIRECT REDUCED IRON: GLOBAL PRODUCTION HAS INCREASED AS A RESULT OF LOW GAS PRICES, BUT CARBON PRICING MAY BE A DRIVER GOING FORWARD

Impact: DRI production is up 30% globally since 2015, reducing GHG intensity of iron and steel

Global DRI production has grown by nearly 30% over last three years

Global direct reduced iron production 2011-2018 (Mt)



DRI lowers CO_2 emissions and energy intensity of ironmaking

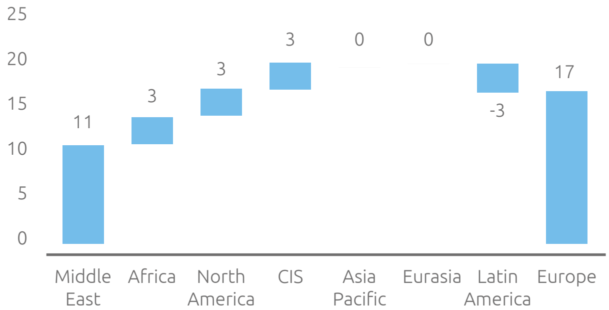
Natural gas DRI lowers CO_2 emissions by 66% relative to standard blast furnace ironmaking.

DRI lowers the energy intensity of ironmaking by using a chemical process, while the conventional method involves melting iron ore.

Drivers & lessons: growth concentration in markets with low gas prices

DRI production growth is centered in regions with access to cheap gas

Regional growth in DRI production 2015-2018 (Mt)



Climate policy can drive greater DRI adoption

Iron & steel make up ~7% of global energy related GHG emissions.

The DRI-EAF route is widely seen as the most viable way to significantly reduce the carbon intensity of the iron and steel industry.

Note: DRI can be coal based or natural gas based – around 90% of global DRI is natural gas based; analysis excludes Indian DRI as most coal based DRI is produced in India.
Sources: World Steel Association, Midrex, ETC, BCG analysis.

82 IFRI, "The Power of China's Energy Efficiency Policies", 2018.
83 IEA, "Energy Efficiency 2018".

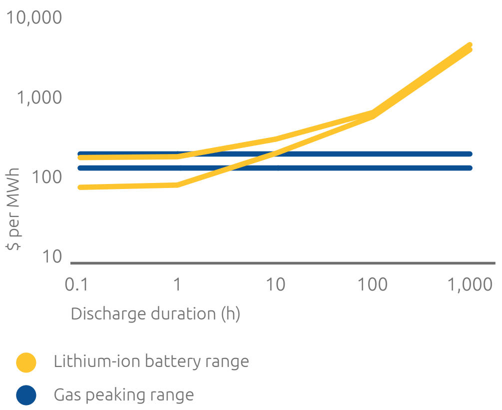
Enabling renewable power

As variable renewable generating capacity grows, natural gas is likely to play an increasing role in managing grid-level intermittency. The evidence to date suggests that developed power grids can integrate an average of up to 40% of renewable power generation through existing reserve capacity, demand management, and grid network interconnections[84]. Beyond that, maintaining reliability would require some form of electricity storage or sufficient balancing capacity. Specific capacity requirements vary depending upon the scale and structure of intermittency, the demand profile, and particular characteristics[85] of a given grid. In aggregate, however, global peaking capacity requirements are expected to double or even quadruple by 2040, given the expected growth of renewable generation[86]. Natural gas provides the lowest-cost, low-emitting source of flexible generation for long durations, hence can play an important role in meeting the demand for future grid capacity requirements. Lithium ion (Li-ion) batteries are a potentially cost-effective solution for short-duration storage. Levelized costs of battery storage have declined and it is nearly competitive with gas peaking in some contexts[87]. However, as the duration of peaking requirements increases, meeting intermittency requirements solely through using battery technology becomes more expensive, and often impossible. The rapid pace of battery discharge results in a tipping point at about four hours, beyond which incremental capacity is required[88]. Thus, for longer-duration peaking requirements, the levelized cost of battery storage becomes exponentially more expensive because greater capacity must be added even as the number of peaking opportunities for recouping capital investment declines. By contrast, a gas plant can continue to operate with its existing capacity for any length of time.

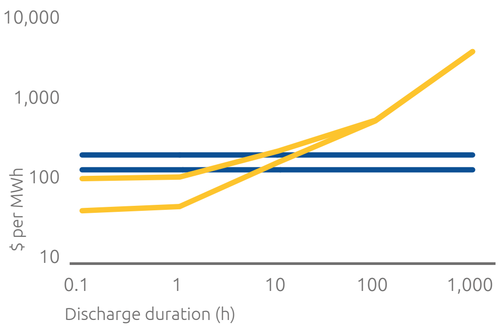
Economic modeling of peaking options indicates that, even with sustained improvements in Li-ion battery costs, gas is likely to remain the lowest levelized cost option for managing intermittency beyond the four- to eight-hour range[89] (see Exhibit 18). Studies of US Regional Transmission Organization markets have indicated that up to 60% of peaking events last less than four hours. However, those same studies show that longer-duration peaking requirements that involve greater renewables intermittency will grow[90]. Thus, the costs of managing intermittency for more than four hours will become increasingly important. In a study of California's power needs, for example, the average production costs of power would rise from about $50/MWh today to more than $400/MWh at 80% renewables plus battery penetration and more than $1,600/MWh at 100% renewables plus battery penetration[91].

Exhibit 18 - NATURAL GAS LIKELY TO REMAIN COMPETITIVE VS. BATTERY STORAGE FOR LONG DURATION PEAKING

Today: levelized cost of storage as a function of discharge duration



2040: projected levelized cost of storage as a function of discharge duration



Source: IEA, Lazard, BCG analysis.

84 BCG analysis of US and European power grids including California, Hawaii, and Denmark
85 Including size, age, interconnections, types and distribution of customers, among others.
86 IEA, 2019 World Energy Outlook; Bloomberg New Energy Finance, 2019 New Energy Outlook.
87 Lazard, "Levelized cost of energy and levelized cost of storage", 2019; Note: based on comparison of new capacity additions.
88 Multiple studies have identified this effect, including Schmidt et al, "Projecting the future levelized cost of energy storage technologies", Joule, 2019; IEA, "The Future of Hydrogen", 2019.
89 BCG analysis.
90 NREL, "Timescales of energy storage needed for reducing renewable energy curtailment", 2017; GTM, "How big is the peak capacity market for batteries?", 2018.
91 Clean Air Task Force, "Where nuclear energy fits into the clean energy future", 2019.

Open-cycle gas turbines are traditionally used to provide gas peaking capacity. Although less efficient than CCGT plants, they are faster to ramp up, smaller, easier to operate, and have lower capital costs. While the technology is an established one, there has been significant innovation to improve operational performance and reduce capital costs.

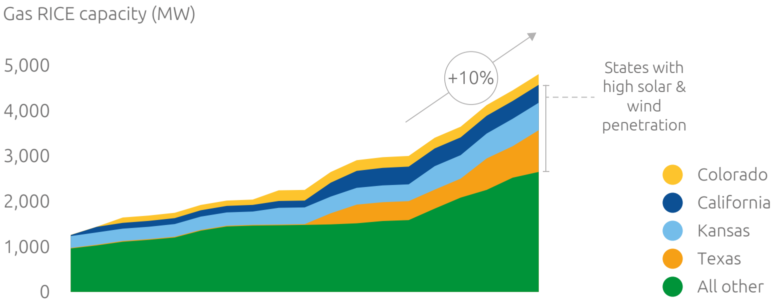
Two prominent gas turbine technologies are typically used for gas peaking: frame gas turbines and aeroderivative gas turbines. Advances in aeroderivative turbine technology over the past two decades have increased combustion efficiency by 10% to 15%, compared with frame turbines, while reducing start times to less than 10 minutes. In response to aeroderivative turbines' growing competitiveness, frame turbine technologies have improved over the past decade and now match their start times of less than 10 minutes. In addition, capital costs per KW have fallen by 10% or more[92]. Today, frame turbines have a lower thermal efficiency than aeroturbines, but they are comparable in their flexibility while the capital cost of a frame turbine is about 30% less.

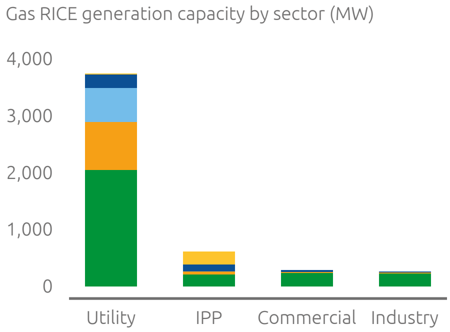
Meanwhile, gas reciprocating internal combustion (RICE) engines are emerging as an alternative way that gas technologies can help manage the intermittency of renewables. While RICE technology is also well-established, it offers several new benefits in dealing with greater demand for peaking capacity: the engines can achieve full output in less than five minutes and operate at a capacity load as low as 25%[93]. Natural gas RICE engines are also relatively small, with an average installation size of 4MW, which reduces the cost of adding capacity and also makes them more modular63. A frame gas turbine installation is typically at least 50MW and can require $60 million or more in capex, while a RICE installation of 4MW only requires $6 million of capex[94]. As a result, RICE technology is the fastest-growing source of peaking capacity in the US, averaging over 350MW of capacity additions per year over the past three years[95]. The growth of RICE capacity is being driven largely by utilities in Texas, Kansas, California, and Colorado, all states with rapidly growing renewables capacity (see Exhibit 19).

Exhibit 19 - US PEAKING: GAS RECIPROCATING ENGINE TECHNOLOGY DEPLOYED TO SUPPORT GROWING INTERMITTENT RENEWABLES

Impact: growth of utility gas RICE deployment in states with high intermittent renewables penetration

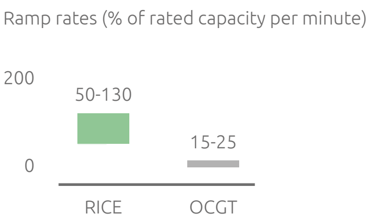
Increased gas RICE capacity since 2000



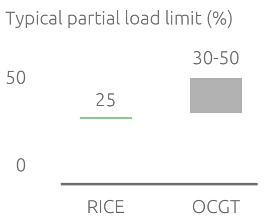


Drivers & lessons: existing Gas RICE technology offers a more flexible option for gas peaking

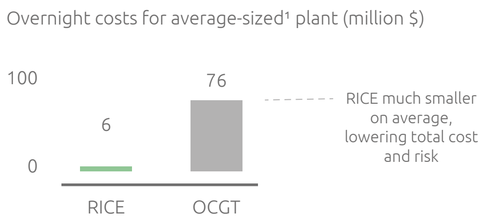
Higher ramp rate



Lower partial load limit



Lower average capital costs



1. Calculated as the average size of each plant type as reported by the EIA.
Source: EIA, EPRI, Power Magazine, BCG analysis.

92 Power Engineering Magazine, "Frame vs. Aero", 2017.
93 Power Magazine, "Turbines vs. reciprocating engines", 2016.
94 Ibid.
95 EIA, "Monthly electric generator inventory", 2019.

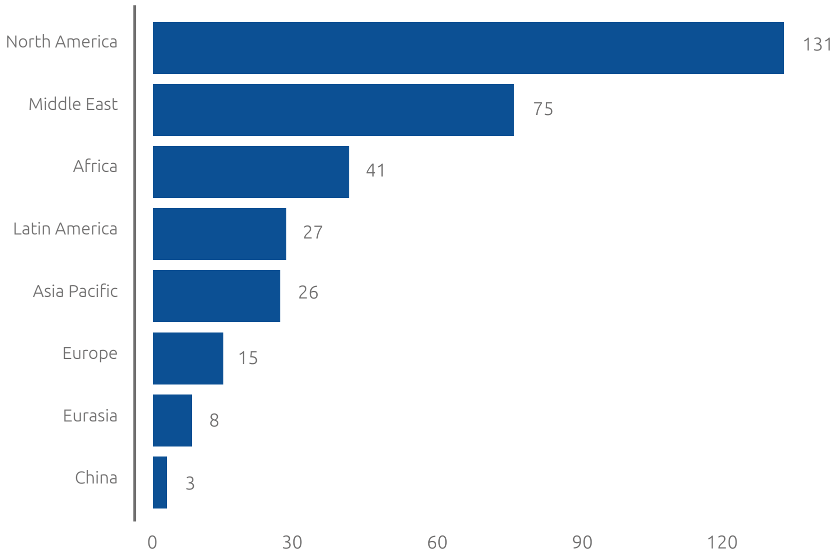
To date, dedicated gas turbine capacity has mainly been developed in North America and, to a lesser extent, the Middle East and North Africa[96] (see Exhibit 20). To ensure sufficient peaking capacity to manage intermittent renewables, a step change is required in investment across Europe and Asia. In sum, an estimated $15 billion to $25 billion of investment per year will be required to develop sufficient peaking capacity to support renewables development in line with the IEA's Sustainable Development Scenario[97].

In order to enable the needed level of investment and achieve the necessary scale of peaking capacity development, government policies are critical to ensure the full value of the capacity is reflected in the market. In regulated markets, policies specifying capacity requirements and incentivizing gas adoption will be essential. In deregulated or unbundled markets, capacity payments are helpful to ensure availability. Dedicated policies for the peaking market are required, though, as wholesale power markets on their own may not be effective in incentivizing capacity development up front.

Exhibit 20 - OPEN CYCLE GAS TURBINE CAPACITY IS CONCENTRATED IN NORTH AMERICA & MIDDLE EAST

Gas turbine capacity is concentrated in North America

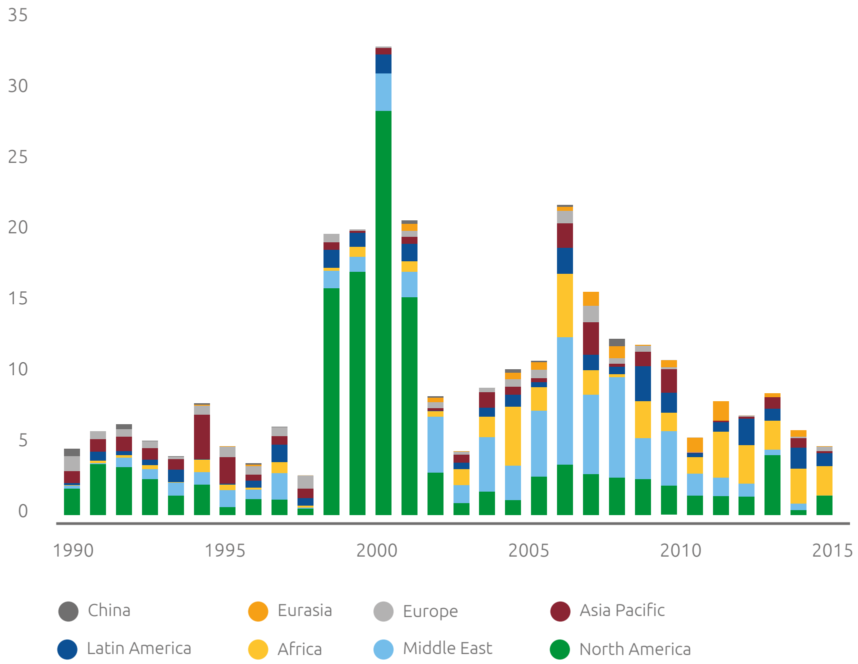
Open cycle gas turbine sales to power producers & utilities 1988-2017 (GW)



Source: McCoy Power Reports, BCG analysis.

Growth in gas turbine capacity is slowing

Open cycle gas turbine sales to power producers & utilities (GW)



96 McCoy Power Reports, power gen equipment data sets, 2019.
97 BCG analysis based on IEA 2018 World Energy Outlook.

Road transport

The use of natural gas as a transport fuel offers significant opportunities to reduce localized air pollutants and reduces GHG emissions. Relative to diesel engines, natural gas emits one sixth of the nitrogen oxide and zero particulates (two key contributors to urban air pollution). Natural gas in transport can be either compressed natural gas (CNG) or liquefied natural gas (LNG). CNG transport fuel technology has been established for some time. The supply is relatively straightforward, as it only requires the compression of natural gas at the point of refueling. The use of LNG as fuel in the transportation sector has emerged more recently, growing in popularity with greater production and availability of supply.

Advances in the design and deployment of natural gas engine technology have been a key enabler for facilitating more widespread gas adoption in the transport sector. While CNG engines for light duty vehicles have been available for some time, a concerted push by the US Department of Energy from the 1990s onward supported the development of more sophisticated heavy-duty natural gas engines, which are the industry standard today[98].

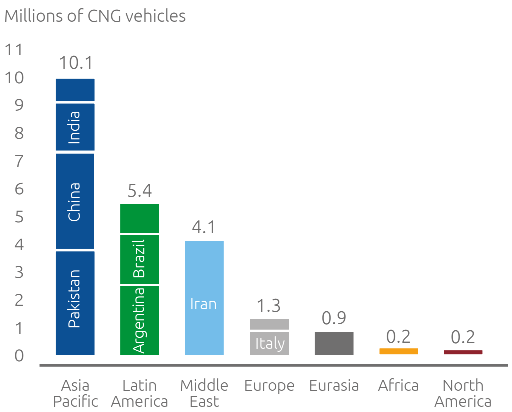
Recent innovations have focused on improving vehicle fuel efficiency and further reducing pollutants. For example, new natural gas engine models have employed a combination of exhaust gas recirculation and new control modules to improve torque output and fuel efficiency, while further reducing NOx emissions[99].

Natural gas use in transport is concentrated in a small number of geographies today (see Exhibit 21). Of about 22 million CNG vehicles globally, around 18 million operate in just seven countries[100]. LNG vehicles are even more concentrated, with nearly all 300,000 of them in China[101]. This highlights two essential enablers for the adoption of natural gas vehicles: cost of gas and/or supportive government policies.

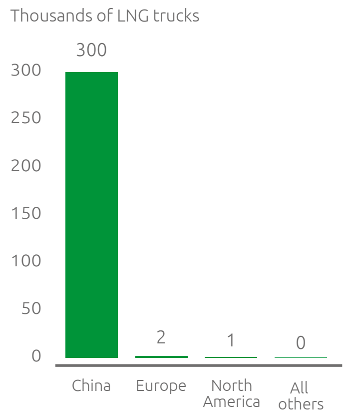
Natural gas-powered vehicles typically have an economic advantage over vehicles fueled with gasoline or diesel, because natural gas costs less than half the price of oil in most markets. However, the upfront costs of natural gas vehicles are higher than those of diesel-powered heavy-duty vehicles or cars that run on gasoline. Retrofitting vehicles with natural gas engines and storage tanks (for CNG or LNG) adds upfront materials and labour costs. These costs can be offset through heavy vehicle use, however. The more a vehicle is used, the more the initial costs will be recovered through fuel savings, especially for the heavy duty vehicles as they consume a greater amount of fuel (due to low fuel efficiency and because they are generally fleet vehicles that operate for a larger proportion of the time).

Exhibit 21 - NATURAL GAS VEHICLE ADOPTION CONCENTRATED IN A SMALL NUMBER OF COUNTRIES

CNG vehicles used in a few specific markets



LNG vehicle market dominated by China



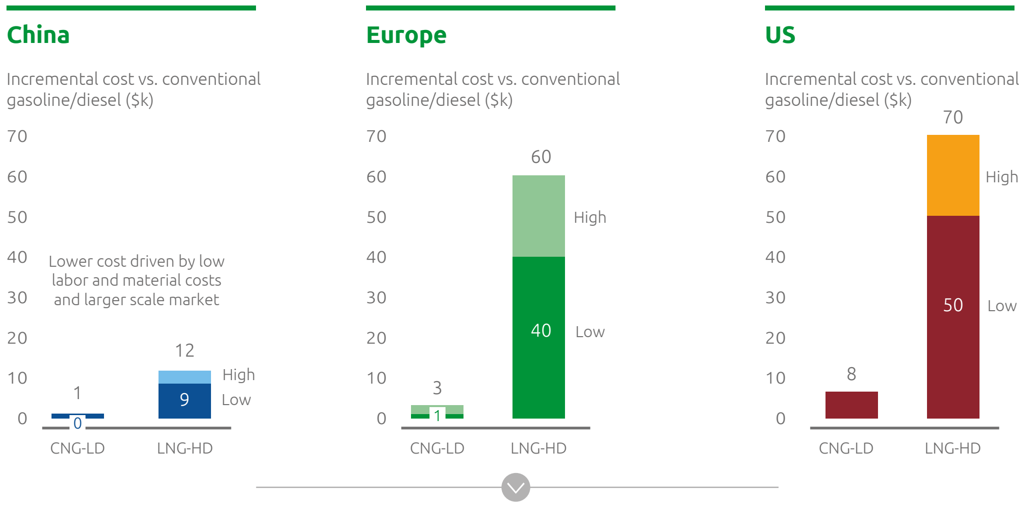
Source: NGV Journal, S&P Global Platts, EIA, press reports, BCG analysis.

98 NREL, "Natural gas engine and vehicle research & development", 2003.
99 Cummins Westport, "Natural gas engines", 2018.
100 NGV Journal, 'Worldwide NGV statistics", 2019.
101 Kallanish Energy, "Chinese LNG market set to grow", 2019; BCG analysis.

The cost structure of natural gas vehicles – both the cost of the gas and upfront costs - varies significantly by geography (see Exhibit 22). In China for example, the incremental cost of an LNG truck versus a conventional diesel truck is around $12,000, whereas in Europe the incremental cost is $60,000 to $70,000[102]. This is due to lower materials and labour costs in China, as well as industry scale effects. Chinese government policy has promoted the development of CNG and LNG in transport, resulting in a large market for supply equipment and conversions. This, in turn, has reduced vehicle unit costs.

Among those countries with high adoption rates of natural gas in transport, enabling policies have been essential for market growth. Several policy mechanisms are available to facilitate the adoption of natural gas vehicles, and the specific policy mix depends on the local context. In China, the rapid growth of the market was achieved through a combination of national and regional targets and offsets for fuel price (which pegged the cost of natural gas to a diesel equivalent). This approach has also been used in India, along with policies supporting the development of refueling infrastructure[103].

Exhibit 22 - INCREMENTAL COST OF CNG & LNG VEHICLES IS HIGHLY VARIABLE BY REGION



Cost differences driven local cost environment plus market scale

Source: International Energy Agency, NGVA Europe, NGV Communications Group, external research, "Natural gas as a vehicle fuel in China: A review", BCG analysis.

102 Hao et al., "Natural gas vehicle fuel in China: A review", 2016; NGV Europe.
103 CSIS, "Pathways for developing a natural gas vehicle market", 2019.

In Europe, a public-private partnership initiated in 2014 combined several policy mechanisms in one program, in a bid to kick-start LNG adoption in long-haul trucking (see Exhibit 23). The Blue Corridors program combined funding from the European Union and the private sector, including OEMs, fuel retailers, and truckers. It aimed to simultaneously develop new refueling infrastructure, sponsor adoption of LNG vehicles, and also undertake further R&D on natural gas engines. The intention was to overcome the typical "chicken and egg" problem relating to weak investment in vehicles and limited refueling infrastructure. While the size of the program itself was relatively small, it still helped to facilitate strong market growth and increased the number of refueling stations and vehicles by five to six times between 2014 and 2018[104].

A key question in the transport sector applications is how natural gas vehicles will compete with electric vehicles in the future. Heavy duty vehicle segments show the greatest promise for natural gas, given that the weight requirements for batteries appear to impair the efficiency of electric technologies more significantly in that segment. In light duty segments though, electric vehicles are more likely to be competitive given their total cost of ownership is already widely projected fall below that for gasoline vehicles in several markets by the mid-2020s[105].

Exhibit 23 - EU LNG TRUCKING: BLUE CORRIDORS PROGRAM FOSTERED PRIVATE INVESTMENT IN INFRASTRUCTURE AND VEHICLE TECHNOLOGY

Impact: Blue Corridors Program enabled infrastructure growth and technology development

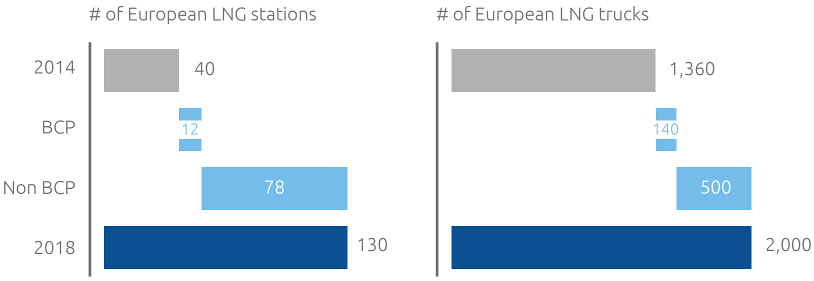
Funded modest deployment and research program over five years

Sponsored fleet of 140 LNG trucks

Opened 12 new LNG stations along four blue corridors

Financed research on engine optimization and development of engines in compliance with new Euro VI emission standards

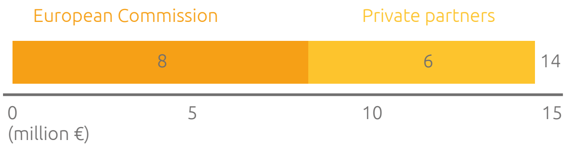
Program coincided with broader deployment of LNG stations and trucks



Source: Press reports, Erdgas Mobil, BCG analysis.

Drivers & lessons: public private partnership model used to overcome infrastructure barrier

European Commission provided a little over half the program funds



PPP model provided incentive for companies to invest & collaborate

Lack of infrastructure is key obstacle to LNG vehicle adoption
- Government funding reduced risk of investment.
- Participants picked strategic locations for new stations.

Design of program fostered collaboration among partners along LNG vehicle value chain
- Participants included OEMs, fuel retailers, & truckers.
- Members coordinated research and data sharing.

104 BCG market research and analysis.
105 BCG, "The electric car tipping point", 2018.

LNG bunkering

LNG use in marine bunkering is an even newer application for natural gas in transport (see Exhibit 24). Starting as a niche technology in the LNG shipping industry, which used boil-off gas[106] as a source of fuel, LNG propulsion systems are now available across different classes of vessel. Innovations in several areas have been essential in making LNG viable across marine applications. First, the power output of LNG engines has improved by 25% or more in new models, improving fuel efficiency and reducing space requirements onboard ships[107]. Second, the development of cryogenic hoses has enabled more flexible transfer between ships and from trucks.

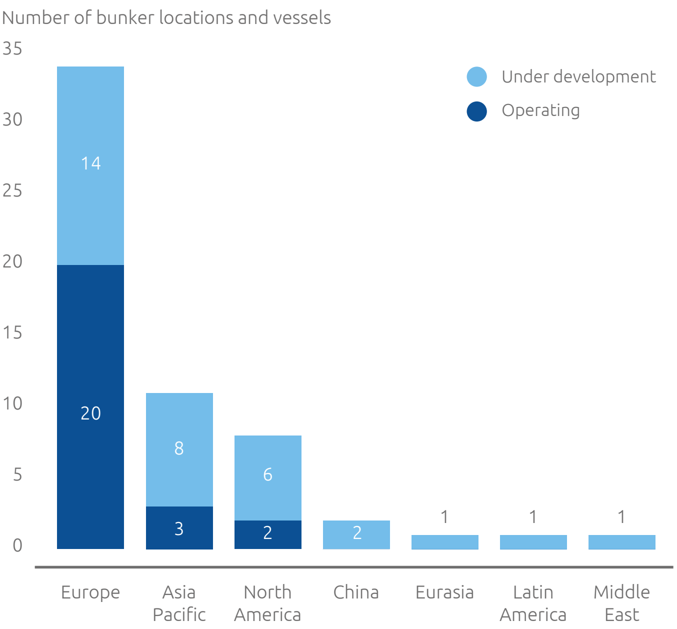
Third, the development of membrane tanks for LNG shipping is now being applied to bunkering, with the potential to reduce the space requirements of LNG storage by up to 60%[108].

Improving air quality is a key rationale for LNG bunkering. The new International Maritime Organization rules on marine fuel, which have limited the allowable sulphur content to below 0.5% from 2020, put a spotlight on LNG marine fuel applications. LNG easily meets the new standard and does not require any additional fuel treatment. However, LNG bunkering is just one of multiple ways of complying with the sulphur limit, and the costs are similar to those of adopting fuel scrubbers in most vessel classes[109].

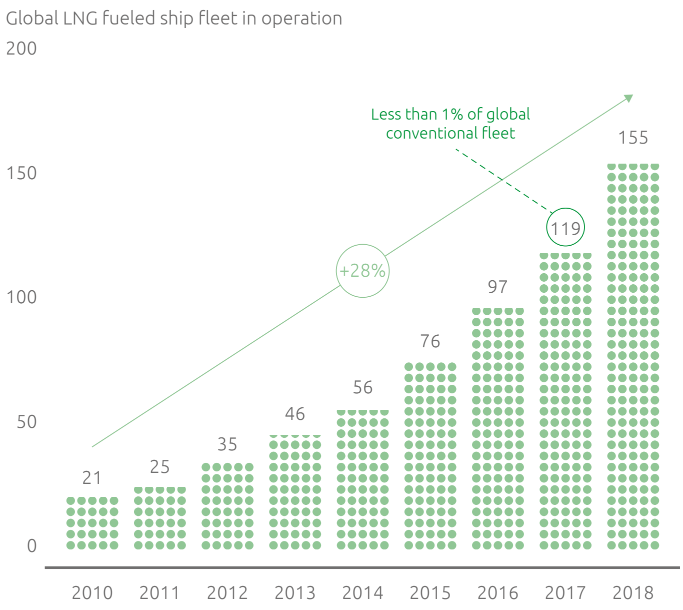
A greater potential differentiator for LNG bunkering, versus other technologies is the low NOx emissions and GHG intensity, which oil-based technology options cannot match. Therefore, policies that promote low NOx and GHG emissions are likely to spur demand for LNG bunkering. The most viable segments for adoption of LNG bunkering are in ports that are customer-facing, including ferries, cruise ships, and service ships. Pollution is also a bigger concern in these locations because they tend to be in close proximity to urban areas.

Exhibit 24 - LNG BUNKERING IS A NEW AND GROWING MARKET

Access to LNG bunker fuel concentrated in Europe, growing globally



The global LNG fleet is small, though growing



Source: SEA/LNG, DNV GL, IEA, UNCTAD, BCG analysis.

106 Natural evaporation of LNG, transforming it from a liquid state to gas.
107 Wärtsilä, "LNG propulsion achieves next step in technologicl revolution", 2014.
108 MarineLog, "Membrane fuel tanks may make LNG viable for more ships," 2018.
109 This assessment does not incorporate the cost associated with disposal of removed pollutant, which are required in an increasing number of ports and national governments are regulating.

Norway is a good example of how policies specifically promoting low NOx emissions can enable LNG vessel adoption. In 2007, Norway implemented a NOx tax of 22 NOK/kg of NOx emissions, while also developing a voluntary fund and compliance program. In lieu of the tax, marine vessel operators could contribute 9 NOK/kg to the voluntary fund if they adopted an emissions abatement plan. The proceeds of the fund were then redistributed among contributors to support the adoption of emissions reduction measures, including the use of LNG-fueled vessels[110]. As a result of this policy, Norway has become the largest LNG marine bunkering market, with more than 40% of all LNG vessels globally[111] (see Exhibit 25).

While LNG bunkering has significant growth potential, due to the availability of technologies and increasing adoption of clean air policies worldwide, the market is still nascent today. LNG-fueled vessels comprise less than 1% of the global marine fleet. Because of the more than 20-year lifespan of most ships, it will take some time for the fleet to change over[112].

To accelerate LNG market growth, targeted support for infrastructure and the adoption of LNG vessels can be key enablers. This includes measures to reduce the upfront cost of LNG vessels relative to conventional vessels, as well as support for LNG bunkering.

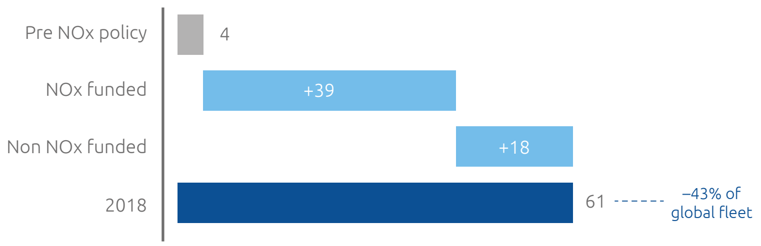
Other technologies are emerging with the potential to compete with, or potentially complement, LNG in bunkering. Electrification of bunkeringis one possibility, although, given the current limitations due to high upfront costs and battery weight, this option is unlikely to be viable outside short-duration ferry services[113]. Hydrogen, as well as de-carbonized methanol and ammonia, could completely eliminate GHG emissions from bunkering. However, all three options are typically more than double the cost of LNG bunkering today[114]. In the event that technology improvements drive down these costs, some components of natural gas systems could become viable, although the scale and cost reductions required are not yet fully clear[115]. As a result, LNG remains the most cost-competitive option for reducing the full range of localized pollutants and GHG emissions, while also providing a potential pathway for zero-carbon fuels in the long-term.

Exhibit 25 - NORWAY LNG BUNKERING: NO$_X$ FUND FACILITATED DEVELOPMENT OF NORWAY AS A WORLD LEADER IN LNG BUNKERING

Impact: Norway hosts ~43% of the world's LNG fueled ship fleet and has built large refueling infrastructure

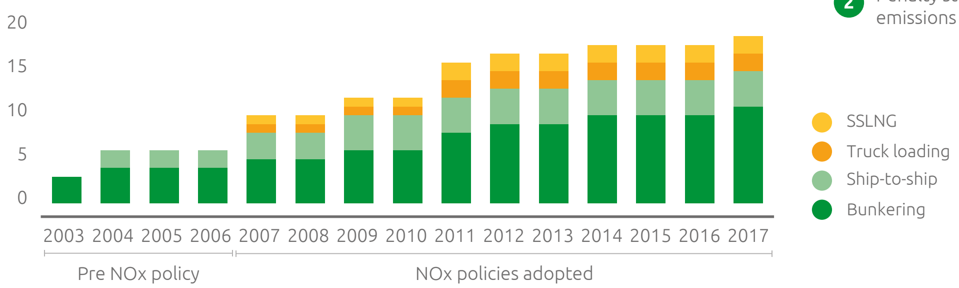
Largest LNG fueled vessel fleet in the world

Norwegian LNG fueled ship fleet



Broader investment in infrastructure followed policy adoption

# of Norwegian marine LNG refueling facilities by type

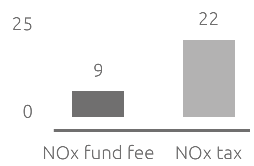


Source: OIES, EDF, BCG analysis.

Drivers & lessons: well-designed local pollution policy can foster strong LNG bunkering adoption

Policy encourages operators to participate and comply with program

NOK per kg of NOx



- Fund fee much lower than tax.
- Members must develop long-term abatement plan to join fund.
- Fees used to support emissions reductions measures.
- Penalties levied if fund member fails to meet commitment.

Lower fee and penalty system are key to NOx fund's success

1. Large difference between fund fee and NOx creates strong incentive to join fund
2. Penalty structure encourages fund participants to meet emissions abatement commitments

110 EDF, "The Norwegian NOx Fund", 2019.
111 BCG analysis and DNV GL data.
112 UNCTAD, "Decarbonizing maritime transport", 2020.
113 DVN GL, "Comparison of alternative marine fuels", 2019.
114 Ibid.
115 Lloyd's Register, "Zero-emissions vessels: Transition pathways", 2019.

Chapter 3

Action on climate change – deployment of low-carbon gas technologies

Highlights

- Low-carbon gas technologies – including renewable gas, hydrogen, and CCUS – all have the potential to substantially reduce the GHG emissions of existing natural gas systems as well as the overall energy system, and can even achieve net negative emissions when bio-energy is paired with CCUS.
- Deployment of these technologies is limited today, but low-carbon gas technologies show substantial potential to reduce GHG emissions going forward (up to 5GT by 2040) given their competitiveness vs. alternative electricity-based technologies.
- Renewable gas has the potential to be a highly flexible for reducing emissions in existing natural gas networks. However, production will need to be scaled up significantly from a negligible global amount today to realize potential scale and learning effects.
- Hydrogen holds great promise, with its zero-carbon combustion profile, and parts of the value chains are already established[116], but low-carbon technologies – including electrolysis, gas reforming with CCUS, and methane cracking – must be further developed and deployed at scale to achieve full potential emissions impacts.
- Carbon capture and storage (CCS) + utilization (CCUS) technologies are going to be critical for the attainment of global emissions reductions goals. While CCS and CCUS capacity has been slow to develop in the past, new enabling policies are set to support near-term growth, particularly in the US, Europe, and China. Technology innovation combined with deployment at scale shows significant potential to reduce costs of carbon capture by 50% or more.

116 I.e. feedstock and parts of the energy system use, such as transport in certain regions.

Introduction

In addition to the value of gas technologies in enabling fuel switching from higher GHG intensity fuels, improving the efficiency, and facilitating the adoption of renewable and distributed power generation, technologies also exist that can substantially reduce the emissions from natural gas in its own right. These low carbon gas technologies include renewable gas, hydrogen, and CCUS, each of which have varying applications across sectors and gas infrastructure.

Among these three technologies, renewable gas (RG)[117] is potentially the most versatile. RG resembles natural gas in terms of its chemistry, but is not a fossil fuel and as such has a low level of GHG emissions[118]. It is produced through the capture of methane released from the breakdown and refinement of organic material, or through a thermal gasification process using solid biomass. It can be utilized in existing natural gas infrastructure to reduce GHG intensity of natural gas at the endpoint of combustion. There are no constraints on blending or combustion, and thus it is a direct substitute across a natural gas supply chain.

Hydrogen can also be blended with natural gas and transported in natural gas infrastructure, but only up to certain concentrations before it requires upgrades in infrastructure and/or gas combustion appliances. For higher concentrations, repurposed or new infrastructure for the transport and use of hydrogen are necessary. Hydrogen can also be used directly as a fuel in many sectors, including industry, transport, buildings, and power.

CCUS provides a separate and distinct pathway for reducing the emissions intensity of gas. But it also complements other technologies and resources. On its own, CCUS can be used across the power and industrial sectors with large stationary emission sources. It also acts as a complementary technology with the production of hydrogen from natural gas when used in combination with steam methane reforming. And CCUS can be used in conjunction with renewable gas production, achieving net negative emissions in some instances.

Significant innovation is taking place across all three technologies (see Exhibit 26). Fundamental research is contributing to the development of entirely new technological applications and is improving the efficiency of key processes by up to 50%. Innovations, such as oxy-fuel combustion processes, show the potential to fundamentally transform the overall cost structure of technologies like CCUS. In parallel, scale and learning effects could halve the cost of key technologies in the coming decades.

These technologies could potentially reduce global GHG emissions by up to 5GT in total by 2040 under their full economic potential[119]. CCUS is likely to play the greatest role (up to 4GT) in the near term, given its compatibility with existing energy infrastructure and competitiveness in sectors with limited or high-cost alternatives for reducing operational emissions intensity.

117 Defined as methane produced from renewable sources including biomass, agriculture, or waste products. This can include the use of biogas which includes impurities, or through upgrading to biomethane in which methane is highly concentrated and can be injected into the natural gas infrastructure.
118 Provided that it is produced and used efficiently.
119 BCG analysis based on review of future scenarios consistent with a 2° Celsius pathway as presented in the IEA World Energy Outlook 2019 Sustainable Development Scenario.

While these technologies are rapidly developing, the key challenge is to facilitate faster and more widespread adoption. Government policies and new regulatory frameworks will be necessary. Economic incentives are critical, including measures to put a price on carbon, as well as sector-specific incentives, such as tax credits and feed-in-tariffs. At the same time, lessons learned from efforts to deploy low-carbon power more widely demonstrate that additional steps—including sector-specific adoption targets and infrastructure support— are necessary to rapidly scale up these new technologies.

Exhibit 26 - LOW CARBON GAS: SUMMARY OF TECHNOLOGY TRENDS

			ILLUSTRATIVE POTENTIAL IMPROVEMENTS	
TECHNOLOGY	**RECENT TECHNOLOGY DEVELOPMENT**	**EMERGING TECHNOLOGY TRENDS**	**EFFICIENCY**	**CAPEX**
RENEWABLE GAS	• Anaerobic digestion enzyme efficiency improvements	• Production scale • Use of new, lower cost feedstocks • Biomethane upgrading efficiency • Adoption of gasification technology	Process advances (up to 40%)	Scale & learning effects (40-65%)
HYDROGEN	• Demonstration of SMR with CCUS • Cost reduction of electrolysis	• Methane cracking • Hydrogen blending and system integration cost improvements	Process advances (electrolysis) (5-10%)	Technology maturity (electrolysis) (20-50%)
CCUS	• Application of post combustion capture to new industries • Efficiency improvements in solvent based post-combustion capture	• Development of oxyfuel combustion • Membrane based post combustion capture • Development of utilization technologies	New materials & process (up to 50%)	New technology (oxy-fuel) (90%)

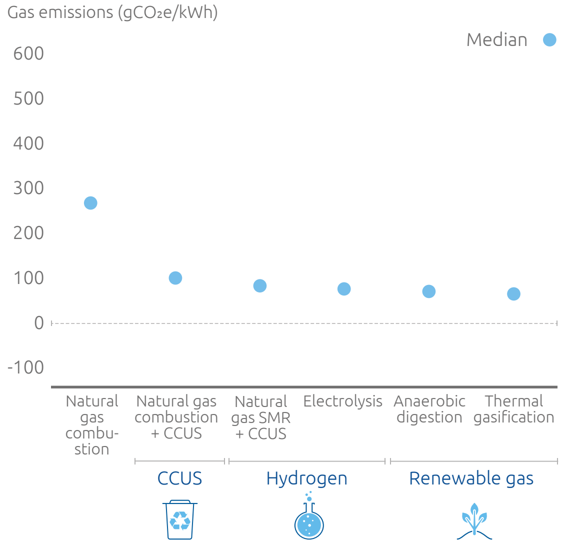
Source: Navigant, IEA, Global CCS Institute, Energia Procedia, BCG analysis.

The emissions reduction potential of low-carbon gas technologies

As low-carbon gas technologies are only at the very early scale and deployment stages, with a very small volume deployed to date, their emissions profiles vary depending on the pathway and the specific application of each technology (see Exhibit 27). As with any new to technology, deployments to date should be examined for lessons on which pathways provide the greatest reduction value. Based on high level trends seen to date, renewable gas shows the greatest range of potential net emissions reduction, relative to natural gas combustion. Fertilizer and land use practices for the production of biomass are the greatest drivers of variability of emissions intensity. However, when RG feedstock is produced using sustainable agricultural practices, limited fertilizer, and effective digestate storage, it can achieve emissions reductions of 80%[120], and in some cases even more[121] .

Exhibit 27 - LOW CARBON GAS GHG EMISSIONS INTENSITY ESTIMATES VARY BY TECHNOLOGY

Full value chain lifecycle GHG emissions by technology



Key drivers of lifecycle GHG emissions intensity

Natural gas	• Upstream and midstream emissions (inc. methane emissions) • Combustion efficiency
Natural gas combustion + CCUS	• Upstream and midstream emissions (inc. methane emissions) • Carbon capture rate and efficiency • Energy for carbon transport, storage, and utilization
Natural gas SMR + CCUS	• Upstream and midstream emissions (inc. methane emissions) • Carbon capture rate and efficiency • Energy for hydrogen compression, storage, and transport
Electrolysis	• Emissions associated with electricity source • Energy for hydrogen compression, storage, and transport
Anaerobic digestion	• Fertilizer and land use emissions from feedstock production • Digestate storage emissions • Other energy emissions from production, storage and transport
Thermal gasification	• Fertilizer and land use emissions from feedstock production • Combustion efficiency and energy source • Other energy emissions from production, storage and transport

Note: includes full value chain emissions.
Source: Imperial College London, EIA, BCG analysis.

120 Imperial College London, "A greener gas grid: what are the options?", 2017.
121 Biogas produced from wet manure can achieve emissions savings of up to 200% (Annex V of European Directive 2018/2001 of 11 december 2018 on the promotion of the use of energy from renewable sources).

Combining CCUS with RG production provides a pathway for achieving net negative emissions – effectively removing CO_2 from the atmosphere. This is because combining RG with CCUS involves two carbon sinks: the use of feedstocks that absorb carbon from the atmosphere and the direct use or sequestration of CO_2 emissions from the production of fuel or energy. The most viable route for this combination is in the conversion of biogas to biomethane. The removal of CO_2 is an essential part of the process for integrating RG into gas infrastructure, and capturing a storing the CO_2 from that process is a relatively simple step. A more nascent innovation is in the field of combining thermal gasification of biomass with CCUS. This process fits under the broader category of Bio-Energy with Carbon Capture and Storage (BECCS). Multiple studies show that BECCS can play a prominent role in global emissions reduction, with one study indicating a technical potential for negative emissions of 3.5GT by 2050 and an economic potential of 0.8GT[122].

The emissions intensity of hydrogen is driven entirely by how it is produced and transported. While hydrogen itself produces zero emissions at the point of consumption (the chemical reaction produces heat and water), CO_2 emissions can occur when fuels are converted into hydrogen. Electrolysis is potentially the lowest emissions source of hydrogen, achieving zero emissions when carried out with renewable electricity. Hydrogen produced using natural gas reforming combined with CCUS can also achieve emissions reductions of over 90% relative to conventional natural gas[123][124].

Carbon capture technologies can reduce the emissions intensity of natural gas combustion by up to 90% after accounting for the energy consumption required for the process. However, this rate is highly dependent on the specific application, and particularly how concentrated the CO_2 stream is. Upstream emissions from the production and transmission of natural gas, as well as energy required for utilization or sequestration, also need to be factored into the total GHG footprint. In sum, today CCUS has demonstrated the ability to reduce full value chain emissions by 50% to 80% depending on specific project applications[125].

Regardless of the low-carbon gas technology, ensuring there are minimal methane emissions through the supply chain is essential for ensuring the lowest emissions intensity.

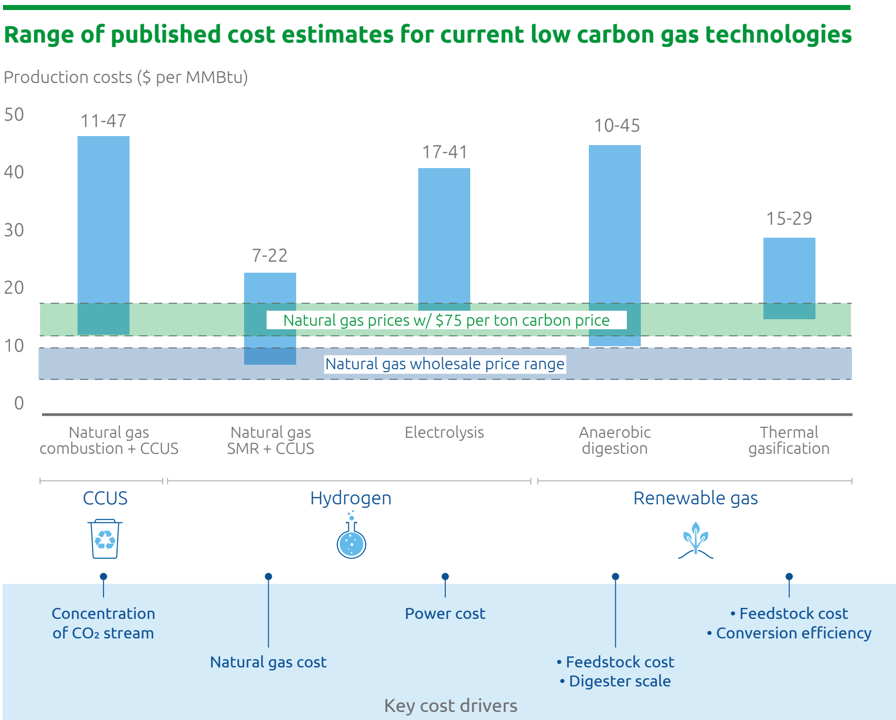
122 Koornneef et al, "Global potential for biomethane production with carbon capture, transport and storage up to 2050", Energy Procedia, 2013.
123 Imperial College London, "A greener gas grid: what are the options?", 2017.
124 Using different gas reforming technologies higher captures rates can be possible (e.g. ~95% with ATR, and higher with advanced gas reforming technologies).
125 Global CCS Institute, 2019 Global Status Report.

The economic rationale for low-carbon gas technologies

Current published estimates of the cost of low-carbon gas technologies vary widely (see Exhibit 28). Some forms of low-carbon hydrogen and RG production can compete with conventional natural gas. Others, like CCUS with natural gas combustion, have the potential to be competitive with a carbon price of $50/t or more. At the top end, however, current technology costs can be three to four times that of conventional gas[126]. As these technologies scale up and further development continues, costs are expected to come down.

Despite the relatively high current costs of low-carbon gas technologies, they are already competitive when compared with other options to achieve low or near-zero emissions. On the basis of delivered energy, low-carbon gas technologies are already cost-competitive with electricity in many instances. For example, in high heat-intensity applications, hydrogen and CCUS have been shown to be the most cost-effective means of reducing GHG intensity[127]. Meanwhile, in building applications, low-cost sources of RG production from waste are cost-competitive with electrification of heating in cold climates or commercial applications[128] (see Exhibit 29). Across sectors, low-carbon gas technologies can also be used with existing gas infrastructure, including pipelines and appliances. As a result, low-carbon gas technologies feature prominently in nearly all modeled scenarios for achieving 2° Celsius warming or less[129].

Exhibit 28: LOW CARBON GAS PRODUCTION COSTS VARY SIGNIFICANTLY BY AND WITHIN TECHNOLOGY



Source: Imperial College London, Navigant, IEA, BCG analysis.

126 BCG review of published cost estimates.
127 Columbia Center on Global Energy Policy, “Low-carbon heat solutions for heavy industry: Sources, options, and costs today”, 2019.
128 BCG levelized cost of service model.
129 Includes IPCC, IEA and industry forecasts.

In each sector of natural gas consumption, different technologies are likely to play different roles in low-carbon transition scenarios, given costs trajectories relative to other low-carbon options. Some of these roles include:

- **In the power sector**: Natural gas with CCUS is the most viable large-scale technology for baseload and peaking generation. RG is most likely to be viable in some geographies and for off-grid generation, while hydrogen, through power-to-gas technologies, can be utilized as a means for converting surplus renewable power production for long-term storage.
- **In the industrial sector**: Electrification is typically very costly, given the heat intensity and high energy consumption in industrial applications. All three low-carbon gas technologies are viable as alternatives, though their relative attractiveness varies depending on each application and geographic context. For example, in industrial applications such as ammonia production or refining (where the CO_2 concentrations of flu gas are high and thus capture costs are low) CCUS is likely to be the preferred option compared with other technologies.
- **In the buildings sector**: RG and hydrogen are already cost-competitive relative to electrification in some instances, namely in geographies with high power prices and with high heating requirements, as well as where gas infrastructure and appliances are established. However, without the appropriate delivery network infrastructure (and adapted end use technology), there is currently a barrier to making it a commercial reality.
- **In the transport sector**: RG and hydrogen are both competitive in road transport (especially in some heavy-duty applications) relative to electrification, given the ratio of energy output to incremental weight required for batteries.

While all low-carbon gas technologies and resources are technically viable today, and are economically competitive in several contexts, further innovation and scaling are required to maximize their adoption. These innovations could include steps to achieve improvements in efficiency or capital costs of existing technologies, or the development of entirely new technological processes or applications. In any case, innovation will serve to increase the potential for adoption, and thereby the potential for global GHG emissions reduction, under any future scenario.

Exhibit 29 - COSTS IN RENEWABLES, LOW CARBON GASSES, AND CCUS ARE CONCENTRATED IN DIFFERENT PARTS OF THE VALUE CHAIN

Average estimated costs on a heat basis[1] ($ per MMBtu)

		Technology	Production[2]	T&D[3]	Consumption[4]	Total
	Natural gas combustion	Multiple	3-4	4-6	1-2	$7-12
	Electrification	Wind, solar	12-15	10-18	-	$22-32
Low carbon gas	CCUS	Natural gas combustion + CCUS	3-4	4-6	4-36	$11-47
Low carbon gas	Hydrogen	Natural gas SMR + CCUS	7-22	4-6+	2-5+	$13-34+
Low carbon gas	Hydrogen	Electrolysis	17-41	4-6+	4-8+	$24-56+
Low carbon gas	Renewable gas	Anaerobic digestion	10-45	4-6	2-9	$16-60
Low carbon gas	Renewable gas	Thermal gasification	15-29	4-6	3-6	$21-42

1. Estimated costs to residential and commercial consumers in the US as an example.
2. All capital operating costs on a net present basis for the production of fuel, including power generation for electrification.
3. All costs associated with the delivery of the fuel to consumers; based on pipelines for gas technologies and grid cost.
4. Any efficiency loss at the point of consumption and the cost of CCUS where relevant; baseline assumption is 100% efficiency hence no incremental cost in the consumption step given the comparison is on a heat basis.
Source: Lazard, UT Austin, EIA, Imperial College London, CCUS estimates compiled from published academic and research papers, BCG analysis.

Renewable gas

Renewable gas is an emerging area in the production of low-carbon natural gas. Just as renewable generation integrated into a power grid provides a means of reducing the GHG emissions intensity of existing energy supply chains, so RG can enable emissions reductions through existing gas networks. While the market is small, and costs can be high at present, innovation and market developments are underway that demonstrate significant potential for production cost reductions. These should make RG even more competitive in the future.

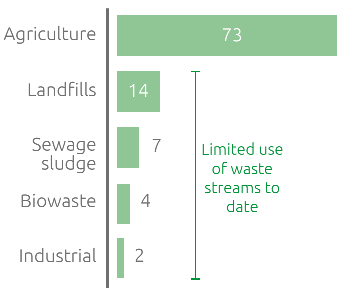
RG begins with the production of biogas through either anaerobic digestion or thermal gasification. Both processes can use a wide range of organic material as feedstock. Anaerobic digestion typically employs enzymes for biological conversion, while thermal gasification uses partial combustion of organic material. In both cases, the output is a combination of methane and CO_2, ranging from 40% to 60% methane content depending on the feedstock and process. Biogas can be used to produce heat and power or upgraded to biomethane to be integrated into natural gas infrastructure, once CO_2 and other contaminants are separated. When biogas is upgraded to biomethane with a concentration of 98% or more methane content, it can be integrated into existing gas pipelines and used in a blend with natural gas in gas combustion appliances or engines[130].

Today, global production of biogas is small (at around 670 billion cubic meters per latest estimates) and is largely concentrated in Europe, which is the location for about 60% of production[131] (see Exhibit 30). At present, most biogas is consumed in close proximity to power generation or in CHP applications. Only about 3 bcm of biomethane upgrading capacity exists globally, almost all of which is concentrated in Europe[132].

Exhibit 30 - BIOGAS PRODUCTION IS RAPIDLY GROWING, BUT LIMITED UPGRADING TO BIOMETHANE

Most biogas sourced from agriculture

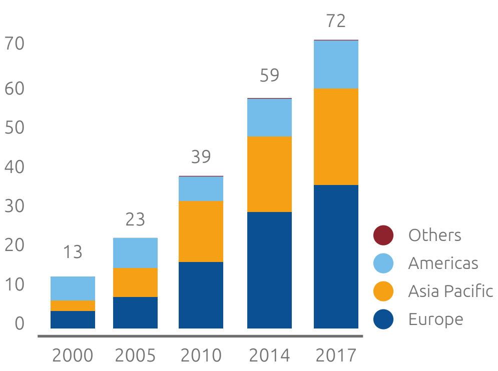
Mix of biogas sources¹ (%)



1. Estimated using production data from reporting members of IEA Bioenergy Task 37.
Source: IEA, World Bioenergy Association; Cedigaz, BCG analysis.

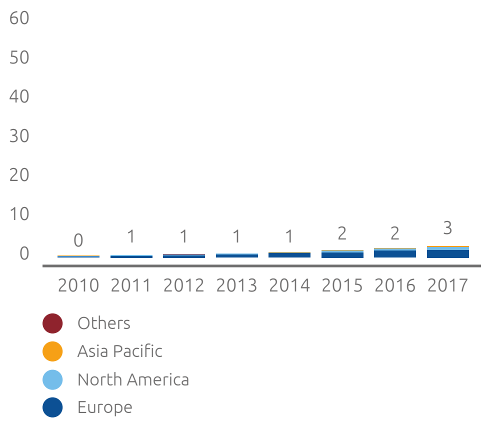
Overall biogas production is small but growing

Global biogas production (Bcm)



Only a small amount of biogas is upgraded to biomethane

Global biomethane production (Bcm)



130 Imperial College London, "A greener gas grid: what are the options?", 2017.
131 World Bioenergy Association, "Global bioenergy statistics 2018".
132 Cedigaz, "Global biomethane market", 2019.

Although biogas production is small compared with the total natural gas market, it has the potential for significant growth, based on improved cost competitiveness. Production costs vary widely depending on feedstock costs, the scale of production, and energy input costs. At the low end, biogas can be produced for less than $10 per million British thermal units (MMBtu); while at the high end, costs can exceed $35 per MMBtu[133]. Improving conversion efficiency is one way to reduce costs. In anaerobic digestion, efficiency can range from between 20% and 70% with new enzymes and the pre-treatment of biomass helping to reach the higher end of that efficiency range[134].

More widespread upgrading of biogas to biomethane is an opportunity to more rapidly scale up RG markets. While biogas is largely consumed onsite or in close proximity to power generation, biomethane is interchangeable with existing natural gas and can be integrated into existing gas networks. Currently, six different process technologies are available for biomethane conversion, all with operating costs in the range of $2.5 to $5 per MMBtu[135]. Yet all have only been deployed in limited capacity, thus there is significant potential for scale and learning effects (see Exhibit 30).

Future cost projections for gas technologies estimate that scale and learning effects could reduce the capital costs of RG production by 45% to 65%, and operational costs by 10% to 20%, by 2050[136]. Yet even if cost reductions are relatively small, RG can provide a more cost-effective means of reducing GHG emissions in buildings and industry applications than electrification in some contexts[137].

A key reason for the competitiveness of RG versus electrification is that it can be used in existing infrastructure, thus minimizing the capital investment requirements for achieving GHG emissions reductions.

To initiate the process of scaling up RG production and consumption, policy changes will play a critical role. Similar policy measures to those for renewable power have been proposed to drive adoption, including low-carbon fuel standards, renewable portfolio standards, and production incentives. So far, such policies have been most widespread and effective in scaling up markets within Europe. In Denmark for example, the use of feed-in-tariffs has enabled RG production to scale up to 10% of the national gas supply, a share that is projected to grow to 30% by 2030[138]. Meanwhile, France recently launched a comprehensive program to provide purchase price stability for the next decade, thereby incentivizing capital investment in RG production.

133 Imperial College London, "A greener gas grid: what are the options?", 2017; Navigant, "Gas for climate", 2019.
134 Mei et al, "Evaluating digestion efficiency in full-scale anaerobic digesters by identifying active microbial population through the lens of microbial activity", Scientific Reports, 2016.
135 IRENA, "Biogas for road vehicles", 2018.
136 For example, Navigant, "Gas for climate", 2019.
137 BCG LCOS analysis.
138 IEA Bioenergy, "Greening the gas grid in Denmark", 2019.

Hydrogen

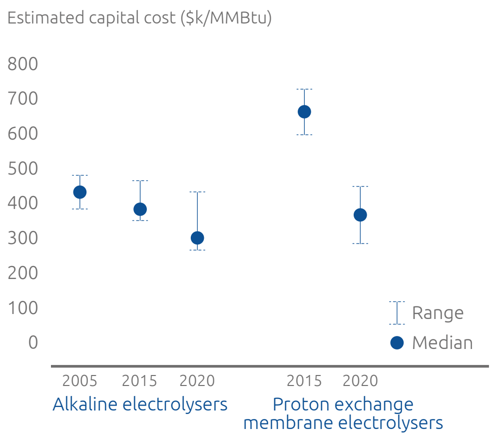
Hydrogen offers a wealth of opportunities for natural gas to achieve a new, low-carbon intensity route to market, as well as being a means for reducing the emissions intensity of energy consumption across sectors. Hydrogen is already produced at scale today with natural gas being the leading source, but largely with no emissions mitigation. Hydrogen is mainly used in industrial applications, particularly in refining and in the production of ammonia and methanol, but it has a wide range of other potential applications[139].

Two primary technologies have emerged for low-carbon hydrogen production that use natural gas supply or which are viable in gas distribution infrastructure: natural gas steam methane reforming (SMR) with CCUS, and electrolysis using renewable power generation. Gas SMR with CCUS is the lowest-cost route to low-carbon hydrogen production today, with cost estimates of $7 to $22/MMBtu[140]. Gas input costs are the most variable factor and depend on local supply costs. Carbon intensity is another key cost driver. Reducing emissions intensity by 60% incurs an average cost of about $50 per ton of CO_2, but the incremental cost of achieving a 90% reduction requires a carbon cost of $80 per ton[141].

Hydrogen produced by electrolysis is roughly double the cost of hydrogen from gas SMR plus CCUS today, but costs are declining (see Exhibit 31). From 2015 to 2020, the capital costs of two commercially viable electrolysis technologies – alkaline electrolysers and proton exchange membrane electrolysers – are projected to have declined by 22% and 42% respectively[142]. This is largely as a result of increasing scale and learning effects since both are established, mature technologies. The greatest driver of the differentiated costs of hydrogen production from electrolysis is the production economics for renewable power (namely, the relationship between capacity utilization and electricity price for renewable power). For example, high utilization of hydrogen electrolysis capacity will result in lower unit costs, but in that case the full costs of renewable capacity would typically be reflected in production economics (i.e. a project would not be using surplus power and zero cost).

Exhibit 31 - GREEN HYDROGEN: PROGRESS ON ELECTROLYSIS, BUT INTEGRATION OF HYDROGEN TO GAS GRIDS PRESENTS A CHALLENGE

Cost of electrolysis technology is falling...



Source: IRENA; Hydrogen Roadmap Europe; Schmidt, et al; Götz et al; BCG analysis.

...but integration with gas networks is a challenge

Integration pathway	Integration cost	Gas pipeline requirements	Gas appliance requirements
Hydrogen methanation (syngas)	33-200 $/MMBtu (vs. gas price of ~20 $/MMBTU)	No integration challenge	No integration challenge
Hydrogen blending with gas	Zero incremental cost	Blending of 5-15% in existing pipelines	Use of up to 20% feasible in majority of existing appliances
Pure hydrogen	Zero incremental cost	Retrofitting or replacement of existing pipelines	Complete appliance conversion required

139 IEA, “The Future of Hydrogen”, 2019.
140 Imperial College London, “A greener gas grid: what are the options?”, 2017; IEA, “The Future of Hydrogen”, 2019.
141 IEA, “The Future of Hydrogen”, 2019.
142 Schmidt et al, “Future cost and performance of water electrolysis: An expert elicitation study”, International Journal of Hydrogen Economy, 2017.

One emerging technology for low carbon hydrogen production is methane cracking, using either thermal or catalytic processes. The thermal route uses plasma to split methane and can potentially use electricity more efficiently than electrolysis while also concentrating the carbon generated from the process in a solid form (carbon black). In Europe, laboratory experiments have shown that hydrogen produced using methane cracking can achieve production costs equivalent to $15 to $30/MMBtu with no CO_2 emissions[143].

Hydrogen is already viable in existing industrial applications such as refining, chemicals, and iron and steel production. Industrial uses of hydrogen in these sectors are well-established, and low carbon hydrogen is cost-competitive compared to alternative low-carbon options[144]. In other industrial applications, hydrogen may be competitive against other low-carbon options, such as electrification, in the longer term, but new processes and infrastructure will need to be adopted.

Blending hydrogen with natural gas in existing transmission and distribution networks is also feasible under specific conditions. The two options currently available for blending involve direct injection and methanation (converting hydrogen to synthetic gas). Direct injection of hydrogen is feasible only up to certain concentrations before it requires pipeline retrofits and changes to end-use appliances. In most instances, pipelines are able to accept a 5% to 15% hydrogen content (in volume) without any incremental capex requirements, whereas existing appliances can accept up to 20% hydrogen with no upgrades[145]. By comparison, methanation requires upfront investment to enable grid integration of hydrogen, but there is no limit on its concentration with existing infrastructure. These costs are currently greater than $30 per MMBtu equivalent, making syngas conversion a key area for innovation to improve the economic viability of low-carbon hydrogen.

There are multiple other potential applications of hydrogen across the transportation and power sectors, as well as in direct-heat industrial processes. However, these specifically require retrofits of existing plants or equipment and the development of entirely new supply chains. Thus, the potential for low-carbon hydrogen in these sectors is highly dependent on the hydrogen production economics and comparative costs within specific geographies.

Developing hydrogen as a viable low-carbon option across sectors will require a combination of policy support, investment, and continued technology innovation. Policies that facilitate investment in new infrastructure projects, as well as stimulate new markets, are critical for ensuring the viability of hydrogen. As has been demonstrated with renewable power generation, a combination of multiple policy measures can be effective in stimulating new markets for hydrogen. These include portfolio standards or low-carbon standards to generate demand, and feed-in-tariffs, tax credits, or guaranteed pricing to enable supply. Equally important is increased R&D funding to help facilitate innovation in core clean-hydrogen technologies, which are showing signs of rapid improvement despite being at an early stage of development.

143 Karlsruhe Institute of Technology, “Energy from a fossil fuel without carbon dioxide”, 2015.
144 IEA, “The Future of Hydrogen”, 2019.
145 Hydrogen Europe, “Hydrogen Roadmap Europe”, 2019.

Japan has taken a leading role in developing an integrated set of policies supporting hydrogen adoption. Japan's national energy policy aims to scale up hydrogen use to 300,000 tons by 2030, equivalent to more than 1 billion cubic meters of natural gas[146]. This scaling-up is conditional on reaching certain benchmarks in cost reductions. Initially, Japan is aiming to reduce the cost of hydrogen to a level 50% higher than conventional fuels by 2030, with cost parity following thereafter.

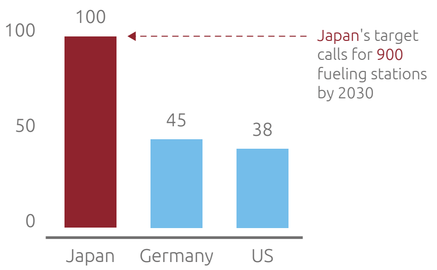
To support these targets, the Japanese government has adopted specific incentives and established a $350-million fund to finance R&D and infrastructure, including hydrogen fueling stations and the development of an international hydrogen supply chain[147] (see Exhibit 32).

Exhibit 32 - JAPAN HYDROGEN: HOLISTIC ADOPTION STRATEGY TARGETING COST REDUCTION AND INFRASTRUCTURE DEVELOPMENT

Impact: Japan intends to be a global leader in hydrogen

Japan is a leader in hydrogen fuel cell development

# of hydrogen fueling stations in leading countries



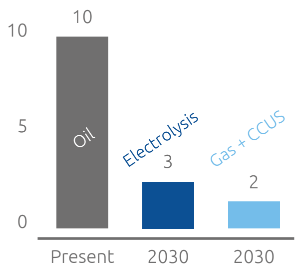
Hydrogen is central to Japan's low carbon ambitions for several reasons

- Japan is highly dependent on fossil fuel imports.
- Fukushima disaster makes increased nuclear power deployment politically unviable.
- Nation has one time-zone and a divided grid, which pose challenges to high penetration of wind and solar.

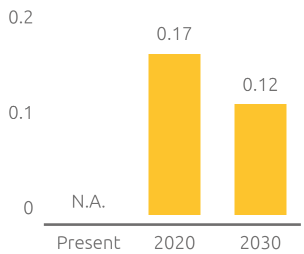
Drivers & lessons: policy focus is on achieving hydrogen production cost improvements

Japan hydrogen strategy targets lower green hydrogen costs

Target H_2 prices ($/kg)



Target H_2 power costs ($/kg)



The Japan hydrogen strategy aims to target R&D and decrease costs

Coordinates public and private hydrogen initiatives.

Focuses research efforts on reducing cost of hydrogen fuel and related technologies along the value chain.

Develops international supply chain – Australia, Saudi Arabia, Norway and Brunei are already involved.

Sources: IFRI Centre for Energy, press reports, BCG analysis.

146 METI "Basic hydrogen strategy", 2017.
147 IFRI, "Japan's hydrogen strategy and its economic and geopolitical implications", 2018.

Carbon capture, utilization and storage (CCUS)

CCUS includes any measure that captures carbon and permanently sequesters it, thereby preventing emissions into the atmosphere. This requires its removal from the global carbon cycle for a climate-relevant time period (centuries or millennia), either in the form of underground storage or by using CO_2 in the production of a commercially valuable product. Storage is most commonly done in depleted oil and gas reservoirs and saline aquifers, while utilization is viable through direct use of carbon or through chemical conversion processes.

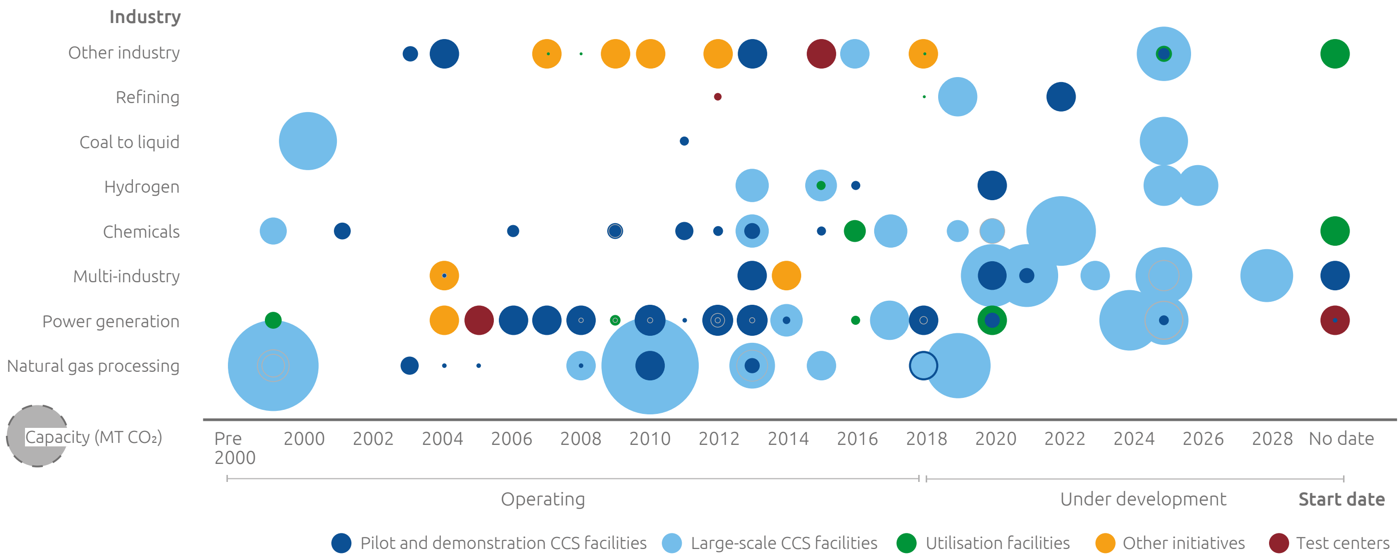
Carbon capture is viable with any large, stationary source of CO_2 emissions. Given the equipment required to capture, transport, and utilize or store carbon, there is a distinct scale benefit to the adoption of CCUS. As a result, CCUS has mainly been used to date with fossil fuel-based power generation and natural gas processing. Approximately 32 metric tons of CO_2 are captured and stored each year through CCUS. Most of this capacity is in the United States, with the majority deployed at natural gas-processing plants that produce pure CO_2 as a by-product of commercial gas production[148].

Compared to other technologies, CCUS is uniquely positioned to abate GHG emissions. It is the only means of reducing current sources of emissions to near zero using existing infrastructure and fuel supply chains. It can also achieve net-negative emissions through capture from renewable biomass processes or direct air capture. As a result, CCUS is widely seen as essential for achieving a 2° Celsius pathway. Nearly all scenarios modelling how the world can stabilize emissions and achieve a temperature rise near 2° Celsius include a significant role for CCUS. Estimates of the potential scale of CCUS range from 4 to 7 gigatons by 2050[149]. Achieving this scale of infrastructure development will require a step change in investment, involving an increase in capacity of between 140 and 216 times current levels[150].

Global growth in CCUS capacity has been slow, but it is poised to accelerate. The amount of capacity currently under development is double all existing capacity in place today. The types of projects are also changing, from demonstration or pilot projects to more commercially driven projects across different sectors. These include a wide range of industries where natural gas is used as a feedstock for combustion, including power generation, chemicals, hydrogen, and refining[151] (see Exhibit 33).

148 Global CCS Institute, 2018 Global Status Report.
149 Based on a review of mainstream climate scenarios, including IPCC and IEA as well as specific company-published models.
150 BCG analysis based on IEA modeling.
151 Global CCS Institute, 2018 Global Status Report.

Exhibit 33 - CCUS PROJECTS SHIFTING TO LARGER SCALE AND MORE DIVERSE INDUSTRIES



Note: Capacity is average of reported range.
Source: Global CCS Institute, BCG analysis.

Post-combustion capture is the primary CCUS technology used with natural gas, at present. Existing processes use either solvents or membranes to remove CO_2 from flue gas streams. Solvent-based applications predominate as the technology is more mature and easily applied to any emissions source. When used with high-concentration CO_2 streams, solvent-based methods are cost effective, incurring costs of less than $30 per ton of CO_2 avoided, when concentrations are greater than 90%[152]. However, costs increase significantly for more dilute CO_2 streams, due to the increased energy and solvent costs. For example, in power generation, where CO_2 concentrations are less than 10%, total costs can range from $50 to more than $150 per ton of CO_2 avoided[153].

Innovations in post-combustion carbon capture technologies can help to reduce these capture costs, however. For solvent-based capture, new types of solvents and new process designs have improved efficiency by up to 50%[154]. For membrane-based capture, fundamental research is underway to identify new materials and process designs that improve carbon capture rates, while lowering the energy inputs required to pressurize flue gas. Beyond established forms of carbon capture other less mature technologies are also emerging, including chemical looping and electrochemical capture methods.
In sum, innovations in carbon capture technology have the potential to reduce the capture costs for more dilute CO_2 streams to less than $50 per ton of CO_2 avoided[155].

152 BCG review of academic literature on CCUS projects. The difference between carbon captured and avoided is based on the efficiency of CCUS systems; an average of 90% efficiency is assumed in this report.
153 Ibid.
154 Zhang et al, "Development of an energy-efficiency CO2 capture process using thermomorphic biphasic solvents", Energy Procedia, 2013.
155 Budhathoki et al, "High-throughput computational prediction of the cost of carbon capture using mixed matrix membranes", Energy & Environmental Science, 2019.

At the same time, developments in oxy-fuel combustion offer an alternative and potentially cost-effective means of capturing carbon. Oxy-fuel processes combust fuel in a high-oxygen environment, which improves combustion efficiency and CO_2 concentration streams. New approaches to the technology in natural gas power plants, such as the Allam cycle, demonstrate that it can achieve a similar levelized cost of electricity to conventional CCGT plants while also producing a pure stream of CO_2[156]. This could significantly transform the economics of carbon capture in power generation. It would require the development of new plants rather than retrofits though, whereas post-combustion capture technologies can be used for plant retrofits.

Utilization of Captured CO_2

Another emerging area is the development of utilization pathways to provide economic value from CO_2 captured and removed from the carbon cycle. Currently, commercial uses of CO_2 are limited to enhanced oil recovery, urea production, and a number of small chemical-conversion applications. However, research into chemical conversion processes is opening up opportunities to utilize CO_2 in new ways. One such approach with significant commercial potential is the mineralization of CO_2 into a solid state through the reaction of CO_2 with alkaline earth metals. The solid created through this process can be used in aggregates and cement production. Thus far, mineralization has been a very energy-intensive process. However, new approaches that use industrial waste and other low-cost materials could potentially be cost neutral[157].

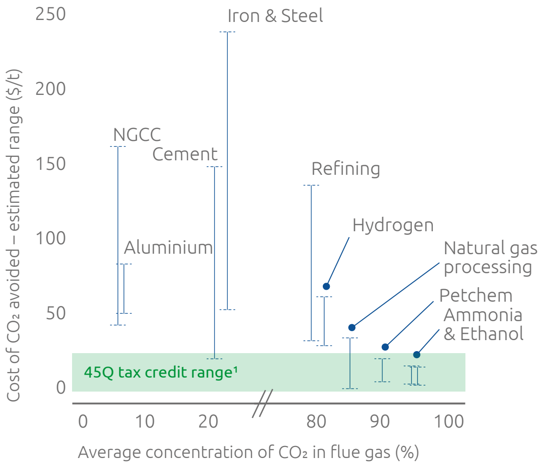
To initiate greater CCUS capacity growth, governments are increasingly introducing policy measures that either directly promote projects or provide market incentives.

In Europe, the UK and Norway award direct project subsidies, while the Netherlands and Denmark have made broad commitments to using CCUS for emissions reductions. Meanwhile, China has endorsed CCUS in its five-year plan, while also providing direct support for capture projects and the development of storage sites. Most significantly, in 2018 the US enacted legislation creating the biggest incentives so far for CCUS projects. The 45Q tax credit will provide $35 per ton of CO_2 captured when utilized, or $50 per ton when stored. The tax credit will be available to projects that start before 2024 and last for a duration of 12 years (see Exhibit 34).

156 Allam et al, "Demonstration of the Allam cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture", Energy Procedia, 2017.
157 Xie et al, "Scientific and engineering progress in CO2 mineralization using industrial waste and natural materials", Engineering, 2015.

Exhibit 34 - US CCUS: TAX CREDITS SET TO INCREASE INVESTMENT AND DEPLOY CCUS IN NEW SECTORS

Impact: high concentration CO_2 streams now commercially viable



Drivers & lessons: new policy provides up to $50/t CO_2 tax credit, prompting new investment

45Q credit creates incentives to invest in CCUS projects

Authorizes $35/t of CO_2 tax credit utilized carbon; $50/t for sequestered carbon.

Expected to kick off CCUS investment in new sectors.

Objective is to drive down unit costs through scale and learning

Companies already announcing new investment in CCUS

Occidental announces objective to become carbon neutral based on use of CCUS with EOR (March 2019).

More than 25 projects have been initiated with potential to secure the 45Q tax credit (including those as pre-FEED stage).

1. 45Q tax range based on value of CO_2 avoided assuming 90% plant efficiency; assumes average of $15/t transport and storage costs for sequestration.
Source: BCG - estimates sourced from published academic and research papers, excluding industry sources, all costs normalised to $ 2019. Cost/tonne avoided includes the emissions from power used from the grid.

With a value for CO_2 of $35 per ton or more, some carbon capture projects are becoming commercially viable. These generally include industries that have high-concentration CO_2 streams and involve natural gas, such as natural gas processing, ammonia production, and petrochemicals. Despite the new incentives, other regulatory barriers to CCUS adoption remain, however. These include the establishment of rules for CO_2 transport, permitting for underground storage, and the management of long term-liabilities related to storage. Thus, to facilitate significant development in CCUS capacity, governments must address barriers holistically and look at economic, regulatory, and legal barriers.

Chapter 4

Access to clean energy – more widespread and affordable access to natural gas

Highlights

- Access to clean cooking fuels remains a major international development challenge with 2.7 billion people lacking access; natural gas shows the economic potential to enable access to up to 1 billion people by 2040.
- Technology and business model innovations are enabling significantly lower cost access to gas in buildings within non-OECD market costs; in India for example, residential gas connection costs have been reduced to less than 10% of those in the US.
- Developments in microturbine and solid oxide fuel cell technologies have made gas viable in microgrid, or other distributed energy systems.
- Efficiency improvements in gas boilers and the use of CHP systems in buildings has demonstrated potential to improve energy efficiency by 20% or more.
- Small scale LNG supply chains have emerged as a new means of enabling access to natural gas, where existing pipeline infrastructure is not present, speeding time to enable access and reducing capital costs by 80% or more, relative to conventional pipeline development

Introduction

Access to natural gas varies widely around the world. In Europe, North America, CIS countries, northeast Asia, and some parts of Latin America, access to gas in buildings is nearly universal in urban areas. However, in non-OECD countries across Asia and Africa, access to natural gas in buildings is practically non-existent. These are also the same regions with significant energy poverty, where almost all of the global population without access to electricity and clean cooking fuels reside.

Improving access to electricity has been a notable success in international development. In the past decade, access to electricity has been extended to more than 400 million households globally, reducing those without access by one third (from 1.2 billion to 800 million)[158]. However, electrification is not the whole solution to energy poverty. More than 2.7 billion people still do not have access to clean cooking fuels and technologies, down 300 million from 2010[159]. Part of the challenge is that even where households have access to electricity, surveys indicate that traditional biomass is still the primary fuel used for cooking in many households due to poor power-grid reliability, high costs of electricity, and cultural preferences[160]. Given the role gas can play as a clean substitute for biomass in cooking, as well as other heating applications (depending on the local climate context), poor gas access is a barrier to the broader provision of affordable and clean energy.

New technologies can help to unlock the potential for wider access to gas and reduce global energy poverty. Within buildings, small-scale, low-cost means of extending gas connections are improving the provision of natural gas. Meanwhile, distributed energy technologies and small-scale LNG are a potential alternative to capital-intensive gas distribution infrastructure, particularly in remote regions, or areas with low population density. These technologies offer innovative ways of accessing natural gas, enhancing the speed and affordability of gas access. (see Exhibit 35).

Exhibit 35 - ENABLING DISTRIBUTED AND FLEXIBLE ENERGY SUPPLY: SUMMARY OF TECHNOLOGY TRENDS

			ILLUSTRATIVE POTENTIAL IMPROVEMENTS		
TECHNOLOGY	**RECENT TECHNOLOGY DEVELOPMENT**	**EMERGING TECHNOLOGY TRENDS**	**EFFICIENCY**	**CAPEX**	**FLEXIBILITY**
BUILDING ADOPTION	• Boiler efficiency improvements • Adoption of CHP in buildings • Low cost building connections	• Development of gas hybrid residential heating solutions	Boiler efficiency (10-25%)	Boiler cost declines (0-5%)	
DISTRIBUTED GENERATION	• Development of smaller scale microturbines	• Development of solid oxide fuel cells (SOFCs)	SOFC fuel efficiency (up to 25%)		
SMALL SCALE LNG	• Distribution of LNG by truck • Modular construction process	• Dedicated off-grid supply chains		LNG by truck vs. pipeline (>80%)	Pace of capacity development (2-7x)

Source: US EIA, EPRI, Power Magazine, US DOE, Bloom Energy, SEA/LNG, BCG analysis.

158 World Bank, Sustainable Energy for All Database, 2019.
159 IEA 2020 data and IEA, "Tracking SDG7: The progress report", 2018.
160 For example: Morlot, et. al., "Achieving clean energy access in sub-Saharan Africa", 2019.

The deployment of these technologies is currently in its early stages, however. While they demonstrate significant potential, examples of adoption are limited. As a result, further investment in testing and deploying these technologies, and developing new enabling business models, is warranted. Scaling public and private R&D investment can play a significant role in unlocking the most promising emerging technologies, like solid oxide fuel cells[161].

Deployment of these technologies offers significant potential to expand gas access, particularly for enabling clean cooking. Overall, gas offers the potential to extend energy access to 1 billion people by 2040, or about one third of the potential population lacking access to clean cooking by that time[162].

That potential is concentrated largely in cities where high population densities make gas one of the most viable, low cost means of establishing clean cooking access. Given that a significant portion of the delivered cost of gas is typically due to capital costs of gas infrastructure, innovations that reduce these costs provide a disproportionate impact on enabling energy access in line with the Sustainable Development Goals.

161 As an example, solid oxide fuel cells can be integrated with gas systems to dramatically increase energy output, thereby making gas more viable for distributed generation applications.
162 Global scenario analysis assessing the economically potential share of natural gas and low carbon gas based on technology trends assessed in this report.

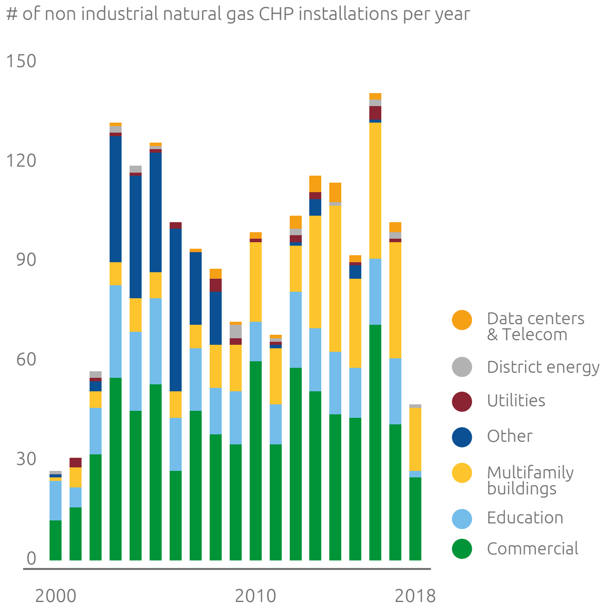
Buildings adoption

Gas boiler technologies have improved in recent years in both buildings and the industrial sector, boosting efficiency by up to 20% while becoming more flexible. Combined heat and power (CHP) technology is one innovation that has expanded gas use in buildings and improved efficiency. While CHP is well-established in industrial applications, the technology has only been deployed in buildings on a wide scale in the past 15 years[163]. The development of microturbine technologies for smaller applications, combined with the deployment of microgrids, have been crucial in achieving this breakthrough. These innovations have reduced the minimum size required to use CHP, making it a viable option for a more diverse range of building applications, particularly in the commercial sector (see Exhibit 36).

Other developments are underway in emerging markets that offer the potential to improve affordable access to natural gas in buildings. New opportunities are emerging for governments and industry actors to deploy technologies and business models which, when combined, can reduce barriers to fuel switching by minimizing infrastructure and connection costs. In India, for example, city gas distribution (CGD) operators achieve economies of scale in developing natural gas grids by using compressed natural gas (CNG) stations for sales to the transport sector, Using CNG customers for baseload demand enables operators to reduce both the overall unit and incremental costs for adding building connections[164].

Exhibit 36 - US BUILDINGS ADOPTION OF COMBINED HEAT AND POWER TECHNOLOGIES IS GROWING

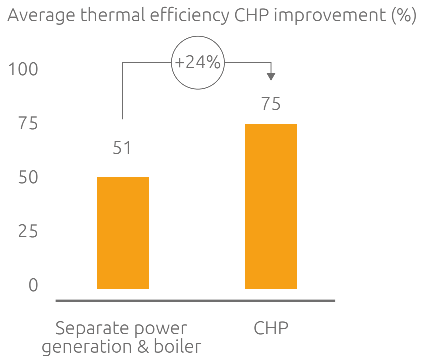
Impact: recent growth in the use of CHP in building applications



Source: DOE, ACEEE, Power Magazine, EPA, BCG analysis.

Drivers & lessons: efficiency improvements, new technology & resiliency concerns spurring adoption

CHPs significantly improve building efficiency



New technology & resiliency concerns spurring adoption outside industry

- Development of microturbines with low power outputs (10-500 kW) enable CHP to be used for smaller scale applications – average CHP installation size has decreased from 26 MW to 7 MW over the last decade.
- Growth of microgrids helps adoption of CHP - technology offers solution to reliability and cost issues associated with microgrids.
- Increasing concerns about grid resilience and power outages has helped adoption of CHP in commercial sectors such as multi-family buildings.

163 US DOE, "Combined Heat and Power (CHP) Technical Potential in the United States", 2016.
164 For example, see Kar et. al. "Natural gas markets in India: Opportunities and challenges", 2017.

As an additional step to reduce costs for build connections, CGD operators in India use low-cost, but safe steel-reinforced rubber hoses for small-scale buildings connections. The hoses are better suited to the requirements of households, proving sufficient scale of gas supply at a low cost. The net result of these measures is that building connection costs for piped natural gas in India are less than $100, whereas in the US costs can be upwards of $1,500[165]. When combined with low-cost gas cooking stoves, as well as financing models that amortize the upfront capital costs of developing gas infrastructure across utility bill payments over time, these approaches can make accessing natural gas much easier. As a result, they lead to far greater energy access while also reducing local air pollution and improving human health through the reduction of traditional biomass use.

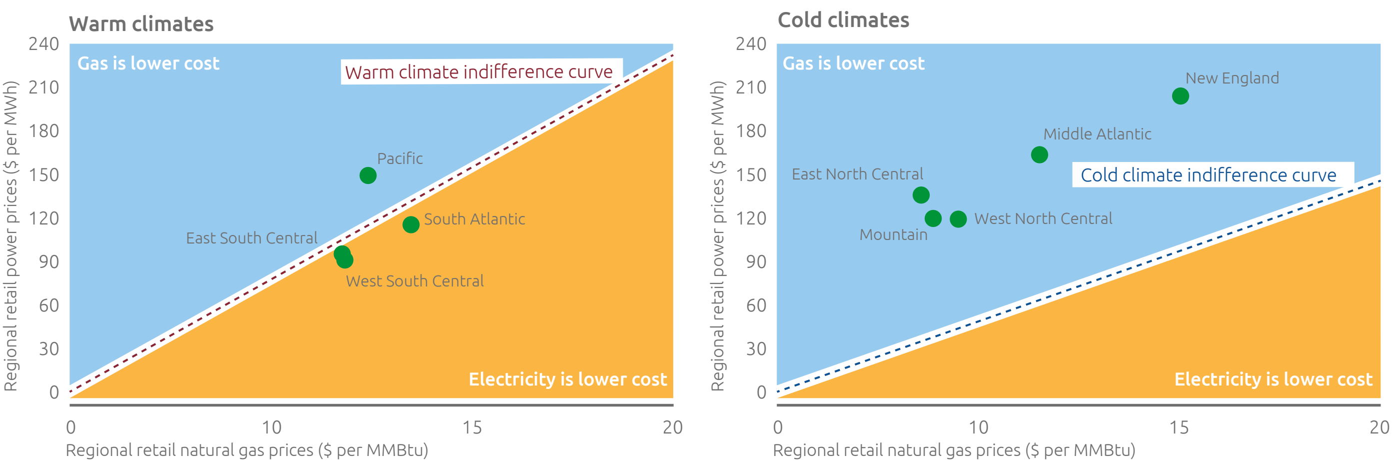
Nevertheless, global fuel switching to gas has been slower in the buildings sector compared with others, with the share of gas remaining roughly constant across regions over the past decade. While the share of gas in the buildings sector is rising in China, the Middle East, and Africa, it has remained stable or declined in other regions[166].

At the same time, technological innovations in electric heat pumps are supporting the electrification of buildings. Cost and operational efficiency improvements have bolstered the relative cost of heat pumps. However, there is still a high cost differential for end consumers, especially due to the relative costs of electricity and natural gas. Consequently, the economics of electrification versus gas in buildings varies, depending on heat requirements. In particular, gas boilers are more cost-effective on a levelized cost of service[167] basis in colder regions with greater heat demand. In the US, the cost of gas heat pumps is nearly equivalent to that of electricity on a levelized basis in some warm regions. But in colder climates, the cost of gas heating can be $900 per year less than electric heat pumps[168] (see Exhibit 37).

The outlook for natural gas use in buildings varies significantly depending on specific regional or local needs and competing technologies. Recognizing this and the fact that a wide range of mature gas technologies exists for use in buildings, the greatest opportunity in this area is perhaps through business model innovations that help to lower barriers to natural gas adoption and sustain gas use. Integrating distributed generation and small-scale LNG can enable more rapid gas infrastructure development and access outside of existing gas networks.

Exhibit 37 - US RESIDENTIAL SPACE HEATING: GAS REMAINS LOWER COST THAN ELECTRIFICATION ON A LEVELIZED BASIS IN MANY REGIONS

Residential power price at which consumers are indifferent between gas and electric space heating



Note: Comparison of new build options for both gas and electrification.
Source: NREL, EIA, BCG analysis.

165 GAIL cited in Deccan Herald, "GAIL gets 21,000 more registrations with fresh strategy", 2020.
166 IEA, 2019 World Energy Outlook.
167 Comparable cost of different energy sources at the point of use, incorporating all opex and capex costs and represented on a unit cost basis.
168 BCG analysis based on NREL and US EIA data.

Distributed generation

Distributed energy is widely seen as playing a key role in global energy transitions. Under specific conditions, distributed energy networks can enable renewable energy production in close proximity to where it is consumed and allow a staged approach to enabling access, as an alternative to larger traditional centralized networks. In other instances, they may also be used as a tool to improve overall grid resilience. Gas technologies can support these systems by providing secure and reliable capacity, particularly when combined with new means of gas distribution like small-scale LNG. Diesel is the current incumbent fuel for providing this function, but it is both expensive and high-emitting, hence replacing it with natural gas would enable reductions in both GHG and air pollutant emissions.

In the case of microgrids, natural gas has helped support the use of microturbines, particularly when integrated with CHP systems. Recently, there have been important innovations in microturbine technologies. Developers have reduced the size of microturbines while still offering the same cost per kilowatt of capacity as large-scale gas turbines, enabling them to be scalable and cost-competitive in a wider range of industrial and buildings applications[169].

An emerging area of research is focused on integrating solid oxide fuel cells (SOFCs) with gas microturbines and reciprocating engines to improve overall system efficiency. SOFCs operate at far higher temperatures than other fuel cell technologies because they use a ceramic separator. This enables natural gas reforming to occur inside the system (i.e. the only inputs are natural gas and steam). The electrical efficiency of SOFCs on a standalone basis is already 50%, but by integrating a turbine to recover energy from the high heat and pressure exhaust, total efficiency can potentially be improved to 70%[170]. Going one step further, adding CHP so that residual waste heat can be used has the potential to improve overall system efficiency to 80% - 95%, compared with conventional CHP efficiencies of 50% to 70%[171].

The use of SOFCs offers distinct advantages due to their small size and scalability. Units can be small enough to power and heat a single home, but they can also be scaled up to match the largest CHP systems in use today. System costs are the greatest challenge for adoption though. Current capital costs are in the range of $6,000 per KW of generating capacity, which is more than six times that of gas microturbines[172].

However, there are potentially significant scale effects in the production of SOFC systems. Analysis sponsored by the US DOE shows the potential to reduce manufacturing costs by more than 70% when there is a ten-fold increase in production capacity[173].

As the energy industry is still in the early stages of determining how and where distributed gas generation technologies can have maximum impact, it is premature to judge their success based solely on the scale of their deployment. At this point, sustained investment in testing and developing opportunities for gas in distributed generation systems is essential. For SOFCs in particular, sustained investment in research and in facilitating broader deployment will be key to uncover potential further efficiencies that can reduce upfront capital costs.

169 Power Magazine, “Microturbines useful in commercial and industrial applications”, 2019.
170 US DOE Advanced Research Projects Agency – Energy, “De-coupled solid oxide fuel cell gas turbine hybrid”, 2018.
171 For example, see Redox Power Systems, “Solid oxide fuel cells or waste to materials & energy”, 2019.
172 GTM, “Bloom Energy Optimistic as it Doubles Fuel Cell Revenue in 2018”, 2019.
173 US DOE, “Manufacturing cost analysis of 1, 5, and 25 kW fuel cell systems for primary power and combined heat and power applications”, 2017.

Small-scale LNG

With the development of small-scale LNG (SSLNG) technologies, the role of gas is shifting from facilitating distributed energy to being a driver of distributed energy in its own right. Small-scale liquefaction technologies, as well as LNG distribution by truck are enabling this shift. As both technologies have been tested and deployed, they have quickly become cost-competitive. In some instances, such as in remote areas with a low population density they provide a lower-cost means of distributing gas than traditional pipelines

Small-scale liquefaction is not an entirely new technology. Liquefaction plants have existed for several decades for the purpose of natural gas peak shaving. However, new plant designs have emerged in the past 10 years that make small-scale liquefaction more flexible and cost-competitive. One new approach is the moveable modular liquefaction system (MMLS). Each MMLS unit provides 0.25 million tons per annum (MTPA) of capacity, is a turn-key system, and can provide similar liquefaction costs to those of world-class LNG systems[174]. As a result, it has been used in a wide range of applications, from single-unit installations to a 10-unit system for the Elba Island LNG export terminal in the US.

At a much smaller scale, "cryobox" technology can produce LNG at capacities of up to 10,000 gallons per day (or about 0.005 MTPA), a fraction of traditional liquefaction capacity. This is done through modular units which deliver economies of scale in the production of the units, not in the production of LNG. Each unit is the size of a shipping container and uses an identical design and components, allowing scalability and replication in production. The technology is already being used in Brazil and Argentina to monetize stranded gas production, by providing LNG for off-grid and small-scale power generation in remote regions[175].

LNG distribution by truck is another new technology spurring SSLNG market growth. The technology is relatively simple, only requiring the availability of truck-loading facilities at LNG import terminals or liquefaction plants plus the production of trucks with cryogenic tanks. A key development is the evolution of this technology has been the adaption of cryogenic tanks in ISO containers, allowing them to be used across transport modes while enabling easy scalability.

The full potential for a small-scale LNG supply chain has been recently demonstrated in China, where the market for LNG distribution by truck has grown rapidly to make China the largest SSLNG market globally. As the Chinese government accelerated the phase out of coal in 2016-2017, natural gas supply from established pipelines could not keep pace with the growing demand. At the same time, a clear opportunity emerged for distributing LNG by truck. While state-owned oil companies had a monopoly on pipeline distribution, LNG-by-truck was widely accessible and could be delivered at a lower cost than regulated city gate prices in many regions[176]. As a result, distributing LNG by truck quickly filled the demand gap. Truck sales grew rapidly, from 19,000 in 2016 to 96,000 in 2017[177]. Virtual markets also emerged via social media, providing pricing transparency and enabling supply to match demand. As a result, LNG distribution by truck now accounts for more than 10% of China's natural gas supply[178] (see Exhibit 38).

174 Poten & Partners, "Shell puts small-scale technology to work at Elba Island", 2013.
175 Galileo, "Distributed LNG production solutions", 2020.
176 BCG analysis of China National Bureau of Statistics data.
177 China State media.
178 Wood Mackenzie, "Meeting gas demand in China – the role of LNG trucking", 2018.

Exhibit 38 - CHINA SSLNG: DISTRIBUTION BY TRUCK NOW A MATERIAL SEGMENT OF THE CHINESE MARKET

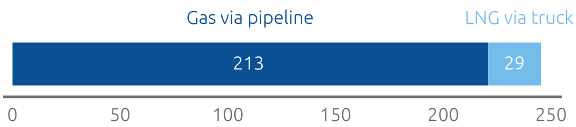
Impact: LNG trucks provide off grid access – now supply 10% of Chinese gas market

Trucked LNG market expands access and fosters market competition

LNG trucks bring natural gas to off grid industrial customers, allowing them to comply with Chinese fuel switching policies.

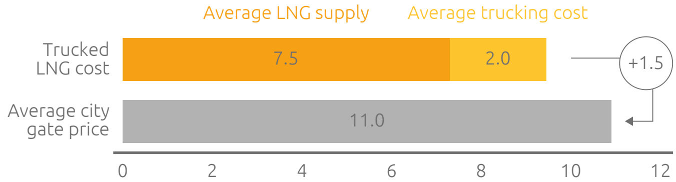
Both pipeline natural gas and off grid customers can check market prices and trading volumes on WeChat groups, improving competition and liquidity.

Over 10% of Chinese natural gas consumption distributed by truck



Drivers & lessons: attractive margin and ability to quickly expand drove market growth

Unit margins on trucked LNG distribution can be attractive



Organic market developed to meet policy-driven demand growth

Pipeline expansion could not keep up with rapid policy-driven demand growth.

The speed with which truck loading infrastructure can be built helped LNG trucking grow quickly and meet excess demand.

An organic trucking market quickly developed in an otherwise heavily regulated market.

Source: IEA, Wood Mackenzie, National Bureau of Statistics of China, OIES, BCG analysis.

Outside of China, participants in other markets have been replicating the Chinese model of LNG distribution by truck since 2017. In North America, merchant truck operators distribute LNG to locations in Mexico that do not have pipeline access. While in India, Petronet recently announced plans to include truck loading at its terminals and estimates the market for LNG-by-truck could soon be1.5MTPA[179].

The recent development of LNG-by-truck distribution speaks to two fundamental advantages of SSLNG for expanding access to natural gas: the pace of development and low capital cost requirements. Compared with the five- to ten-year period typically required for developing gas transmission pipelines, LNG distribution by truck can be established in one to two years. Meanwhile, capital costs for this distribution method are only about 10% of what is required for distribution pipelines[180].

These benefits are especially relevant in the Asia Pacific region, where countries are increasingly importing LNG, but currently lack domestic transmission and distribution infrastructure. SSLNG provides a gas transmission solution in its own right while also providing a stopgap until broader gas networks can be developed.

Looking ahead, the greatest opportunities for enabling the development and deployment of SSLNG technologies are in measures that reduce production and transport costs. While SSLNG distribution is already cost-competitive in China in some regions, this depends on the availability of LNG imports and the tariff structure for gas transmission[181]. Greater investment in fundamental R&D and LNG plant development to tackle this cost structure has the potential to improve the commercial viability of SSLNG in more markets.

179 Offshore Energy, "Petronet advocating LNG distribution by trucks", 2016.
180 BCG analysis based on assessment of system development costs in China.
181 BCG analysis based on China NDRC data.

Conclusion

Conclusion

The world is currently experiencing a period of dramatic innovation in its energy systems. How energy is supplied and consumed are set to be significantly disrupted in the coming decades. Indeed, such disruption is essential if the world is to meet the commitments of the Paris Agreement and achieve the United Nations Sustainable Development Goals.

This report demonstrates, that technology developments and innovation in natural gas value chains are of equal importance with other cleantech developments, such as renewable power advances. Gas technology and innovation can have a similarly transformative impact and needs to be an integral part of the cleantech development and energy innovation discussion. While gas technologies are already mature in many applications, technological advances have the potential to reduce the costs of gas combustion by a third or more, cut the capital investment necessary to access gas by half, and improve the flexibility of gas in end-use sectors.

Even more significantly, innovation is occurring in low-carbon gas technologies, including renewable gas, hydrogen, and carbon capture, utilization, and storage (CCUS). While the costs of these technologies are high today, and deployment is limited, a combination of fundamental technological breakthroughs as well as scale and experience-driven impacts could cut these costs by half over the next one to two decades.

As a result of ongoing and emerging developments in gas technologies, the potential market for natural gas is set to be much greater than it is today. Factoring in the improvements outlined above, along with the greater value that gas provides in reducing greenhouse gas emissions and localized pollution compared with other fuels, the global market for gas could be two and a half times its current size by 2040 based on its economic potential. The power sector offers much of that growth potential, based on the scale of fuel switching possible and the role that gas can play complementing renewable power.

Achieving the economic potential for the adoption of gas technologies would, in turn, provide substantial environmental and social benefits. Under such a scenario, gas technologies could mitigate up to one-third of global energy sector greenhouse gas emissions, reduce the emissions of pollutants such as nitrogen oxide by up to a third, and enable access to clean cooking fuels for one billion more people by 2040 – which is more than a third of the presently lacking access. When compared with the costs of other fuels, gas technologies also provide the lowest-cost means of reducing emissions in many applications, particularly in the buildings, industry, and transport sectors.

Such an outcome is far from assured, however. Lessons from the development and adoption of gas technologies in the past, as well as that of other cleantech solutions, indicate that three drivers are essential for their future development and deployment:

- First, supportive government policies are vital for promoting sustained R&D in gas technologies, while ensuring their environmental and social value are properly reflected in the market (for example, through the implementation of carbon pricing).
- Second, substantial investment is required to enable access to gas, deploy technologies for gas consumption, and scale up the supply of low-carbon gas. Achieving the economic potential for gas and its associated benefits would require $400-800 billion of annual investment.
- Third, innovation by the gas industry is necessary, particularly through investment in R&D and early-stage deployment. The industry also needs to develop new business models and applications for gas technologies to lower deployment barriers and speed adoption.

Transforming the global energy system so that it simultaneously enables climate change mitigation, promotes sustainable cities and communities, and provides access to affordable, clean energy will require sustained action and innovation across the entire breadth of energy applications worldwide. As this report demonstrates, innovations in gas technologies are already starting to deliver significant benefits and have substantial potential to enable these vital goals in the coming decades.

Sources

Allam et al, "Demonstration of the Allam cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture", Energy Procedia, 2017

American Energy Innovation Council, "Energy Innovation: Fueling America's Economic Engine", 2018

BCG, "The business case for carbon capture", 2019

BCG, "The electric car tipping point", 2018

BCG, "The real promise of hydrogen", 2019

Bloomberg New Energy Finance, "2019 New Energy Outlook"

BP, "2019 Energy Outlook"

Budhathoki et al, "High-throughput computational prediction of the cost of carbon capture using mixed matrix membranes", Energy & Environmental Science, 2019

Cedigaz, "Global biomethane market", 2019

China National Bureau of Statistics, Statistical database, 2019

China National Development and Reform Commission, Natural gas consumption data, 2019

Clean Air Task Force, "Where nuclear energy fits into the clean energy future", 2019

Colpier et al, "The economics of the combined cycle gas turbine – an experience curve analysis", En-ergy Policy, 2002

Columbia Center on Global Energy Policy, "Low carbon heat solutions for heavy industry: Sources, options, and costs today", 2019

CSIS, "Pathways for developing a natural gas vehicle market", 2019

Cummins Westport, "Natural gas engines", 2018

Deccan Herald, "GAIL gets 21,000 more registrations with fresh strategy", 2020

Distributed Energy Magazine, "CHP: Innovations and applications", 2019

DVN GL, "Comparison of alternative marine fuels", 2019

EDF, "The Norwegian NOx Fund", 2019

EIA, "2019 Energy Outlook"

EIA, "Monthly electric generator inventory", 2019

EIA, "Residential end uses: Historical efficiency data and incremental installed costs for efficiency upgrades", 2017

EPRI, "EPRI, 20 power companies example the role of reciprocating internal combustion engines for the grid", 2018

European Environment Agency, "Emission Factors Database", 2019

Facility Executive Magazine, "Breakthroughs in boiler technology", 2019

Frontier Economics, "The value of gas infrastructure in a climate-neutral Europe", 2019

Galileo, "Distributed LNG production solutions", 2020

Global CCS Institute, "2018 Global Status Report"

Global CCS Institute, "2019 Global Status Report"

Götz et al, "Renewable Power-to-Gas: A technological and economic review", Renewable Energy, 2016

GTM, "Bloom Energy Optimistic as it Doubles Fuel Cell Revenue in 2018", 2019

GTM, "How big is the peak capacity market for batteries?", 2018

Hao et al., "Natural gas vehicle fuel in China: A review", 2016

Hydrogen Europe, "Hydrogen Roadmap Europe", 2019

IEA, "2016 World Energy Outlook"

IEA, "2017 World Energy Outlook"

IEA, "2018 World Energy Outlook"

IEA, "2019 World Energy Outlook"

IEA, "Energy Efficiency 2018"

IEA, "Global Energy Review 2020"

IEA, "SDG7: Data and projections", 2019

IEA, "The Future of Hydrogen", 2019

IEA, "The Role of Gas in Today's Energy Transitions", 2019

IEA, "Tracking Clean Energy Progress", 2019

IEA, "World Energy Investment", 2019

IEA Bioenergy, "Greening the gas grid in Denmark", 2019

IFRI, "Japan's hydrogen strategy and its economic and geopolitical implications", 2018

IFRI, "The Power of China's Energy Efficiency Policies", 2018

IPCC, "Global Warming of 1.5 °C", 2018

IGU, "2018 Global Gas Report"

IGU, "Case studies in improving urban air quality", 2016

IGU, "Case Studies in Urban Air Quality", 2019

Imperial College London, "A greener gas grid: what are the options?", 2017

IRENA, "Biogas for road vehicles", 2018

Kallanish Energy, "Chinese LNG market set to grow", 2019

Kar et. al. "Natural gas markets in India: Opportunities and challenges", 2017

Karlsruhe Institute of Technology, "Energy from a fossil fuel without carbon dioxide", 2015

Koornneef et al, "Global potential for biomethane production with carbon capture, transport and storage up to 2050", Energy Procedia, 2013

Lazard, "Levelized cost of energy and levelized cost of storage", 2019

Sources

Lloyd's Register, "Zero-emissions vessels: Transition pathways", 2019

LNG Blue Corridors, project data, 2018

MarineLog, "Membrane fuel tanks may make LNG viable for more ships," 2018

McCoy Power Reports, power gen equipment data sets, 2019

Mei et al, "Evaluating digestion efficiency in full-scale anaerobic digesters by identifying active mi-crobial population through the lens of microbial activity", Scientific Reports, 2016

METI "Basic hydrogen strategy", 2017

Midrex, "World direct reduction statistics", 2018

Morlot, et. al., "Achieving clean energy access in sub-Saharan Africa", 2019

Navigant, "Gas for climate", 2019

NETL, "Power Sector Life Cycle Analysis Tool", 2012

NGVA Europe, "Statistical report", 2017

NGV Journal, 'Worldwide NGV statistics", 2019

NREL, "Natural gas engine and vehicle research & development", 2003

NREL, "Timescales of energy storage needed for reducing renewable energy curtailment", 2017

Offshore Energy, "LNG blue corridors project beats targets", 2017

Oxford Institute for Energy Studies, "A review of demand prospects for LNG as a marine transport fuel", 2018

Oxford Institute for Energy Studies, " A review of prospects for natural gas as a fuel in road transport", 2019

Oxford Institute for Energy Studies, "The Outlook for Natural Gas and LNG in China in the War Against Air Pollution', 2018

PJM, "PJM cost of new entry", 2018

Poten & Partners, "Shell puts small-scale technology to work at Elba Island", 2013

Power Engineering Magazine, "Fast start combined cycles", 2017

Power Engineering Magazine, "Frame vs. Aero", 2017

Power Magazine, "GE HA Turbine Snags Another World Record for CCGT Efficiency", 2018

Power Magazine, "Microturbines useful in commercial and industrial applications", 2019

Power Magazine, "Turbines vs. reciprocating engines", 2016

Redox Power Systems, "Solid oxide fuel cells or waste to materials & energy", 2019

Schmidt et al, "Future cost and performance of water electrolysis: An expert elicitation study", In-ternational Journal of Hydrogen Economy, 2017

Schmidt et al, "Projecting the future levelized cost of energy storage technologies", Joule, 2019

SEA/LNG, "LNG as a Marine Fuel – The Investment Opportunity", 2019

UNCTAD, "Decarbonizing maritime transport", 2020

US DOE, "Combined Heat and Power (CHP) Technical Potential in the United States", 2016

US DOE, "Energy savings potential and R&D opportunities", 2017

US DOE, "Manufacturing cost analysis of 1, 5, and 25 kW fuel cell systems for primary power and combined heat and power applications", 2017

US DOE, "Quadrennial Technology Review", 2015

US DOE Advanced Research Projects Agency – Energy, "De-coupled solid oxide fuel cell gas turbine hybrid", 2018

UT Austin, "Levelized cost of electricity with environmental costs", 2019

Wärtsilä, "LNG propulsion achieves next step in technologicl revolution", 2014

WHO, "Ambient air pollution: Health impacts", 2020

WHO, "Global Health Observatory Data", 2019

Wood Mackenzie, "Meeting gas demand in China – the role of LNG trucking", 2018

World Bank, PM 2.5 air pollution data, 2019

World Bank, Sustainable Energy for All Database, 2019

World Bioenergy Association, "Global bioenergy statistics 2018"

World Steel Association, Steel statistics database, 2019

Xie et al, "Scientific and engineering progress in CO2 mineralization using industrial waste and natu-ral materials", Engineering, 2015

Zhang et al, "Development of an energy-efficiency CO2 capture process using thermomorphic bipha-sic solvents", Energy Procedia, 2013

Concept & Design
Inarea Strategic Design

Layout
Inarea Strategic Design

July 2020