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PERSPECTIVE

Natural gas: A transition fuel for sustainable energy system transformation?

Abstract

Current discourse on the transition to a decarbonized energy system future is dominated by renewable energy solutions. Initial conditions for this transition may vary across different regions and countries. There are, however, also opportunities for innovative solutions that utilize other low-carbon energy sources and technology mix. Sustainable development is a contested concept and varies with priorities attached to social, economic, and environmental goals. Therefore, the one-size-fits-all type of solution paradigm needs to be broadened, to accelerate action in the short to medium term. Our argument is that natural gas can be an important complementary transition fuel to support renewable energy in the short- and medium-term transition phases. This means that the goal of zero fossil fuel as a short- and medium-term solution needs to be reconsidered. This takes us to the next argument that innovation and upgraded technology in the low-carbon fossil fuel sector will provide an important impetus for low-carbon transition, which we see as a phase lasting until the middle of the century. However, the transition toward a sustainable energy future of gas-fueled solutions has challenges from the social, technical, economic, geographical, and political points of view. Suitable local solutions should, however, also be assessed. These should take into consideration infrastructure, local demands, resources, and economic aspects as well as national energy policies. An analysis based on the experiences of four countries, both developed and developing, is presented in this study. The countries selected for this study can be placed in two categories: those with an abundance of natural gas reserves (Iran and Norway) and those that are import-dependent (India and UK). The cross-country analysis will help us to understand the realistic challenges and opportunities of natural gas as a transition fuel.

1 | BACKGROUND AND MOTIVATION

Keeping the natural gas (NG) option open as an addition to renewable energy (RE) will provide innovation scope, diversity in technology development, and choice, due to the resource endowment differential and short-term priorities. In addition, to highlight that there is no threat of struggle with fossil-dependent countries, a smooth, socially and economically acceptable transition needs to happen.

The environmental constraints of energy use are becoming more apparent with economic growth, and the debate concerning economic growth and its environmental impact has been ongoing. One of the important parameters of development is access to modern energy conversion and/or distribution technologies. An increasing global population has resulted in challenges related to access to energy and to living conditions. It is recognized that it is of great importance to the world today that these are dealt with in an environmentally sustainable manner.[1] The "sustainable development" discourse has resulted in a range of policies due to the integration of environmental elements into the economic activities required at the individual and collective levels. Control and diversification of the energy supply and energy use are agreed to be one of the important mitigation policies for dealing with climate change.[2,3]

Parties in the already-historic Paris Agreement converged to stabilize the global temperature increase to within 1.5°C. The parallel Sustainable Development Goals (SDGs) framework adopted by the United Nations Development Programme (UNDP) in 2015 also shows how national priorities vary and require simultaneous consideration in the short term. The low-carbon transition of the energy system has since become imperative to the participating countries, irrespective of their development status, along with the efficiency improvement of the energy system and an increasing use of renewable energy sources (RES) that has become more important across the nations. The combustion of fossil fuels emits greenhouse gasses (GHG) that contribute to global warming, which makes the positive environmental impact of RES more important. The International Renewable Energy Agency (IRENA) has noted that approximately 2000 GWs of renewable generation capacity existed globally at the end of 2015.[4] The greatest new renewable energy capacity installation ever was recorded in 2016, wind and solar energy accounting for the majority of this due to falling technology costs, according to IRENA's annual update.[5]

Energy has been a major impetus of social and economic development, as it aids poverty eradication, increases food production and access to clean water, improves public health and education, creates economic opportunity for young people, and empowers women. It has been proven that combating climate change requires a fundamental change in energy production and consumption patterns that do not conflict with human progress and economic development. Access to affordable, reliable, and sustainable energy has also been put on the agenda of the Sustainable Development Goals (SDGs) of the UNDP. At the same time, energy supply from the traditional source of fossil fuel has enormously increased the carbon level in the atmosphere. It is therefore also emphasized in SDGs that access to energy must be provided in an economically viable and environmentally sustainable manner by using both conventional and nonconventional emerging energy sources. Low-carbon and clean energy policies have been proposed as a way to mitigate energy security and climate risks.[6] Uninterrupted growth by creating less environmental pressure is achievable by decoupling GDP growth and emissions from energy use.[7] The development path followed by a nation is not always integrated across sectors and sometimes emerges from a fragmented decision made by various actors in the economy. Climate change is no longer solely an environmental concern; it has a far-reaching impact on economic and social development. Internalization of environmental challenges into social and economic planning can lead a nation into an alternative development trajectory. Countries are therefore increasingly coming to the realization that climate change needs to be supported by an integrated, crosscutting policy approach. In other words, it needs to be mainstreamed into national development planning. Understanding the linkages between climate change and national development needs in this context is also of utmost importance. In the literature, various transformation pathways are advocated to achieve the goal of "low carbon development." Researchers concluded that achieving the best possible result requires a mix of technology and greater use of energy sources with a lower carbon content.[2,3,8,9]

A better quality of life is dependent on access to energy from any energy resource, and almost 1.6 billion people, 20% of the world's population, do not have access to modern energy services.[5] Technical barriers are also a concern, with the lack of infrastructure (ie, large storage units), experts in the field, and noncontinuous renewable energy sources being the most significant. Renewable sources are intermittent by nature, an attribute that is important in energy network design and development. Renewable energy is therefore not affordable enough for most of the population.[4] Fuel affordability, access to existing infrastructures, and economic consequences represent a third aspect, besides the energy poverty and technical barriers which mentioned above. The costs associated with developing infrastructure in countries and regions with little or no infrastructure would be significant. Lack of infrastructure therefore makes investment in nonrenewable resources more reasonable. The costs associated with RES technologies are also currently far greater than those for traditional fossil fuel generation.[5] The most cost-effective solar or wind power solutions may be a lower-cost alternative than electricity generation based on coal, but not natural gas (NG).[10] Renewable resources also have other disadvantages: They are unreliable and difficult to store, and have a low generation levels as well as higher cost per energy than almost all other energy types.

A new energy equation system is required if we are to be able to meet the challenges described here. Such an equation system does not, however, have just one solution. The most important challenges of the coming years could furthermore be mitigated by systems that use fossil fuel-driven energies, enhanced by efficient technology solutions. These fossil fuel-driven energies can act as facilitators of the realization of RES, as well as competitors. This would significantly improve the energy efficiency (EE) of conversion systems, both current and future. NG is the cleanest and most reliable fossil fuel. According to the International Energy Agency (IEA) and Wood Mackenzie,[11] the demand for NG is projected to increase by 50% in 2035. NG will therefore overtake coal in the future global energy mix. The increase in NG demand is expected to remain strong up until 2035 where natural gas continues, in all consuming sectors, to make inroads in, for example, countries such as China and in the Middle East.[11] International reports state that Europe and Asia's increasing dependence on imports will drive the strong expansion of net inter-regional gas trade, which is expected to grow by 3.1% annually up until 2035. On the other hand, current US shale gas production has changed the global gas supply scenario. The USA has become a net exporter of natural gas. The withdrawal of the USA from the Paris Agreement brings another dimension to such discussions, as the agreement significantly reduces the carbon emission space for the rest of the world[12] and has an impact on global climate governance.[13] The first global stocktake of the Paris Agreement is scheduled for 2023, and it will be challenging for many developing countries to meet their NDC targets.[13]

There are many openings, incentives, and technological enablers that can help countries meet their NDC targets. These include distributed generation (DG), combined cooling, heating, and power (CCHP) production, combined cycle gas turbines (CCGTs), and other novel efficient cycles. Various types of gaseous fuel can also be produced from, for example, CNG, LPG, LNG, ssLNG, biogas, syngas, and H_2. Projects such as Global Gas Flaring Reduction (GGFR) can promote reductions in gas flaring and new challenges in the future electricity market such as (in the petroleum sector) the offshore/onshore green decommissioning industry and intermittent renewables.

There are, however, NG-related use risks and challenges that should not be overlooked, global climate change being the most important. The Paris Agreement is a framework agreement, and the true effect of the agreement on the global energy world is dependent on how it is implemented at the national level. The energy sector is, however, brought firmly into the spotlight by its entry into force. Technical aspects are also important. For NG, methane leakage is a great GHG emissions risk.[11] This means that regular infrastructure and transport facility maintenance and inspection are of great importance. A new level of commitment to energy supply and global warming is therefore required in regard to energy demand and supply, from, for example, oil and gas companies, renewable system developers, environmentalists, and governments, to ensure development that can be achieved through a new common understanding. There is also a risk of a "built-in" trap, as investments in conversion technologies last 30 years and infrastructure more than 50 years. Such investment decisions lock in a situation that is difficult to change.

A final but important point is that energy demand and availability are not uniform across the world. Each world region should therefore arrive at its own solution and approach. One example of this is choosing natural gas as the fuel to ensure a smooth transition to a sustainable energy world. Many of the issues inherent in energy sustainability are site-specific, even though energy sustainability is a global challenge. Local challenges and attitudes must therefore be understood whether suitable local solutions are to be found. These solutions must not only take into account socioeconomic aspects, infrastructures, and resource endowment, but also the local/national energy policy and political choices. No single solution fits all. This is something that should be acknowledged; solutions must be designed specifically for the circumstances present.

Four countries are compared in the case studies presented in this paper. The comparisons include industrially advanced versus developing economies and net exporters of oil and gas versus importers. The choices and approaches may seem very different. The case studies, however, show that all choices and approaches use medium-term low-carbon solutions to achieve long-term carbon-free/carbon-neutral energy solutions:

- India. A developing country that is a net oil and gas importer
- Iran. A developing country that is an oil- and gas-rich exporter
- Norway. A developed country that is an oil- and gas-rich exporter
- UK. A developed country that is an oil- and gas-rich importer

Figure 1 shows the power plant percentage by technology in the various countries. The first five columns clearly show that the selected countries have a diverse energy mix for electricity generation.

The following section presents the reasons natural gas can conceptually play a key role as a transition fuel. How the concept can be supported by technologies and innovation will be discussed in the following section, and where natural gas can mainly be considered to be a sustainable solution for energy transition and/or medium-term future energy mix will be deliberated in last part of the paper.

2 | NATURAL GAS AS A TRANSITIONAL FUEL: THE CONCEPT

The impact of energy consumption on the level of GHG emissions is highly dependent on the primary energy mix.

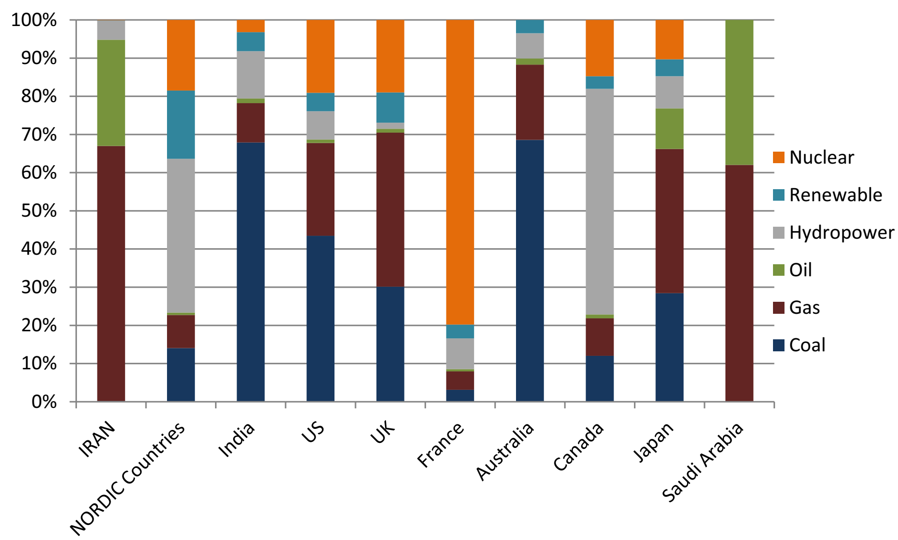

FIGURE 1 Power plant fleet by technology (%)[5]

It is indisputable that the global energy mix will need to be dominated by low-carbon sources by the end of next two decades. The role of natural gas in the ideal energy share in the near future may be crucial in optimizing the energy mix. NG will be instrumental as a transition fuel and in dealing with the intermittency of the energy supply as the share of renewables in the global energy mix increases. According to the 450 scenario,[14] the share of natural gas in the global energy mix would be approximately 22%, even though the fossil fuel share of the world's total primary energy demand (TPED) decreases to 57%.[15] Total electricity demand is expected to increase by 70% by 2035, gas-fired generation almost doubling to facilitate this.[5] It is also expected that the share of natural gas in the global energy mix will be higher than that of coal and oil by 2035. The transportation of natural gas, via liquefied natural gas (LNG), will also increase globally.[16] It has been anticipated that natural gas will be the second largest contributor to the global energy mix after oil by 2040, 80% of this projected growth coming from developing nations.[17] The demand for coal in the power sector is falling in OECD countries as the share of coal capacity is replaced by renewable and natural gas.

An assessment of the Nationally Determined Contributions (NDCs) in a recent UNFCCC report found that the increasing number of countries putting forward their cross-sectoral climate commitment, which is not sufficient to slow down the growth of GHG emission before 2025 and 2030. It was also found that cumulative CO_2 emission, after implementation of all INDCs, is not consistent with scenarios stabilizing a global temperature increase below 2°C.[18] This indicates that more stringent efforts are needed in the form of additional mitigation measures to cut down CO_2 emission. This is subject to respective national development goals and the available resources for the energy supply and the end-use sector.

The scope of natural gas in the reduction of carbon dioxide (CO_2) emissions is significant, as natural gas with a lower default carbon content of 15.3 Kg/GJ is the cleaner option as compared to coking coal (25.8 Kg/GJ), noncoking coal (26.2 Kg/GJ), and crude oil (20 Kg/GJ).[2] Natural gas is a prominent option for delivering industrial emission targets. Natural gas emits 56 100 Kg/TJ of CO_2 when used in stationary combustion processes in power generation, manufacturing industries, and construction. This is much lower than coking coal (94 600 Kg/GJ), lignite (101 000 Kg/GJ), or diesel oil (74 100 Kg/GJ). Emission from a natural gas-based power plant is approximately one-half of that of a coal power plant when used in a combined cycle gas turbine (CCGT) subject to the upstream emission.[3,8,9] CCGT as a technology has several advantages over coal plants. These include a thermal efficiency improvement of 55%-65% compared to that of a coal plant, resulting in a lower carbon emission. Natural gas is also a better option for the residential sector and for agricultural activities. Natural gas has as yet to play any significant role in the transport sector. The potential efficiency of natural gas in mobile combustion in various forms (such as compressed natural gas (CNG) and liquefied petroleum gases (LPG) in CO_2 reduction) is low compared to gasoline or diesel. However, natural gas might play the role of transition fuel for hydrogen in the transport sector.

Natural gas has increasingly been viewed as a bridging fuel by providing a low-carbon energy alternative to other fossil fuel sources. According to the Intergovernmental Panel on Climate Change (IPCC), mitigation scenarios with a low concentration of GHGs of between 450 and 530 ppm CO_2e require the transformation of the energy system.[8] It has in this context been argued, with a basis in robust evidence, that natural gas–based power generation without CCS technology can act as a bridging technology to achieve a 450 ppm CO_2e concentration by the turn of the century.[19] It has been expected that the increase in the use of natural gas will start to fall by the middle of the century and will continue to decline further in the last half of the century. This scenario is, however, highly dependent on the mitigated or low level of upstream emission of natural gas. Whether or not natural gas can act as a transition fuel toward a low-carbon future is has been thoroughly discussed in the literature. These studies are broadly categorized into two groups. The first evaluates the viability of natural gas to replace coal and/or oil, and to achieve a smooth transition toward a zero or negative-carbon future and its overall impact on GHGs emission.[19-21] The second has questioned the potential delay in achieving a zero-carbon future with the increasing use of natural gas as a transition fuel.[22,23] Another concern with the growing use of natural gas is its fugitive methane emission.[24-26]

Many view natural gas as a transitional fuel in the medium term. However, this is highly debated in the literature, as the potential climate benefit of natural gas can be outweighed by the upstream emission of methane during gas extraction. The mitigation potential of natural gas as a bridging fuel has been evaluated in the literature by developing various scenarios that take into consideration differing shares of coal and natural gas in power generation. Most of the studies on the transitional potential of natural gas have been carried out in the context of the USA and its recent discovery of shale gas reserves. For example, Lenox and Kaplan found that both the total system CO_2 and the system CO_2e emissions have declined across all upstream methane leakage rates [19]. However, they have questioned whether or not, in future and with increasing extraction of natural gas with falling natural gas prices, this fugitive emission may increase, which could offset the total climate benefit of natural gas. Brown et al[27] have expressed a concern that the relative abundance of natural gas might affect the possibility of it becoming a bridging fuel toward a low-carbon future. They argued that in the absence of proper policy intervention, the low price of natural gas may lead to a rebound effect and greater consumption of energy. Michael Levi has developed a "bridge scenario" at the stabilization level of 450 and 550 ppm CO_2e, where it is assumed that the demand for natural gas will increase initially but then fall in the latter half of this century.[28] They have concluded that the impact of the increasing natural gas use is not significant in lowering the temperature increase in order to achieve a 450 ppm level of stabilization, irrespective of the methane emission level. However, they have found that the use of natural gas as a transition fuel can have a greater impact in achieving a 550 ppm level, even with a high rate of fugitive emission. Following the life-cycle assessment of natural gas using a 100-year GWP, Burnham et al have found that when coal-fired power plants are converted into natural gas–based combined cycle plants, GHG emission is reduced by 50% per kilowatt hour electricity generation.[29] This fall in emission is attributed to both the low carbon content of natural gas and the higher efficiency of combined cycle power plants. However, the impact of fugitive emission from natural gas extraction is still unclear. Howarth has concluded that the GHG footprint of unconventional natural gas is even larger than that of conventional natural gas.[26] Busch and Gimon have found that the time frame is important in assessing the environmental impact of natural gas.[19] The impact of replacing coal with natural gas in GHG emission is significant in the long run, given a 2%-4% methane emission. This implies that if upstream emission can be kept within a certain range, then the low concentration of GHG level can be achieved in the long term with a short-term use of natural gas. Furthermore, the scenarios that are being developed to assess the actual impact of natural gas in the background of upstream emission have not taken into consideration carbon capture storage (CCS) and carbon sequestration.

Fugitive emissions of methane are major concern in increase in use of natural gas as transitional fuel.[3] The oil and gas industry contributes 24% of methane emission,[30] which is a potent greenhouse gas (GHG) with a very high warming potential.[3] It is important to have some estimates of methane emission from natural gas extraction in hand as natural gas extraction contains a range of leaks which is varying in levels, from very low to high.[31] Alvarez et al[32] found that in USA emission of methane only in natural gas production is 7.6 Tg/y and total process emission of methane in natural gas industry is 13 Tg/y, which is 60% more than EPA standard. Significant gap in technology is found to be one of the important concerns in identification and mitigation of methane leakage from natural gas field.[33]

Some studies have expressed concern that the use of natural gas as a transition fuel might delay the attainment of a zero- or negative-carbon future.[22,23] It has been argued that a renewable energy system for a zero-carbon future depends on the length of the transitional phase of natural gas. Leapfrogging to a renewable energy future using more innovation would be more viable than using natural gas as a transitional fuel. A considerable investment is required to develop the infrastructure required to transport natural gas. If this is considered to be a short- to medium-term solution, then this investment can be shifted to other sustainable energy-related innovations.[34]

It has been predicted that European gas demand will decline in the future,[17] which may lead to a fall in global gas prices. The falling price of natural gas might enable developing countries in particular to increase their energy access with low environmental impact. Natural gas can provide the opportunity to transition away from coal in cases where it is difficult to move away entirely from coal and oil as an energy source, particularly for developing countries. Another important concern where the capacity share of renewable electricity generation is growing is the support of peak demand using a technology that ramps up quickly. Natural gas–based power generation can provide an important support.

3 | TOWARD A PRAGMATIC SOLUTION: THE ROLE OF TECHNOLOGY AND INNOVATION

The transition discussed in this study is envisaged to take place in the next one to two decades. It is therefore helpful to link this to various SDGs, which are also valid to 2030. This paper, in this regard, discusses[35]:

- Goal 1: End poverty in all its forms everywhere;
- Goal 7: Ensure all are provided with access to modern energy that is reliable, affordable, and sustainable;
- Goal 8: Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all;
- Goal 9: Build resilient infrastructures, promote inclusive and sustainable industrialization, and foster innovation;
- Goal 10: Reduce inequality within and among countries;
- Goal 13: Take urgent action to combat climate change and its impacts;
- Goal 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development.

Large-scale power generation capability would be provided by NG during the transition period, while NG would be replaced by green methane (ie, from power to gas) and thereby support gas-based flexible energy conversion technologies and their development, which in turn represents an investment in the bringing the carbon-free energy system of the future to fruition. All alternatives, including improved energy efficiency, low-carbon energy (natural gas), carbon-free energy (renewables), and carbon-neutral energy (biogas), must be combined if medium- and long-term climate change is to be controlled and managed.

In this section, the key role of innovation in supporting the position of gaseous fuels in the decarbonization of energy systems will be discussed. These technologies and innovative solutions could be applied in various segments of the gas cycle, including production, transmission, retail, and consumption.

3.1 | RES-dependent grid stability and backup

Increasing the share of renewables is globally accepted as a viable way to decarbonize the energy sector. Renewables are, however, inherently intermittent and can also be unpredictable. This can lead to instability of the electric grid. Balancing power will be required to maintain the stability of sustainable energy systems of the future with significant shares of intermittent renewable energy, such as solar or wind power. All grid operators will experience this as a growing challenge, as[5]:

- Intermittent generation significantly affects system stability. This impact includes aspects such as voltage control and frequency control (primary and secondary control). Furthermore, the lower number of conventional power plants, particularly in Europe, results in a lower inertia in the grid.
- Higher levels of voltage instability can result from increased load flows and in turn the loss of reactive power. Conventional gas-fired power plants provide the grid with voltage control. The number of these plants is, however, continuously decreasing, leading to higher levels of grid instability. Voltage stability can therefore only be maintained where a number of initiatives are implemented.

3.2 | Carbon capture and storage (CCS)

Carbon capture and storage technologies can contribute 13% of CO_2 reductions in the power sector.[36] CCS deployment is, however, taking place too slowly as a result of high deployment costs and the lack of political and financial commitment. Advanced CO_2 capture concepts for use in power generation are under development. Their designs are, however, founded on base load, which does not exist in the same way anymore. These technologies should, where possible, be rearranged for load flexibility, the unavoidable penalty of efficiency, and costs being taken into consideration. Some CO_2 capture concepts are poorly compatible or incompatible with load flexibility requirements.

3.3 | Novel cycles

Novel cycles should focus on increasing the ability of new and/or existing dispatchable gas-driven thermal power plants to meet fast load changes through innovative cost-effective solutions. This development would lead to better support of the grid when fluctuations in peak energy demands and power output from renewable sources arise and would do so with minimal fuel consumption and emissions while mitigating the effects of cycling operation. This would avoid excessive wear and reduction in service life. The potential CO_2-capture readiness of power plants would at the same remain unimpeded. The main technologies are as follows[5]:

3.3.1 | Combined cycle gas turbines (CCGTs)

The integration of RES into the grid is supported by the privileged technology of flexible CCGTs and gas-peaking units, through a large load range and fast ramp-up times and start-up. Very high electrical efficiency (>60%) is achieved by modern gas turbines where they are in a combined cycle setup. Minimizing the level of conventional power production is required to secure grid stability; producing as much renewable green energy as possible is the goal. Gas turbine–based combined cycles will therefore play a role in the grids of tomorrow. The contribution from CCGTs in the grid providing grid services is CO_2-free, due to the use of green methane from power to gas. CHP applications of CCGT plants can also provide heat generation and therefore a decarbonization of heat generation. Whether or not the ramping rate of CCGT would be enough to provide grid services is also an issue under discussion. Current plant layout does not provide the level of fast reaction required. Therefore, innovation and further development is needed, although there is no support for this right now.

3.3.2 | Concentrating solar power (CSP)

Concentrating solar power is one of the more viable sources of renewable energy. Hybrid solar gas-turbine power plants, both natural gas and green methane, are a promising alternative to the conventional steam cycle. The water consumption of CSP plants is low. This, combined with competitive electricity costs, makes the deployment of hybrid solar gas turbines an attractive choice in high-insolation desert areas. Such deployment can lead to higher capacity and lower costs, as well as a reduction in our fossil fuel dependence. Key issues for gas turbine–based solar power systems and their future development include the following:

- Gas turbine firing temperatures should be maintained as close to solar receiver temperature as possible, thereby giving low temperatures and low thermal efficiencies;
- Where carbon emissions are to be reduced and the cost of electricity is to be kept low, it is necessary to integrate both thermal energy storage and a bottoming cycle into the hybrid solar gas-turbine power plant (taking away the advantage of low water consumption).

3.3.3 | Supercritical CO_2 (S-CO_2) cycle–based gas turbine plants

The supercritical CO_2 cycle is targeted at a steam cycle with supercritical CO_2 as the working fluid. The use of S-CO_2 not only gives a highly cost-effective solution, but also achieves this with much lower environmental and space impacts than do other CO_2 capture fossil fuel–based energy conversion systems. It should be noted that S-CO_2 GT cycles:

- Can be used to develop gas turbine backup power plants with greater load flexibility and at near-zero emissions;
- Can be adapted to, when operating continuously at their base load operating point, achieve high efficiency (>50%), achieving a CO_2 capture strategy that is both highly cost-effective and integrated;
- Can be easily adapted to external heat sources, including waste heat recovery (WHR) applications, and achieve efficient use.

Furthermore, the implementation of S-CO_2 technology can enhance the decarbonization of various applications and sectors. However, it should be mentioned here that there are many open questions concerning material, sealing, combustion, etc., that require basic research. This basic research however requires high levels of time and cost resources.

3.4 | Large-scale polygeneration/ CCHP plants

There is considerable scope for the achievement of higher energy efficiency and a higher degree of environmentally friendliness in combined cooling, heating, and power (CCHP) generation plants. One of the most attractive novel concepts in the field of worldwide energy consumption in this framework is polygeneration: the simultaneous production of multiple energy vectors, such as electricity, heat, and cooling, and other products such as water, hydrogen, and glycerine. The primary objective of polygeneration is to increase energy efficiency levels via renewable and alternative sources, thereby reducing the environmental impact of energy-related technologies.

3.5 | Distributed and small-/ microscale generation

The most efficient, flexible, and cost-effective low-carbon solution, distributed generation (DG), is the gas-fueled micro-combined heat and power (mCHP) system. This system provides electricity generation and useful heat on-site. It can also provide cooling through the utilization of heat as an energy source in absorption chillers. The mCHP system can also empower consumers by providing them with control of their natural gas and electricity bills, due to the fact that this DG alternative is the most controllable. Furthermore, the system offers important benefits, such as empowering energy costumers, fostering economic growth, decarbonizing heat and electricity production, balancing renewables, and saving primary energy and supporting energy security. MCHP systems can also achieve lower primary energy consumption and CO_2 emissions than conventional boiler and grid-sourced electricity. microgas turbine (MGT)–based CHPs are considered to be one of the gas-fired CHP technologies that is most suitable due to its operational flexibility, controllability, size, volume, reliability, maintenance costs, vibration and noise levels, and its environmental and pollution impact. MCHP unit electrical efficiency can range from 20% (Rankine cycle, Stirling engine) to 50% (for solid oxide fuel cell), the electrical efficiency depending on the technology used. Thermal efficiency (utilization factor) ranges from 40% to 80%.

3.6 | ICT-supported smart energy hubs

Identifying reliable and cost-effective ways of integrating future DG systems into the public grid is achieved with information and communication technology (ICT), taking into consideration operational regime data dependency and complex energy systems' maintenance plans. The "more data, less energy" concept is achieved through the integration of smart energy systems and smart networks/grids via ICT. Sophisticated ICT can make such a "smart grid" possible. In a smart grid, ICT forms an essential control mechanism, matching supply and demand in the most economical way.

3.7 | Fuel cells

The fuel cell working principle is as follows:

- Conversion in a fuel reformer of natural gas (or green methane) to hydrogen;
- DC power generation in the stack from hydrogen, air, and DC/AC conversion in the power conditioner;
- On-board heat exchanger recovery of useful thermal energy.

Fuel cells, though small, are highly efficient. This is the most important fuel cell aspect in relation to other forms of power generation. Clear Edge Power Fuel Cells achieve an efficiency of 42% in electrical power generation and 90% overall full heat recovery efficiency, although this is dependent on application. Furthermore, fuel cells reduce the negative environmental impacts of conventional fossil fuel consumption, primarily as a result of combustion being avoided in which NOx, etc, also is formed. Therefore, fuel cells represent a clean on-site power alternative with low pollutant emissions.

3.8 | Bifuel (gas-gasoline) vehicles

Vehicles fitted with a bifuel system can use two types of fuel. The system allows the user to switch between the two fuels (they are not mixed) and in this way achieve the highest fuel efficiency possible. The price of the fuel rather than efficiency can be the dominant factor behind system installation. Vehicles with bifuel systems can run on only one of the fuels, but less efficiently than when both can be used.

3.9 | Power to gas (P2G)

Power to gas is considered an important contributor to large-scale renewable electricity storage by many of the energy market's key players. The gas grid is a gas storage asset in itself. Gas-based energy conversion technologies can also however convert "green methane" or renewable gas into green electricity on demand. Markets and energy sources are more closely integrated by P2G. P2G, through the use of surplus electricity

TABLE 1 Summary of gas-related technology and innovation

Type of relevant technology	Compensations	Challenges	CO_2 Mitigation
1. Renewable energy systems & grid stability (flexible plant)	Contribution to a totally carbon-free and free source of energy (ie, solar/wind)	- Weather conditions and time of day - High capital costs - Significant O&M cost in comparison with other technologies - Increased voltage instability	Very high
2. Carbon capture and storage (CCS)	—	- High costs and a lack of political/financial commitment - Negatively impact load flexibility - Advanced CCS under development - Lack of enough R&D activities	High (Approximately 13%)
3. Novel cycle: CCGT	- Very high efficiency by using modern GT - Technology developed and available - Low carbon - Acceptable capital cost	Mentioned above	High
4. Novel cycle: CSP	—	- High capital cost - Low temperature - Low thermal efficiency - Technology should be upgraded to increased capacity, lower costs, and a reduction in dependence on fossil fuels	Very high
5. Novel cycle: S-CO_2 gas turbine plants	- Minimum environmental and space impacts - Reducing transmission costs - Low carbon - High efficiency - Highly cost-effective technology	Mentioned above	Medium
6. Large-scale poly-generation/CCHP plants	—	- Relevant infrastructure required - Modern technologies under developed	High
7. Small-/micro-scale and distributed generation (DG)	- Most efficient, cost-effective, and flexible low-carbon solution - Saving energy cost for end-users - High levels of fuel flexibility - Reductions in the costs of transmission and distribution - Contribution into future smart cities and making capable prosumers	Monitoring/operation and control/grid integration/economy	High
8. Natural gas and fuel cells	—	- Very expensive - Not matured technologies	High
9. Bifuel vehicles (gas-gasoline)	—	—	High
10. Power to gas (P2G)	—	Large-scale installation/H2 handling (storage/transport/safety, etc)	Very high

and the hydrolysis of water to produce hydrogen, represents a storage technology enabler and intermittent renewable electricity storage. Furthermore, gas pipelines can transport much higher volumes of energy than can electricity transmission lines; P2G acts therefore as a transport option. The conversion from H2 to CH4 does, however, reduce total efficiency considerably. The synergies provided by fossil fuels, S-CO_2 power plant technology with oxy-combustion, P2G, and methanization, can play an important role in storage and energy backup. CO_2 separation can also be made easier through the easy integration of the P2G concept and the adoption of hydrogen and/or oxygen through oxy-combustion (Table 1).

Levelized cost of electricity (LCOE) is often cited as a convenient summary measure of the overall competitiveness of various generating technologies. As The Institute for Energy Research (IER) has stated the maximum percent of levelized capital costs of new electricity generation technology in recent years is owned by Solar PV. On the other hand, natural gas advanced/conventional combined cycle has the lowest average levelized capital cost at approximately 25% of all new electricity generation technologies in Figure 2. Looking across the technologies in this figure, wind and solar represent more than half of all LCOE %.

4 | CROSS-COUNTRY INVESTIGATION: A STEEP ANALYSIS

In this section, the role of natural gas is explored as a future sustainable energy source, a secure energy supply source, and as a means to promote a clean environment, as illustrated by examples from multiple country contexts. The countries taken into consideration meet the two following criteria: their respective development status (developed or developing) and natural gas trade status (net importer or exporter). The countries selected are India, Iran, the United Kingdom, and Norway. These four countries have different energy use profiles, energy reserves, energy policies, and development goals. Together, they form an interesting combination in terms of their use and supply of natural gas (Figure 3). Iran has 91% of the total natural gas reserves of the four countries. Production and consumption of natural gas are also significantly high in Iran, 52% and 60%, respectively. The large reserves of natural gas in Iran are one of the main reasons behind the high dependence on natural gas. On the other hand, production of natural gas in Norway is 30% of the total for these four countries. Norway's natural gas domestic consumption is, however, very low. Approximately 86% of the natural gas produced by Norway is exported. India and the UK are import dependent, their reserves and production being small in relation to the two other countries. This variance in production, consumption, reserves, and trade share of natural gas makes the selection of these four countries interesting. The diverse characteristics of the selected countries make the results more representative and make it possible to arrive at general conclusions on the use of natural gas as a transition fuel.[16,37,38]

We have selected a few indicators of development to help us understand energy access to energy reserve pattern and the development status of the countries considered. These are summarized in Table 2. Iran and Norway are in a good position with respect to their domestic reserves of conventional energy resources such as coal, oil, and natural gas. They both possess a significant proportion of the global reserves and export a large proportion of their domestic reserves. On the other hand, domestic reserves of NG sources are not significant for India and the UK. Their energy import is also high. According to the Global Energy Architecture Performance Index 2017,[39] which ranks: (a) economic growth and development, (b) environmental sustainability, and (c) energy access and security, Norway ranks as number 2, the UK as

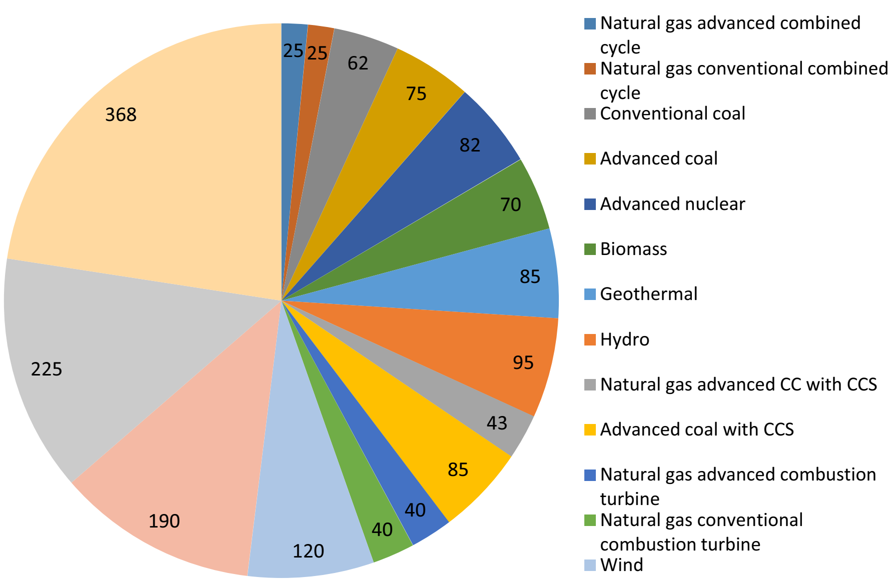

FIGURE 2 Percent of levelized capital costs of new electricity generation technologies in recent year ($ per MWh)[53]

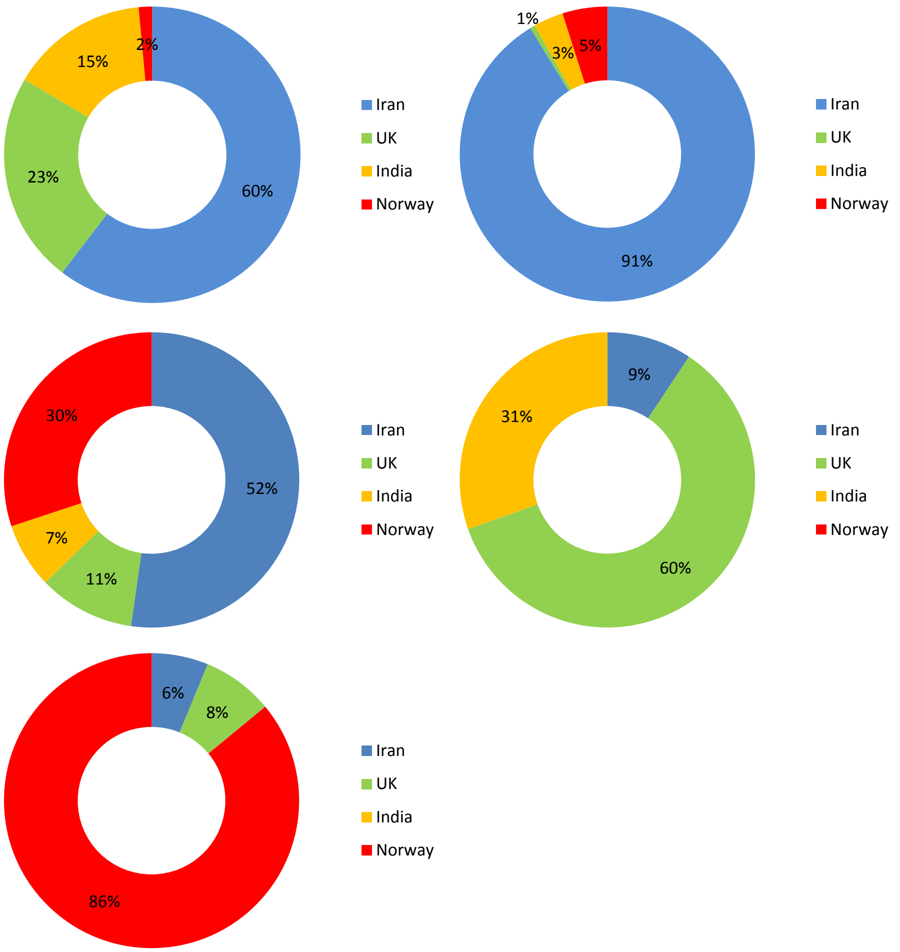

FIGURE 3 Distribution of natural gas indexes by countries in 2016

number 14, India as number 87, and Iran as number 120 out of 127. The very large share of global conventional energy reserves and energy export means that the energy security of both Norway and Iran can be considered to be very high. The energy security of both India and the UK, based on a moderate reserve of conventional energy sources and a considerably high energy import, can be considered to be medium. However, the issues relating to use of natural gas as a transition fuel for the countries with and without domestic reserves are different. Per capita, the GDP is considerably higher for Norway and UK than the world average of USD 10150[40] at the time of this writing. The entire population of both these nations has access to electricity. Per capita, the GDP of both Iran and India is less than the world average. It is particularly low for India. However, almost the entire population of Iran has access to electricity (Table 3).

4.1 | Sectoral policy push for natural gas

4.1.1 | India

There has been a strategic policy push in India to increase the use of natural gas and its derivatives. The policy push for the residential sector, which enables the shift to LPG, has primarily been focussed on replacing cooking fuel (firewood and chips, dung cake, and kerosene) with LPG. The policy push has aimed to create affordability and accessibility to cleaner fuel for the economically poor section of the population. Under *Rajiv Gandhi Grahmin LPG Vitaran Yojana*, 42 million rural households have benefited as of 2012, and 25 million economically poor users have been benefitted under *Pradhan Mantri Ujjwala Yojana* as of June 2017. These policies include both subsidies and one-time financial assistance. The subsidy initially had a broader base, but has been gradually removed for the affluent population and retained only for the poorer segment of the population. The subsidy removal policy, named "*Give it up*," is basically voluntary. The policy aimed to achieve a better distribution of the subsidy by giving it to those who had a real need for it. The "*Pahal*" scheme was initiated after 2015 to transfer the subsidy directly to the consumer and to increase transparency in the financial assistance distribution system. Subsidies and financial assistance are also provided to facilitate the distribution network so that more distributors can be created and incentivized. Both CNG and LPG have been tried in the transport sector, depending on accessibility to the resource across the states. While CNG was pushed in states such as Delhi, Maharashtra, and

TABLE 2 Energy and development interface[38,40]

	Conventional energy reserve as percentage of world's total reserve (2016)								
	Coal	Oil	NG	Share of energy import in total energy use (2015)	Energy supply security	Prevalent source of energy	Per capita GDP at current USD (2016)	Access to electricity (2014)	Phase in development process
India	8.3%	<0.05%	<0.05%	34.31%	Medium	Coal & biomass	1680	79%	Developing
Norway	<0.05%	0.4%	0.9%	-583% No import	Very high	Hydro	82 330	100%	Developed
Iran	<0.05%	9.3%	18%	-33.4% No import	Very high	Natural gas	6530	99.44%	Developing
UK	<0.05%	0.1%	0.15	39.7%	Medium	Natural gas	42 390	100%	Developed

Gujarat, LPG was initially pushed in cities such as Kolkata, Bangalore, Ahmedabad, and Chennai. The power sector is a major commercial consumer of natural gas in India. To improve the supply of natural gas, the policy has targeted improving infrastructure by constructing new domestic and cross-border interstate pipelines. The 458-km Kochi-Salem pipeline and 1987-km Gujarat-Gorakhpur pipeline are two important domestic pipelines for improving gas supply within the country. Two major international pipeline projects have been proposed: the Iran-Pakistan-India (IPI) pipeline and the Turkmenistan-Afghanistan-Pakistan-India (TAPI) pipeline. However, geopolitical uncertainty is the major barrier to their progress and completion. LNG terminals are developed exclusively for the long-distance import of LNG. India's LNG import is currently mainly through four terminals, which constitute 45% of the total gas supply in India. These four terminals are mainly located on the west coast of India. India is now planning to develop LNG terminals on the east coast. The supply shortage and absence of required infrastructure is the major barrier to India becoming a gas-based economy.

The scope of natural gas in India, in terms of CO_2 reduction, mainly lies in the electricity and transport sector. Natural gas accounts (in power generation) for only 11.5% of the thermal capacity and 7.75% of the total installed capacity in 2016-2017. Electricity demand in India will, in the coming decade, rise twofold from 1235 to 2400 TWh by 2030.[6] The share of renewable energy in power generation will also rise in the future. However, coal will continue to dominate Indian power generation in the near future. Fuel switching within thermal capacity can therefore be an important additional mitigation option for India. According to the Central Electrical Authority of India, the emission factor of natural gas from the Indian power generation sector is 0.47 tCO_2/MWh, which is 45% less than the emission factor of coal-based power plants in India.[41] An effective short- to medium-term GHG mitigation option for India can be to switch thermal generation from coal- to gas-fired power plants. The high rate of urbanization means that the demand for energy by the transport sector will also rise in the coming decade. Oil has been the dominant fuel in the Indian transport sector. The transport sector's share of total CO_2 emission is approximately 7.5%, which has shown an annual average growth rate of 4% since 1994.[42] Electrification of the transport sector is difficult to achieve in the near future. Better natural gas penetration in the transport sector can, however, contribute to CO_2 reduction.

4.1.2 | Norway

Domestic consumption of gas in Norway is low. More than 95% of the gas produced in Norway is exported. Where crude

TABLE 3 Energy-environment sustainability potential with technological upgradation and more NG in the energy mix[54-57]

		Technological upgradation		Energy Mix		
	Scope for fuel mix	Technology	Additional mitigation potential	Dominant source of energy	Switched mainly to	Result in
India	High	CCHP, CCS	Very high	Coal	Solar and NG	Low carbon and carbon free
Norway	Low	Polygeneration	Low	Hydro	Bioenergy and wind	Carbon neutral and carbon free
Iran	Very high	CCHP, micro-CCHP, CCGT, CCS	Very high	NG	Solar and wind	Carbon free
UK	High	CCHP, micro-CCHP, CCS	High	NG	Solar and biogas	Carbon free and carbon neutral

oil is included, petroleum exports amounted to approximately 47% of the total value of Norway's export of goods in 2016. Natural gas export accounts for 22% of this, and the revenues from this export are of great importance to the Norwegian economy. A significant proportion of the income derived from oil and gas has been invested in "The Government Pension Fund Global" (current value of NOK 8237 billion).

Norway therefore has a major interest in the continuation of natural gas as a part of Europe's energy solution and wants to see natural gas remain in the energy mix and eventually replace coal in the transition into a renewable future. Countries directly connected to Norwegian reserves by the Utsirahøyden gas pipeline and NCS pipeline are those that are most relevant for future exports. Large volumes of Norwegian natural gas are therefore imported by France, Belgium, Germany, and the UK.

Liquefied natural gas is exported mainly from the Snøhvit field in Norway. New markets that gas liquefaction can open beyond the gas pipeline infrastructure are, however, difficult to reach. Progress in the global market is slow, partly due to high LNG plant costs. The transport of LNG in the summer to Asia from Norway may be made possible where The Northern Sea Route can be used, thereby reducing distance. The facility on Melkøya is well positioned for LNG export along the Northern Sea Route. Investment in LNG facilities at well-suited locations may, for some scenarios, be a sound long-term strategy for Norway. It is however highly uncertain due to a great deal of competition from other sources and the future risk of stranded assets.

There are few sectors within domestic use in which natural gas is being pushed. There has been some oil to gas fuel switching in industries, but the potential here is limited. There has been a rapid replacement of fossil fuels with electrification in the Norwegian transport sector. Generous tax and fee exemptions, unique license plates for EV, permitted EV use of bus lanes, and falling EV prices have led to a boom in electric cars in Norway. New electric heavy transport vehicles will also soon be on the market. Examples include Tesla's truck and the Nikola 1 hydrogen fuel cell truck.

Initiatives to create an infrastructure for hydrogen cars, one that is not based on natural gas reformation but on electrolysis, have been attempted. In Rogaland, the Lyse Company furthermore combines upgraded biogas with NG for use in transportation. Hence, in the transport sector, biogas is seen as a far better option than natural gas, for two reasons: greenhouse gas emissions (GHGs), and the fact that Norway—with the exception of Rogaland—has no gas distribution network. An EV charging infrastructure based on renewable hydroelectricity is being expanded. Furthermore, home charging is also well established. Developing a new natural gas infrastructure in Norway therefore does not make sense.

A far more promising natural gas transport solution is marine transport. The emissions from marine transport can be potentially, significantly reduced by natural gas. Even here, the focus in Norwegian marine transport is however increasingly on the electrification of short-distance ferries. However, the national climate policy and negotiations with the EU place a high priority on large GHG emission cuts in the transport sector.

4.1.3 | Iran

Iran is in an excellent strategic position to benefit both economically and politically from this growth in demand, due to having one of the world's largest reserves of natural gas and an excellent geographical location for energy transit. Efficiency of domestic appliances has increasingly been improved to use natural gas more economically and safely. Operating costs of natural gas–based equipment are generally lower than those of other energy sources.[43]

Due to its geographical and politically strategic position, Iran can play a leading role in the global gas supply and act as a bridge between the enormous Middle Eastern gas reserves with major gas consumption and demand centers in Europe and Asia. Natural gas has the fastest consumption growth rate among the world's primary energies and the highest consumption growth among developing countries.[37] The Iranian government has therefore increased its rural and urban natural gas pipeline network investment and credit allocation.

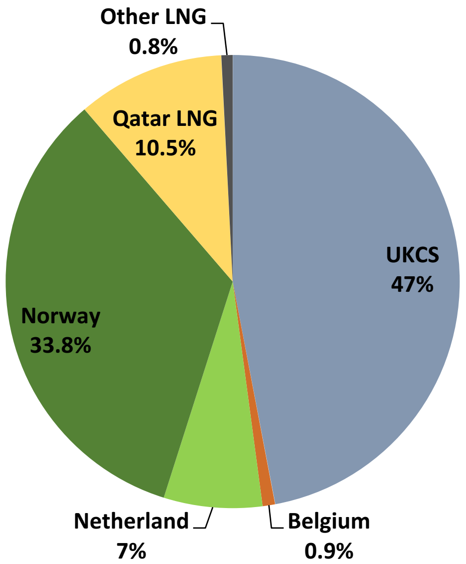

FIGURE 4 UK gas supply sources 2013[45]

Policy and sanctions on Iran suggest that, as with oil, natural gas will hasten the shift of power away from the west toward both the Persian Gulf and Asia, thus becoming an ever more important factor in geopolitics.[44] Development of Iran's natural gas industry to the point where it is able to meet demand in these nations would bring considerable revenue to the country, potentially enough to offset much of the economic impact of sanctions.[43]

The national Iranian gas company has adopted the policy of increasing the gas supply safety margin through construction of gas networks in diversified routes, implementation of underground storage projects, and construction of national and regional control and dispatching centers.[37] The policy of natural gas export to Europe, for example, to Italy, is pushed toward LNG. On the other hand, Iran can develop and expand its gas pipelines to export natural gas to Europe via Turkey. Tehran proposed the construction of an LNG plant in the Iranian port city of Chabahar as part of a plan to ship LNG to India, bypassing Pakistan.

Gas supply to distant areas via CNG to increase availability and general welfare and provide environmental benefits is another natural gas policy in which Iran's government pushes transport and residential sectors. Increasing the strategic natural gas storage of the country is another policy to increase the impact on the global gas market. Iran's policy to increase the impact on the global gas market is to increase the strategic natural gas reserves in the country.

4.1.4 | UK

The most important energy source in the UK is natural gas, as 80% of UK homes are powered by gas and 25% of the UK's electricity is generated by gas-fired power stations.[37] In the UK, gas is supplied by North Sea producers through pipelines from Norway, Belgium, and the Netherlands through shipments of LNG from more distant fields and gas storage.[45] The UK's infrastructure is able to deliver over 700 mcm of gas per day, well over double the average winter demand (243 mcm/d in winter 2013/14) and over 50% more than the highest single-day demand ever recorded in the UK (465 mcm). These diverse sources are capable of providing significant volumes of gas to meet the UK's requirements. This means that the UK gas market is resilient. A low probability but high impact event still remains a risk, which the UK government takes seriously. The UK has one of the largest gas markets in Europe, an extensive import infrastructure, and a diverse range of gas supply sources. It is therefore well placed to manage gas supply risks (Figure 4).[45]

The island nature of the UK means that pipelines are subsea, four running from the European continent to UK. These are the UK-Belgium interconnector (IUK) with an import capacity of 25.5 billion cubic meters (bcm) a year, the UK-Netherlands pipeline (BBL) with an import capacity of 14.2 bcm a year, the Vesterled pipeline link connecting St Fergus in Scotland to a number of Norwegian gas fields with a capacity of 14.2 bcm a year, and the Langeled pipeline from Nyhamna in Norway to Easington in Yorkshire (the 1200-km pipeline being the longest underwater gas pipeline in the world) with a 26.3 bcm capacity.[37]

The UK has three LNG import facilities (Dragon, Isle of Grain, and South Hook). Together, these three are capable of supplying nearly 50% of annual demand. Europe has provided the UK with strong energy security and a reliable and easy consumer access to energy at reasonable prices.

The UK's oil and gas imports are increasing. The UK will compete for its oil and gas with potential emerging economy markets such as China and India. This could represent a potential future political issue which the UK government should address. This can furthermore explain the political support of the renewable energy sector by the UK government, renewable countering the country's heavy reliance on oil and gas imports (Table 4).[46]

The government's political decisions are furthermore influenced by global warming and commitments to reduce carbon gas emissions. Renewable obligations oblige providers to supply specified levels of energy from renewable sources. Switching to renewable energy is also essential if long-term strategic plans are to be realized. These changes are, currently, not affordable, despite the UK having almost 30 low carbon energy tax credit and subsidy incentive programs. The UK's energy sector will therefore, in the short and medium term, be focussed on oil and gas.[47]

4.2 | A STEEP analysis

The concept of sustainability is discussed extensively in the literature. Understanding any kind of sustainability issue requires

TABLE 4 Sectoral scope of natural gas in India, Norway, and Iran

	INDIA		NORWAY		IRAN	
	Policy/Society/Environment	**Infrastructure/Technology/Economy**	**Policy/Society/Environment**	**Infrastructure/Technology/Economy**	**Policy/Society/Environment**	**Infrastructure/Technology/Economy**
Residential	1. Subsidy on LPG for residential use[a] 2. Increasing access to LPG in economically poor area[b]	1. Increasing LPG distributorship in economically backward area to increase the availability[c] 2. In case of subsidy direct benefit transfer to the consumer[c]	CO2 tax on NG for residential use	Currently no plans for domestic pipeline distribution. Instead, there is a possibility that natural gas will be banned for heating purposes in residential buildings	1. Increasing the availability and environmental benefits by accessing CNG for about 90% of inhabitants 2. Supply CNG to distant area	1. Increasing investment and allocation credit for rural and urban natural gas network
Commercial	1. Macroeconomic policy regulation like duties and tariff structure to encourage investment in hydrocarbon sector 2. Additional investment for refining sector	1. Construction of interstate national pipeline for better distribution[d] 2. Proposed under construction cross-border pipeline[d] 3. Construction of new LNG terminals[e]	Some interest organizations (like Energigass Norge) are working to increase the use of all types of gas (biogas, natural gas, propane, butane, and hydrogen)	Domestic consumption of gas in Norway is low. There are only two pipelines for domestic distribution (both in the county Rogaland). Nearly all the produced gas is exported. A network of subsea pipelines links Norway's offshore gas fields and onshore terminals to other European countries. There are four production facilities for LNG in Norway. The only large-scale plant however is the Snøhvit field off Hammerfest		1. Increasing LNG allocation in natural gas trade 2. Construction of new LNG terminals 3. Export LNG to Europe countries 4. Export of wasted and burned natural gas as FLNG
Industry				Fuel switching from oil to gas in industries, but limited potential	1. Replacement of diesel and gasoline by NG 2. Direct conversion of NG to liquid and other product such as GTL	1. Largest growth in NG come from petrochemical, power sectors, and other industries
Transport	1. Conversion of diesel-based public transport to LPG and CNG through judicial intervention[f]	1. Construction of new gas refilling stations to connect the places[g]	The authorities have given priority to zero emission vehicles (electric, hydrogen fuel cell) and vehicles on climate neutral fuels (like biogas). Hydrogen production from natural gas will require carbon capture and storage (CCS) to be a viable option in Norway. Natural gas is mostly seen as an option in marine transport	Both electric and hydrogen infrastructures are under construction and expanding	Development of dual-fuel (gasoline-NG) cars	1. Construction of new gas grid to Europe via Turkey 2. Construction of ship LNG to India, again bypassing Pakistan

[a]Indian Oil Corporation Ltd.
[b]http://www.pmujjwalayojana.com/Ministry of Petroleum and Natural Gas
[c]Ministry of Petroleum and Natural Gas, GoI
[d]Petroleum & Natural Gas Regulatory Board
[e]www.petronetlng.com
[f]R Anumita, 2010, 'CNG Programme in India: The Future Challenges', Centre for Science and Environment: Fact sheet series 2010
[g]www.indiastat.com

the analysis of the social, economic, political, technological, environmental, and legal parameters. Together, these parameters form the PESTEL framework. We do not take legal sustainability into consideration in the context of this paper. Instead, we adopt STEEP analysis which utilizes five sustainability dimensions. They are social (S), technological (T), economic (E), environmental (E), and political (P).[48-50] All these sustainability parameters must be justified to understand whether natural gas can play the role of transition fuel in the achievement of a sustainable energy solution. The STEEP framework has been applied to integrate different issues with identified key drivers and potential barriers. These should be addressed by policymakers to ensure the increasing use of natural gas.

4.2.1 | Social sustainability

Both developed and developing nations have recognized that economic growth with fewer burdens on the environment has become inevitable. They have realized that achieving the integration of climate and development strategies across multiple sectors is a necessity. Enhanced energy access with less or no environmental harm has become the social responsibility of all nations around the world.[1] A social enabler of greater natural gas use as a transition fuel could ensure access to modern energy (for both electricity and cooking) in a developing country such as India. It is, however, difficult to plot any societal context for using natural gas in a country like Norway, which has the highest electricity consumption per capita in the world and 100% electrification. Climate goals have inherently become a part of social development in Norway, meaning that replacing oil with natural gas in the industry and transport sectors could be a way forward for this country. Iran, which possesses a significant global reserve of natural gas, and has an energy system dependent on natural gas, can reduce its overreliance on fossil fuel by balancing use with renewable energy. Growing energy demands and strong population growth (0.8%) in comparison with the other European nations (0.5%)[40] are one of the social

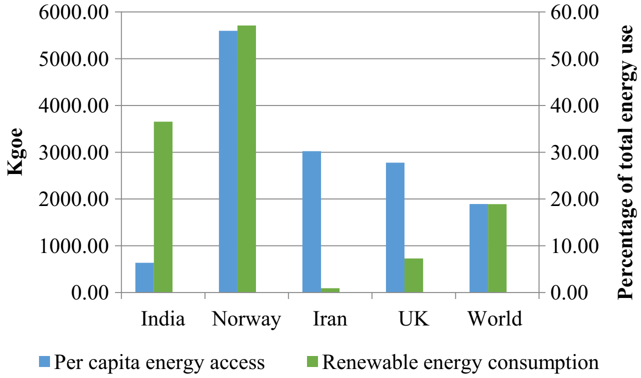

FIGURE 5 Percentage of total energy use for different countries

factors that could be taken into consideration. The entire UK population has access to electricity. It is therefore difficult to meet this huge demand in the near future with only renewable sources, which underlines the role in the UK of gas-fired power plants (Figure 5).

4.2.2 | Technological sustainability

The share of renewable energy in total energy use will increase globally in all countries. Natural gas power plants can therefore be an important support for balancing the load on the grid in the event of intermittency of the renewable energy system. The quick peaking time of this is one of the biggest technological enablers of the integration of natural gas with low-carbon energy supply technologies. Furthermore, this could contribute to mitigation pathways of the future. Natural gas used with efficient technologies could prove to be an important source of mitigation. One of these technologies is carbon capture and storage (CCS). This is expected to reduce GHGs mitigation from 50% to 85% worldwide by 2050.[8,9] However, CCS is yet not a commercially proven technology. Successful CCS implementation must, however, be achieved in developed countries before this can be of use to developing countries such as India. Norway has taken the lead in investing in CCS research. Methane emissions in the exploration of natural gas are highly debated in the literature. More technological intervention is needed in the exploration of natural gas to reduce the fugitive emission of methane.

In Iran, the low cost of electricity and gas makes it impossible to achieve a reasonable payback period for the implementation of energy efficiency measures such as building wall insulation.[51] The annual increase in electricity consumption in Iran and the need for the construction of new power generation facilities have led to the development of policies that encourage parallel connection to utility national networks selling electricity generated by local CHP and CCHP installations, as noted by Iran's Ministry of Energy.[37] The availability of natural gas through the nationwide piping network system encourages the utilization of natural gas for CHP and CCHP systems in Iran, especially during spring, summer, and fall, as creating a higher demand for the available excess capacity favors the utility.

4.2.3 | Economic sustainability

Both production and proven reserves of natural gas have shown a steady increase globally since 1970.[52] The global supply of natural gas has also increased with the increase in gas production in the USA, following the discovery of shale gas.[17] This ensures a steady supply price of natural gas for importing countries such as India and the UK. Iran and Norway are two of the biggest natural gas exporting

TABLE 5 STEEP parameters

	India	Norway	Iran	UK
Social	*Enabler-* Enhanced access to clean energy input for cooking and electricity	*Enabler-* Population growth, but the demand for energy from mainland Norway has been declining slightly from 2010 and onwards. No energy (or fuel) poverty in Norway	*Enabler-* Largest growth in NG usage comes from petrochemical plants, power sectors and other huge industries	*Enabler-* Developed culture for optimized energy management and consumption Wide access to modern energy
	Barrier- Land acquisition and displacement for pipeline expansion	*Barrier-* Availability of large hydropower resources, growth in other renewable energy resources together with national GHG emission targets and policies limits the use of natural gas domestically	*Barrier-* Population growth and increasing demand for safe and clean energy	*Barrier-* Strong population growth and increasing demand for energy Growing pressure for reducing emission from its own population
Technological	*Enabler-* Known proven technology Flexible/peaking power supply	*Enabler-* NG with CCS—high potential for emission reduction, but compete with technological developments related to renewable energy	*Enabler-* CNG as a gas supply method to distant areas to increase the availability and environmental benefits Mature technology of gas turbines and gas compressors	*Enabler-* The UK economy is capable of developing expertise in a wide range of renewable technologies due to the availability of facilities and manpower
	Barrier- Physical distance from the importing countries Geological uncertainties	*Barrier-* Domestic use of natural gas in large quantities requires a breakthrough for CCS technologies, which has not yet materialized	*Barrier-* Lack of modern technologies for growth in production of natural gas Shortage of knowledge in direct conversion of NG to liquid (and other products) such as GTL technology Lack of construction of new LNG terminals	*Barrier-* Lack of appropriate skills compatibility The required infrastructures which needs a huge investment to come by
Economic	*Enabler-* Improved energy efficiency and energy intensity	*Enabler-* NG (and oil) exports important for economic growth and national income	*Enabler-* More export of natural gas–based electric power will lead to high trade balance Increasing investment and allocation credit for rural and urban natural gas network Growth in natural gas revenue	*Enabler-* The UK government is currently working on creation of interesting investment opportunities for the investors
	Barrier- Supply bottleneck Investment for infrastructure development Price competitiveness	*Barrier-* Investment in infrastructure development Price competitiveness Low electricity prices Expected increase in carbon price	*Barrier-* No specific comments	*Barrier-* Unemployment which is a direct consequence of economic meltdown

(Continues)

TABLE 5 (Continued)

	India	Norway	Iran	UK
Environment	*Enabler-* Reduced GHG emission Reduced urban/rural indoor pollution	*Enabler-* Some potential for GHG emission reductions (with fuel switching from coal and oil to NG) in industries and marine transport	*Enabler-* Less in carbon content comparing crude oil Increasing LNG allocation in natural gas trade and then less environmental impact Export of wasted and burned natural gas as FLNG	*Enabler-* Target for the UK to reduce its greenhouse gas (GHG) emissions by at least 80% from 1990 levels by 2050
	Barrier- Fugitive methane emission Upstream carbon emission Water stress relative to renewables	*Barrier-* Increased use of NG domestically will in many instances increase national GHG emissions	*Barrier-* Overreliance on fossil fuel (like NG) resources leads to environmental concerns	*Barrier-* Cold and unstable weather results in high consumption
Political	*Enabler-* Overcompliance with Paris commitment by reducing share of coal use in energy mix	*Enabler-* Some political will (among some political parties in Parliament) to increase the use of NG domestically	*Enabler-* Governmental incentive for growth of gas-based DG energy systems Export of NG to European countries after signing the Joint Comprehensive Plan of Action (JCPOA)	*Enabler-* To reduce import bill Short term and mid-term, the main focus of the energy sector in the UK will be concentrated on oil and gas in the main
	Barrier- Geopolitical instability Increase in import bill	*Barrier-* Increased use of natural gas domestically disputed in Parliament National GHG emission targets and policies limits the use of natural gas domestically	*Barrier-* Problems in construction of new gas grid to Europe via the neighbors like Turkey	*Barrier-* Low available sources Global warming and commitment to reducing carbon gas emissions UK should compete the potential markets with emerging economies like China and India for its oil and gas

countries in the world, and the export of natural gas is an important component of their national income. Increased demand for natural gas globally will therefore boost the macroeconomic parameters of these countries, and the increased use of natural gas in transport, industry, and other sectors will help improve the energy efficiency of these countries. However, the greater use of natural gas involves a considerable amount of investment in infrastructure development.

4.2.4 | Environmental sustainability

One of the important enablers of natural gas as a transition fuel is its low carbon content. Its low emission potential increases even when integrated with efficient technologies such as CCGT and CCHP. However, emissions of methane during the extraction of natural gas are an important environmental concern. Methane is the main component of natural gas, which has a higher global warming potential (GWP) than does carbon dioxide (CO_2). The 100-year GWP is 34 for methane, which implies that its warming impact is 34 times more than CO_2.[8,9] Fugitive emission during the extraction of natural gas is one of the biggest environmental barriers for natural gas, GWP for over 20 years rising to 86. Methane is a short-lived gas. Its GWP is therefore higher in a short-term perspective. Greater use of natural gas in a scenario where almost the entire world is moving toward a global solution for a zero- to negative-carbon future may not be viewed as being an environmentally sustainable solution.

4.2.5 | Political sustainability

The political context of natural gas is different for these four countries. Norway's natural gas story is made up of two stories that are very different. One concerns the export of natural gas to Europe and the other concerns natural gas domestic use. Climate change was placed on the political agenda in the late 1980s. The export of natural gas from Norway has been viewed as a means of mitigating climate change by giving coal-dependent nations in Europe the opportunity to substitute coal with natural gas. Since the early 1990s, all governmental and white papers have argued (and still do) that Norwegian gas is good for the environment. This also forms the primary justification for the expansion of oil and gas activities, including into the Arctic.

Greater domestic use of natural gas has, however, been highly controversial and disputed in Norwegian politics. This is for one obvious reason—that the electricity sector in Norway is almost 100% hydropower. Hence, hydroelectricity is the dominant source of Norwegian energy consumption, and heating. Natural gas can only reduce GHG emissions where it replaces other fossil fuels. Efforts have been made to increase the domestic natural gas use. The potential is, however, limited. Investment in new renewable energy such as small-scale hydro plants, the upgrading of large existing hydro plants, and in onshore wind power affords Norway a large emission-free electricity surplus. This surplus can be used either domestically to replace natural gas, for example, in district heating, or be exported to neighboring countries. Attempts to use natural gas for electricity production have failed disastrously, such as the natural gas-fired power plant at Kårstø, which was terminated and dismantled in 2016. Climate change concerns will therefore continue to limit domestic use of natural gas. Natural gas will, at home in Norway, play a very limited role in the country's sustainable energy future. However, the extent to which Norwegian natural gas plays a role in Europe's sustainable energy future is a very different matter. Growing numbers of political players are also questioning the role of natural gas as a transition fuel and, furthermore, are also questioning petroleum activity expansion in the Arctic. Upcoming domestic political struggles will include just these questions (Table 5).

5 | CONCLUSION

Global energy sources are, in the next two decades, to move from high-carbon to low-carbon energy sources to prepare the roadmap for a zero-carbon future. Oil and gas will, however, continue to dominate the market. Ignoring this reality will lead to misleading policy action. Debate on renewable versus oil and gas dominance is likely due to fugitive emission risks from gas. The practical relevance of gas-based power generation where renewable penetrates more quickly in many countries, however, needs careful discussion and deeper analysis. Keeping natural gas and oil in the demand and supply equation will avoid bias in picking multiple technological innovation and learning both in power generation process technologies and in end of pipe solutions, such as carbon capture and storage, while maintaining the current resource endowment and human capacity engaged. Four country studies show that there is a need for bringing low-carbon fossil fuel into the energy transition discourse to address the economic, political, and societal needs of the countries. However, a much broader and open dialogue is required if this discourse is to remain focussed on the long-term goal, rather than it being pushed aside.

KEYWORDS

companion to renewable energy, energy transition, natural gas, sustainable development

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