is shale gas an attractive transition energy option for India?

Lawrence M. Cathles III

India has significant shale gas resources that can be developed with less surface and environmental impact as compared to other energy options. Encouraging the development and use of shale gas can significantly decrease greenhouse gas emissions, and shale gas recovery will foster technological developments that could further expand the gas resources, perhaps even to include gas hydrates. Gas can provide the time needed for transition from fossil fuels to sustainable zero-carbon energy sources. However, gas (and oil) is not a permanent solution because, at the projected consumption rates, the resources will not last much more than a century; but a century is an adequate duration for transition.

India is presently an energy-poor nation. Even though India is the fifth largest producer of electrical energy in the world [1], the average Indian consumes about 85 W as compared to an EU citizen's 688 W [2], and over 300 million Indians have no access to electricity [1]. In 2010, India consumed 0.68 Gtoe (billion metric tons of oil equivalent) of fossil fuel energy [3], which is equivalent to 772 W of primary energy per capita. In the European Union, the per capita primary energy consumption is ~4970 W [4]. To reach the EU standard of prosperity, India needs to increase its primary and electrical energy supplies by a factor of 7-8.

If India is to increase its energy supply to the EU level in the next century using fossil fuels, about 238 Gtoe will be required (at the present consumption rate of 0.68 Gtoe multiplied by an increase factor of 7 divided by 2 to give an approximate average). This could be provided by coal, but might as well be provided by non-conventional gas resources.

In India's current fossil fuel supply, coal leads with a share of 63%, followed by oil (30%) and gas (7%). India's coal reserves are huge. They are enough to sustain India's present levels of primary energy consumption for 285 years (Table 1). On the other hand, India's reserves of oil are negligible, and its reserves of conventional gas are modest [3]. But this situation may be changing. The ability to recover gas from shale has caught the world by surprise. Countries like the United States, which were just a few years ago building LNG facilities to import gas, are now preparing to export natural gas from resources like the Marcellus Shale, which alone has producible reserves of ~12.5 Gtoe (489 tcf) [5]. India may have similar-sized shale gas resources [6], and Southeast Asia has huge resources of seafloor hydrates, which might one day be recovered [7]. If India is to increase its energy supply to the EU level in the next century using fossil fuels, about 238 Gtoe will be required (at the present consumption rate of 0.68 Gtoe multiplied by an increase factor of 7 divided by 2 to give an approximate average). This could be provided by coal, but might as well be provided by non-conventional gas resources.

Table 1: India's Fossil Fuel Consumption (2010) Compared to Reserves [3] and Resources (the Last Two Rows)

	Consumption (Gtoe/yr)	Reserves or Resources (Gtoe)	Commodity Reserve Life (yr)	Total Supply Reserve Life (yr)
Coal	0.425	193.24	454	285
Oil	0.206	0.8	4	1
Gas	0.047	1.1	24	2
Shale gas		6.7*	144	10
Hydrates		387**		571

*Notes: The commodity reserve life is the reserve of a particular commodity divided by the consumption rate of that commodity (Column 1). The total supply reserve life is the length of time a commodity could supply India's total 2010 fossil fuel consumption of 0.68 Gtoe (total of Column 1). *Reference [6]; **Reference [8].*

The focus of this issue of energy^{n} manager is on whether natural gas is a promising transition energy option towards a sustainable energy future. For India this depends on the amount of gas India can tap in the next century, the relative risks and benefits of alternative fuel options, and how the transition time provided by gas is utilized. Of late, discussion on such issues has been intense in New York State, and some of these deliberations may be of general value.

How Much Gas Can India Tap? Conversion of Resources into Reserves

As a resource geologist I have long been struck by the tendency of every generation to believe that they have found all the resources there are to be found and the future holds only the doom of depletion. However, economists have a different view, and I believe that their view is closer to reality. At least it is a view worth understanding and considering in the current discussion.

Historical experience suggests that, in the long run, technology can be expected to cap price increases and convert resources into reserves right up to the point where close to all the resources that can possibly be recovered (the so-called resource base) have been recovered. The road may be bumpy. As the present reserves are depleted, prices rise and technological innovations that convert resources to reserves are encouraged and funded, whereupon prices fall. Economists like Rogner [7] have argued, convincingly I think, that this bumpy oscillation will continue until the resource base is nearly all recovered.

In economic terms, reserves are stocks of a commodity that are producible with current technology under current economic conditions. They are continuously replenished from resources, which are known or suspected quantities of the commodity that are currently not profitable or possible to recover. Historical experience suggests that, in the long run, technology can be expected to cap price increases and convert resources into reserves right up to the point where close to all the resources that can possibly be recovered (the so-called resource base) have been recovered. The road may be bumpy. As the present reserves are depleted, prices rise and technological innovations that convert resources to reserves are encouraged and funded, whereupon prices fall. Economists like Rogner [7] have argued, convincingly I think, that this bumpy oscillation will continue until the resource base is nearly all recovered.

From this perspective, one can optimistically say that the ~238 Gtoe of non-conventional gas needed for gas to be a true alternative to coal for India could be available in 30 to 40 years. The hydrate resources shown in Table 1 consist of a locally ubiquitous frozen methane (hydrate) layer a hundred metres or so below the seafloor that traps methane gas below it. Recovery could be effected by horizontal drilling coupled with recovery stimulation, just as it has now been shown to be economical in recovering shale gas. Gaining experience in the recovery of non-conventional shale gas is a logical step towards recovering hydrates.

Global Warming

Global warming is perhaps the main risk associated with continued use of fossil fuels. Table 2 shows Rogner's global reserve base estimates for gas, oil and coal. His tabulation includes shale gas and shale oil but considers gas hydrates to be unrecoverable "occurrences" that lie outside the resource base. Rogner considers his estimate of the reserve base to be generously large.

Table 2: Resource Base Estimates by Rogner [7]

Commodity	Resource Base (PAL = 595 GtC)		
	Conventional Units	Gtoe	GtC/PAL
Gas	33,852 tcf	870	0.9
Oil	6066 Gbbl	814	1.2
Coal	5041 Gt	3400	6.6
TOTAL		5209	8.8

Notes: PAL is the pre-industrial carbon content of the atmosphere. At 280 ppmv CO_2, the pre-industrial atmosphere contained 595 gigatons of carbon (GtC). Tcf, trillion cubic feet; Gbbl, gigabarrels; Gt, gigatons.

Even though 2.13 PAL is introduced in the business-as-usual scenario, half of this CO_2 is removed from the atmosphere quite quickly (with a residence time of <19 years). The atmospheric CO_2 is thus doubled, and this is expected to produce a 3°C rise in average global temperature. The 3°C rise is reduced by ~1°C by heat exchange with the ocean.

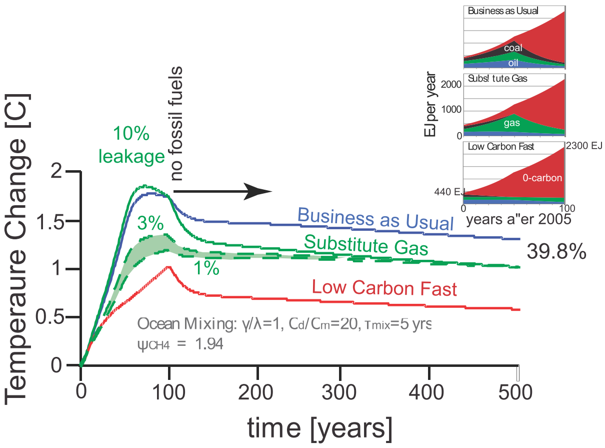

Figure 1: Predicted Global Average Temperature Change for the Fuel Use Scenarios Described in the Text and Illustrated in the Inset.

Figure 1 shows the global warming predicted for three fossil fuel scenarios. All three scenarios meet the goal of supplying each human in the estimated 2010 world population of 10.5 billion with 7 kW of primary energy (2300 EJ/yr = 74 TW/yr = 7 kW per person × 10.5 × 10^9 persons), the primary energy consumed today by the average Frenchman. The methods used to calculate the warming levels are standard and non-controversial, and are described by Cathles in Reference [9], where many additional details can be found. The business-as-usual scenario produces warming that peaks at about 1.8 $^{\circ}$C in 2100 and then declines very slowly (26% of the introduced CO_2 is removed with a decay constant of 173 years). The substitute-gas scenario reduces the warming by about 40% of what could be achieved by the rapid substitution of zero-carbon energy sources and does so at all times provided the leakage rate of methane is what it appears to be at present (between 1% and 3%) [9,10a]. Even if the leakage rate were as high as 10% of the gas consumption and the substitute-gas scenario provided no reduction in global warming over the 100-year transition period, the 40% reduction would still be realized later because methane leaves the atmosphere quickly (exponential decay time of 12 years) as soon as gas production stops. The warming is of the magnitude one might expect. For example, even though 2.13 PAL is introduced in the business-as-usual scenario (see Table 3), half of this CO_2 is removed from the atmosphere quite quickly (with a residence time of <19 years). The atmospheric CO_2 is thus doubled, and this is expected to produce a 3°C rise in average global temperature. The 3°C rise is reduced by ~1 °C by heat exchange with the ocean.

Table 3 shows that a substantial portion of the resource base of oil and gas would be consumed in all the three scenarios. Depletion of oil and gas will force a transition to other energy sources in a period not too longer than 100 years, but this is not the case for coal. Coal poses the main global warming threat. Consuming all the oil and gas in Rogner's generous resource base will introduce 2.1 times the pre-industrial atmospheric carbon content to the atmosphere (i.e., 2.1 PAL) and add about 1 PAL to the atmosphere. But burning the coal reserve base would introduce an additional 6.6 PAL.

Risks and Benefits of Fuel Options

All energy options have both attractive and unattractive aspects, but, in comparison to alternative energy sources, natural gas looks quite better.

Table 3: Fuel Consumption in the Three Fuel Use Scenarios Shown in the Inset of Figure 1

	Business as usual			Swap gas			Low C fast		
Fuel	Conven-tional Units	%RB	Gtoe	Conven-tional Units	%RB	Gtoe	Conven-tional Units	%RB	Gtoe
Gas	16,847 tcf	50	433	34,829 tcf	103	896	11,299 tcf	33	291
Oil	3,573 Gbbl	59	479	2,462 Gbbl	41	330	2,462 Gbbl	41	330
Coal	731 Gt	**15**	497	93 Gt	**1.9**	63	93 Gt	**1.9**	63
GtC/PAL	2.13 (1268 GtC)			1.57 (935 GtC)			0.91 (544 GtC)		

Notes: %RB is the percentage of the resource base consumed. GtC/PAL in the last row is the number of times the pre-industrial carbon content of the atmosphere that shall be introduced by burning of fossil fuel in the scenario. The gigatons of carbon released into the atmosphere are shown in parentheses. The reduction in GtC introduced into the atmosphere in the swap-gas scenario is 46% of that achieved in the low-C-fast scenario. tcf, trillion cubic feet; Gbbl, gigabarrels; Gt, gigatons, GtC, gigatons of carbon.

If the Marcellus resource were recovered steadily over a 30-year period and this power production were spread over the 246 × 10^9 m^2 area of the productive Marcellus shale, the power production would be 1.6 W/m^2. Normalized to the pad area the power production would be 414 W/m^2. Wind turbines produce energy at about 2 W/m^2, and concentrating solar facilities' efficient photovoltaic panels capture solar energy at ~15 W/m^2. Thus, considering that some areas will not be accessible, wind turbines would have to blanket the entire area underlain by the productive Marcellus, and solar panels or reflectors would need to cover an area 28 times the pad area, to deliver an equivalent amount of power.

Spatial intrusion

Horizontal drilling allows 2 square miles (518 ha) of sub-surface shale to be tapped from a single 5 acre (2 ha) drill pad, about 0.4% of the area from which gas is recovered. What this means in comparison to other energy options can be appreciated by a simple calculation. If the Marcellus resource were recovered steadily over a 30-year period and this power production were spread over the 246 × 10^9 m^2 area of the productive Marcellus shale, the power production would be 1.6 W/m^2 [10b]. Normalized to the pad area the power production would be 414 W/m^2. Wind turbines produce energy at about 2 W/m^2, and concentrating solar facilities' efficient photovoltaic panels capture solar energy at ~15 W/m^2 [11]. Thus, considering that some areas will not be accessible, wind turbines would have to blanket the entire area underlain by the productive Marcellus, and solar panels or reflectors would need to cover an area 28 times the pad area, to deliver an equivalent amount of power. Furthermore, over much of the time the pad will show only a few pipes, whereas the solar panels or reflectors will be permanent fixtures. There will be road construction and increased road traffic for all the options, but the spatial intrusion of shale gas will be remarkably less in comparison to many of the other options.

Water requirement

There has been a great deal of concern over the water requirement of shale gas, and it is true that handling of water, particularly when chemicals are added, poses the risk of surface spills. However, as shown in Table 4, the water requirement for generating electrical power from gas is smaller as compared to biomass-based, hydroelectric, coal-based or nuclear power generation. Biomass fuels use copious amounts of water in irrigation and lose copious amounts of water through evapotranspiration. In the case of hydroelectric power generation, large amounts of water evaporate from the reservoirs behind the dams and the water from the reservoir suffers heat gain and quality degradation just as it is when power is generated by turbines. In coal mining water is used for dust suppression, for washing the coal, and sometimes for transporting it as a water slurry through pipelines. But most of the water used is for cooling and condensing steam during power generation, which is also true in the case of nuclear power generation. Carbon capture and sequestration can increase water consumption by 7-50 times over that shown in Table 4. The upstream use of water in producing gas is mainly for enhancing production by water injection and in processing for pipeline transport. Combined cycle (gas turbine followed by steam turbine) electricity generation reduces water

Table 4: Water Use and Consumption for Various Fuels

Fuel Used for Electric Power Generation	Withdrawals (gal/MWh)	Consumption (gal/MWh)
Biomass	43,908-376,569 (irrigation)	25,839-219,681 ET losses
Hydroelectric	440,000 (turbine throughput)	9,000 (evaporation)
Coal	16,052 (3%) (dust, slurry transport)	692 (27%) (cooling)
Nuclear	14,811 (0.5%)	572 (7%) (cooling)
Natural Gas	6,484 (5%)	172 (13%)

Notes: ET, Evapotranspiration. The percentage of withdrawals or consumption that occurs upstream of the power plant is shown in parentheses, as are brief comments. Data is from Wilson et al. 2012 [12].

usage and consumption to a large extent. Table 4 does not include the water used in hydrofracturing. However, assuming 10 million gallons are used to hydrofracture a well that ultimately produces only 0.5 bcf of gas with a thermal heat content of 43 GJ/ton, ~5 gal/MWh is required for hydrofracturing, which is negligible as compared to the water requirement of the other energy sources.

Capillary seals are remarkably durable and resistant to rupture. This is attested to by the fact that gas is still there in shales like the Marcellus: had there been a leakage of even 1 in 200 million parts of the contained gas per year, the gas would have been entirely gone by now. Capillary seals will contain whatever gas is left after human extraction is finished for additional hundreds of millions of years.

Gas leakage

Concerns regarding leakage of methane from the source shales, and perhaps enhanced leakage as a result of hydrofracturing, have been raised, but such concerns ignore the capillary seals [10d] that have kept the gas incarcerated in shales such as the Marcellus in an over-pressured state for hundreds of millions of years [10c]. Capillary seals are remarkably durable and resistant to rupture. This is attested to by the fact that gas is still there in shales like the Marcellus: had there been a leakage of even 1 in 200 million parts of the contained gas per year, the gas would have been entirely gone by now. Capillary seals will contain whatever gas is left after human extraction is finished for additional hundreds of millions of years.

Gas vents

If gas is not leaking from the source shales, what does explain the gas vents commonly observed in gas resource areas and the gas commonly found dissolved in the ground and drinking water in these areas? Such gas vents do not represent current leakage. Gas was expelled from source shales like the Marcellus at the time when the gas was generated in these shales, that is, hundreds of millions of years ago. It gas-fracked its way out of the shale at that time, and moved into the adjacent stratigraphy, where it got trapped in myriad small (and sometimes larger, even conventionally recoverable) pockets. Ever since, ground water flow has been slowly dissolving and removing this gas, often producing small gas vents [13]. This leakage should be documented before drilling starts so that it is not mistaken for leakage caused by the extraction process.

Shale gas appears to be an attractive transition energy option for India. It is a distributed resource that can be recovered with very little surface impact. Gas is the cleanest of the fossil fuels and much cleaner than coal (no particulates, Hg, acid mine drainage, acid rain or ash piles). Shifting to natural gas, particularly by India and China, will significantly reduce CO_2 emissions and the global-warming risk. Choosing coal is a risky option because there will be pressure to curtail its use until carbon can be sequestered safely or methods for coal gasification are developed. Currently the main uncertainty as far as India is concerned is the size of India's shale gas resource; but the experience gained in shale gas recovery is likely to be the source of new technologies that will expand India's reserves, perhaps eventually even to include methane hydrates, which is a very large gas resource accessible to India. Gas (and oil) is not a permanent solution because, at the projected consumption rates, the resources will not last much more than a century (Table 3); but a century is an adequate duration for transition.

Notes and References

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8. *Hydrate resources are huge but how much might be recoverable is anyone's guess. The main basis of this data in the table is Rogner's [7] estimate of additional occurrences in Southeast Asia (his Table 7). A resource estimate specific to India, which is 3.5 times larger (1361 Gtoe), is offered by http://twentyclicks.in/index_files/the-next-frontier-gas-hydrates-offshore-indias-east-coast.php. A good general discussion of hydrate resources is available at http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2011Reports/MH_Primer2011.pdf.*

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10. http://blogs.cornell.edu/naturalgaswarming/. (a) Topic 9 provides a brief summary and access to the extensive and full discussion that has taken place on the impact of natural gas on global warming, including a detailed discussion on what is known about methane leaks during conventional and non-conventional gas recovery and delivery. (b) Calculation of 1.6 W/m2 is given under Topic 1. (c) The geological story of the Marcellus is told with illustrations and references under Topic 2. (d) Topic 13 discusses capillary seals and provides links to the literature.

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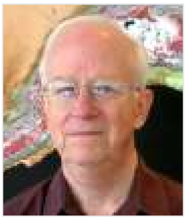

Mr. Lawrence M. Cathles III is a Professor of Geological Sciences at Cornell University, USA. He has carried out research on a variety of topics (the viscosity of the earth's mantle, heap and in situ leaching, ore genesis, CO_2 generation and titration, hydrocarbon systems, gas hydrates, capillary seals, and nanoparticle tracers) at the Kennecott Copper Corporation, the Pennsylvania State University and Chevron Oil Field Research Laboratory.