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The Future of Global Energy Systems

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I Introduction

In this paper we present an overview of the opportunities and challenges in energy resources, exploration, production and infrastructure in various regions of the world. To assess the requirements for future energy resources and systems and their environmental impacts, a number of parameters need to be defined by each nation and/or region. These will impact the amount and kind of energy systems that will be needed and developed. Key questions include:

- At what number and date will the population stabilize?
- What will be/are the economic development goals of a country? For example, what is the timeline of the average per capita electric energy desired?
- What energy resources exist locally and on what time scales can they be exploited?
- What will be the nature of the public-private partnership that will be effective in raising the capital required to build the needed infrastructure and meet the energy demand?
- Governance, policies, regulations and investment climate?
- Economic and environmental stewardship and advocacy by civil society and non-government institutions and the impacts of their pressure on the government?
- Regulations on greenhouse gas emissions and their implementation?
- Impacts of climate change on health, infrastructure, agriculture and economics?
- International climate change policies?

The answers to these questions have large variations within and between countries. For many countries they have not yet been adequately researched or defined. Developing countries have growing populations, inadequate infrastructure and limited resources. Their priority is to increase capacity in the cheapest and fastest way possible.

For most developed countries the answers are better known because:

- Their populations have stabilized and they have a much better characterization of the demand. Consumption in OECD countries is projected to stay almost flat out to 2035.
- They are installing 2nd and 3rd generation systems and have sufficient experience to incorporate the latest efficient technologies.
- The energy consumption per capita is decreasing because of improvements in efficiency and because their economy is less dependent on manufacturing.
- They have overbuilt capacity for generating electric power and are able to switch fuels quickly to optimize the system with respect to regulations, efficiency, emissions and costs.
- They have much better implemented control systems and a more extensive and robust transmission grid that facilitates the integration of wind and solar systems.

The global energy system is enormous, complex and far from transparent. Even when sufficient resources (fossil fuels, wind and solar potential) have been identified to meet demand, there is considerable uncertainty in prices and how various energy systems will evolve. Some of the important reasons are:

- Fluctuations in economic growth create uncertainty in demand. Uncertainty in demand impacts the investment into exploration, production and installation of new systems. As a result, the time scale on which new resources are brought on line has significant uncertainty.
- New regulations in response to public opposition, accidents, environmental concerns, climate change and government fiscal policies can have large impact on production and demand.
- Uncertainty in the time line and performance of new technologies, their adoption by the public and unintended environmental consequences that result in new regulations.
- Political turmoil in countries that are large producers and/or consumers.
- Geopolitics, sanctions, and the use of commodities as bargaining chips by countries.
- Breakthroughs in technology and novel opportunities can happen unexpectedly and over a short period of time. They can significantly alter the energy landscape. A recent example is the coming together of deep horizontal drilling and hydraulic fracturing that opened up the extraction of oil and natural gas from tight/shale formations.

Faced with fundamental limitations in adequate real-time information, analysts create scenarios using reasonable ranges for the many variables such as economic growth, energy demand and supply, cost and impacts of greenhouse gas emissions and correlations between them. In this study we do not propose a new model but extract and integrate common plausible trends from existing studies to build a high level picture.

The consensus of experts is that, worldwide there is enough accessible fossil fuel to power the world through the 21st century even though there are large variations in distribution of these fuels between countries/regions. Overall, based on known reserves, humankind has at least 50-100 years to transition from a fossil fuel based economy to a zero-carbon one. On the other hand, the rising concentrations of CO_2 in the atmosphere (already at 400 ppm compared to about 275 ppm in the preindustrial era) could have long-lasting consequences for the climate on the order of 100,000 years[i], and any future accumulation is cause for further concern. The annual total and per capita historic and projected CO_2 emissions, as reported in the BP Energy Outlook 2035[ii], are shown in Figure 1 by region. While emissions from OECD countries will continue to decrease, albeit slowly, large increase is projected to come from non-OECD countries, in particular from China and India. While the annual world per capita emissions will grow only slightly to about 5 tons per year, the total emissions will increase by ~30% as many more people are expected to share in 21st century opportunities and contribute to GDP. To cap CO_2 concentrations at 450 ppm (IEA 450 scenario shown in Figure 1 that would result in ~2^{o}C rise in global mean temperature) requires dramatic reductions starting today: a very sharp departure from business-as-usual behavior.

Rising global temperatures and ensuing climate change require humankind to move away from burning fossil fuels as soon as possible or if fossil fuels are combusted, then the CO_2 emitted must be captured and sequestered. This dilemma poses a challenge unprecedented in human history.

Humankind will have to resist using readily available, low-cost, high-density and easy to use fossil fuels; instead it must rapidly transition to "zero-emission" technologies. The most promising in terms of both scale and low climate impacts are nuclear, solar and wind for power generation and electric vehicles for transport. Solar and wind systems are still maturing and face operational and technical challenges (intermittency, fluctuations and low density); electric vehicles need breakthroughs in battery technology; and nuclear is controversial. Even with the noblest of intentions, the current fossil fuel based global system is so large and well-entrenched that it will take decades of concerted effort to change it. The goal of any study, such as this, is to identify options to accelerate the transition.

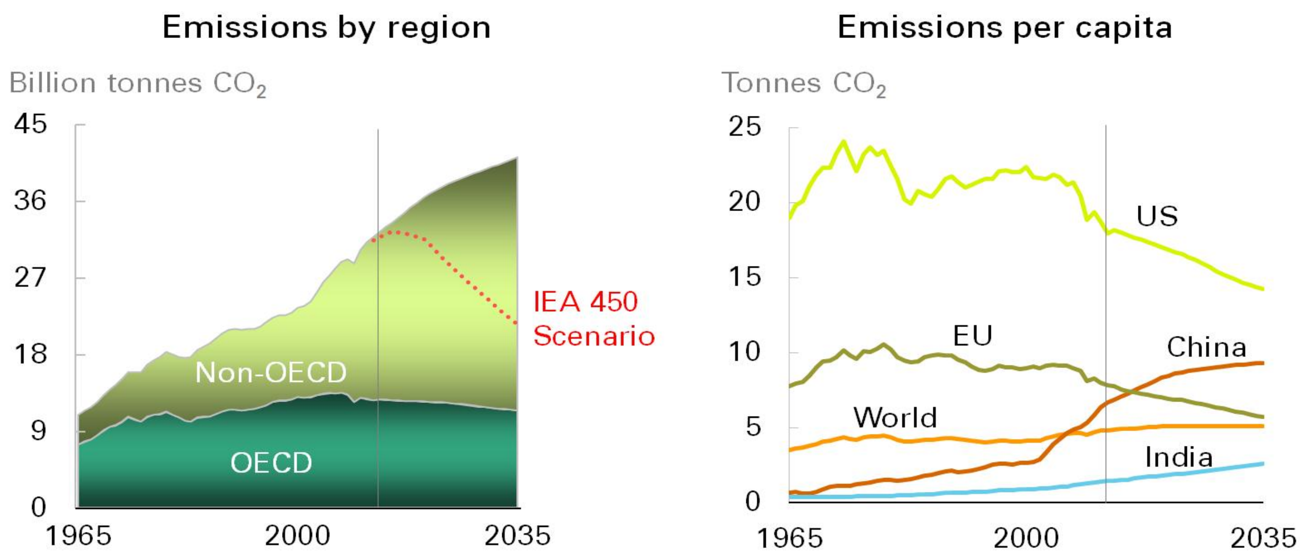


Figure 1: Historic and projected CO_2 emissions by (left) region and (right) per capita. The IEA 450 scenario is based on the requirement that CO_2 concentration in the atmosphere peaks at 450 ppm. To achieve it requires dramatic reductions in emissions starting today!
[Source: BP Energy Outlook 2035, slide 34]

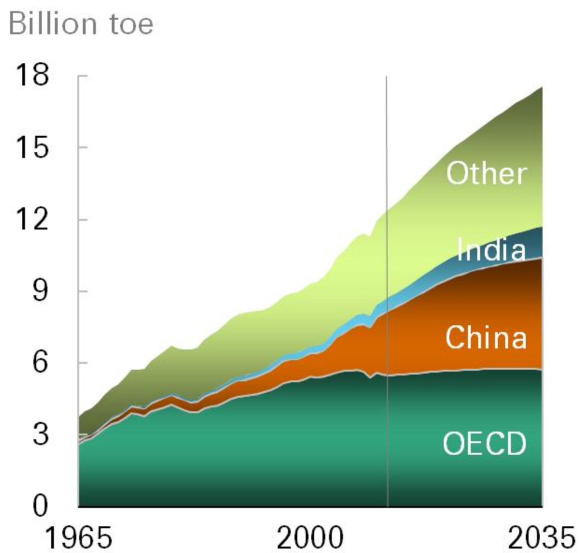
In this paper we focus on the high-level picture colored by the need of all countries for energy security and examine the options for meeting energy needs in different regions of the world. We will consider three time frames:

- near-term implying up to 2025,
- medium-term from 2025-2040, and
- long-term beyond 2040 and up to 2050.

The paper is organized as follows. In the second section we summarize the current status of energy systems and resources. In the third section we examine the opportunities, options and hurdles for building and sustaining energy security in different regions of the world. Examples of breakthroughs that would accelerate the transition to renewable systems are presented in section four. We present our conclusions at the end.

II Overview of Current Energy Resources and Systems:

Fossil fuels (coal, oil and natural gas) have been the dominant sources of energy that drove unprecedented development in large parts of the world in the 20th century. Four figures, shown in Figures 2 and 3 and taken from BP Energy Outlook 2035,[ii] summarize the historical data and projections up to 2035 and set the stage for our discussion. EIA, IEA, Statoil, ExxonMobil, etc. have also made similar projections; therefore, we have taken appropriate figures from all the above organizations to illustrate our points. Figure 2 (left) shows the consumption of primary energy by region with almost all the growth coming from China, India, and other non-OECD countries. Figure 2 (right) shows the consumption by sector with the largest growth coming from the electricity generation sector, followed by industry and transport. Figure 3 (left) shows the contribution of different sources with growth projected in all six: oil, coal, gas, nuclear, hydro and renewables. Figure 3 (right) shows that oil, coal and gas are expected to constitute 81% of primary energy used in 2035 (down from 86% in 2012) with each of these three contributing about 27% of the total. The decrease in the share of oil is largely matched by the growth in the share of natural gas, and other renewable sources are projected to catch up with nuclear and hydro.



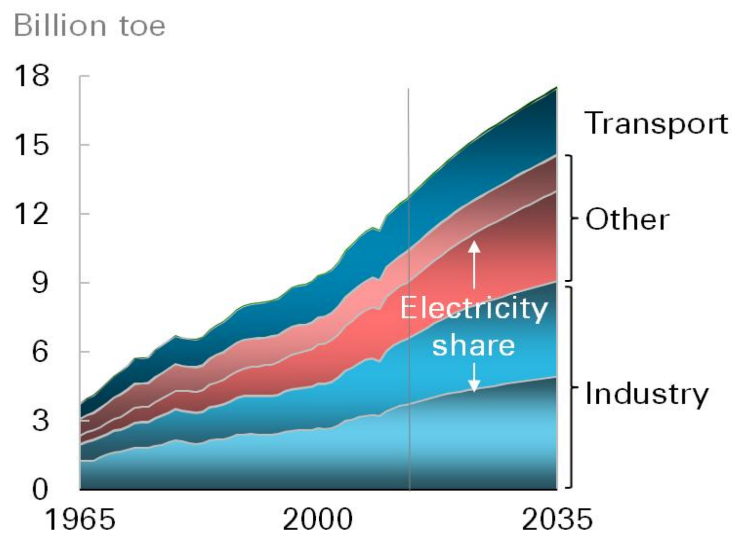


Figure 2: Historic and projected global consumption of primary energy by region (left) and sector (right) (toe = tons oil equivalent).[Source: BP Energy Outlook 2035, slides 4 and5.]

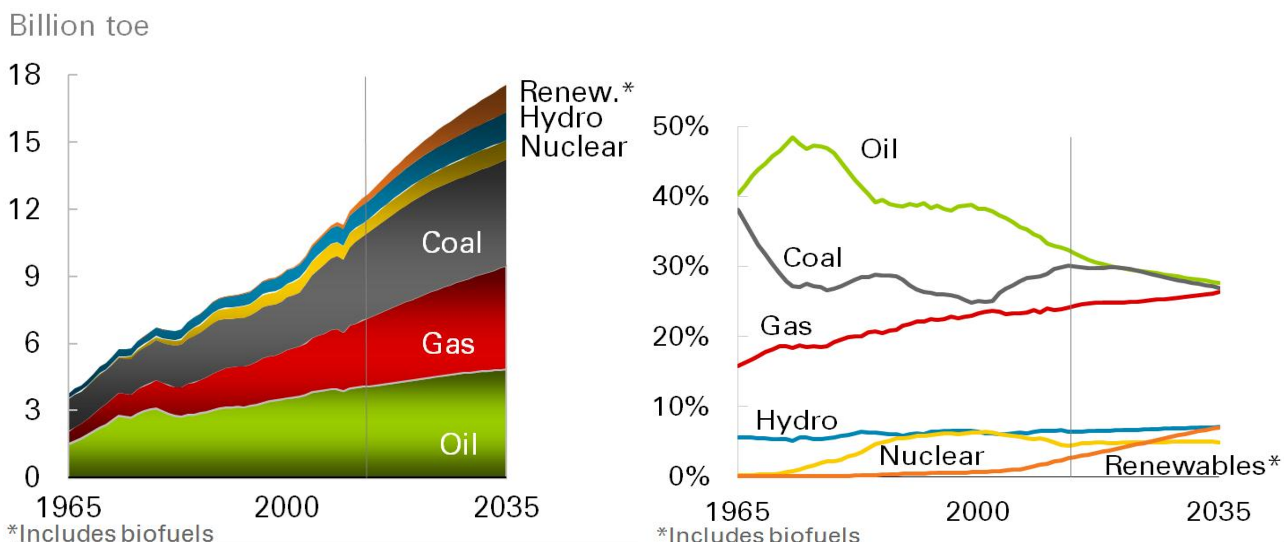


Figure 3: Historic and projected share of global primary energy consumed by source (left). Total in billion toe and as a percentage of the total (right). [Source: BP Energy Outlook 2035, slides7 and 8.]

The consensus of all studies is that there are no impending shortages of fossil fuels globally, at least for the next 50 years, and their consumption is projected to continue growing. Even in 2035, they are projected to provide about 81% of the primary energy, only a small decrease in relative share compared to 86% in 2013. Recognizing their dominant position (safe, high energy and power density, vast accumulated investment and long experience in exploiting them for power generation, transportation and heat), we consider it appropriate to examine them first.

II.1 Oil and Transportation

Fossil oil is and will remain the dominant fuel for transportation in the short- and mid-term. With a growing global population and more people wanting the convenience of individual transport and being able to afford it, the total number of personal light duty vehicles is projected to grow as shown in Figure 4. The almost one billion cars and small trucks on the roads today will continue to need diesel and gasoline for at least the next decade and most new models are only incrementally more efficient versions of these. Concomitantly, global usage of oil will continue to grow, with the Middle East, India, China, and South-East Asia accounting for most of the growth as shown in Figures 4 and 5. [iii]

There are significant variations in the pattern of use of oil in different countries of the world; these include the fuel efficiency standards of vehicles, average miles driven per year and the price of gasoline. In developed countries with stabilized populations, the amount of oil being consumed is decreasing because of improvements in fuel efficiency, safe and effective public transport systems and reduced usage due to high price of gasoline as well as lifestyle changes. Growth in demand is coming mainly from the developing world.

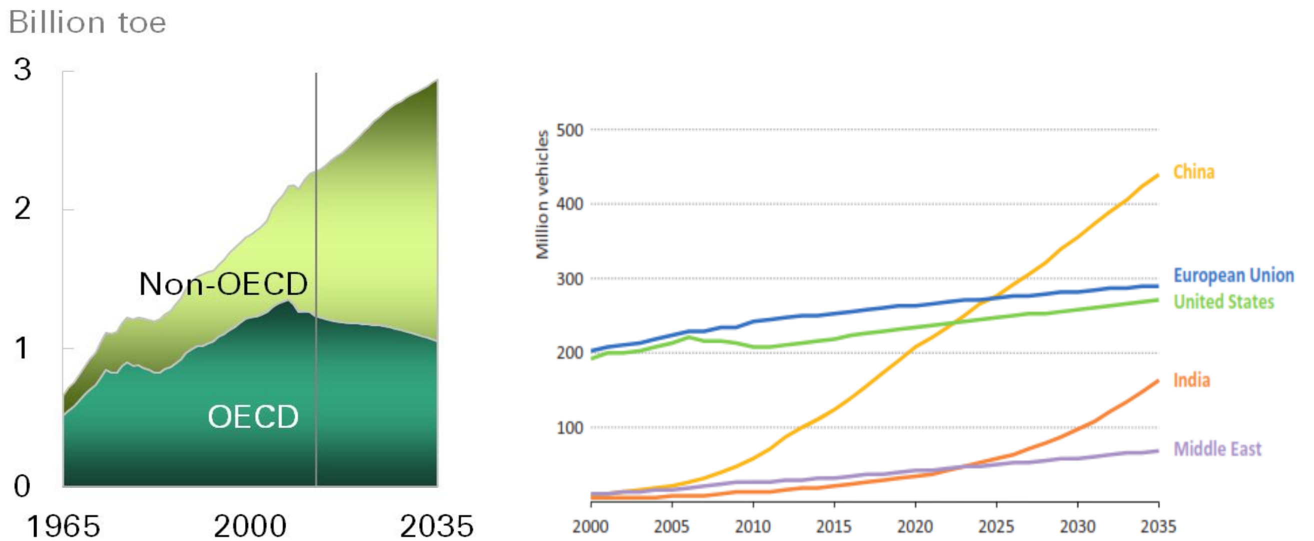


Figure 4: Historical and projected increase in fuel for transportation (left) [BP Energy Outlook 2035, Slide 19] and personal light duty vehicles (right) [IEA WEO 2013 New Policies Scenario].

Globally, there continue to be major opportunities for reducing oil consumption in the transport sector in the near- and medium-term through
(i) efficiency gains,
(ii) penetration of cost-effective hybrids and CNG vehicles,
(iii) safe and more effective public transport systems and
(iv) better designed cities to reduce commute distances and road congestion and to encourage people to walk and use bicycles.
These trends, leading to reduction in oil used by the transportation sector, are already visible in developed countries[iv] and can easily be accelerated though government policies and incentives. Significant penetration of electric vehicles is, however, expected only in the long-term.

In the extraction of oil, technological innovations have allowed the exploitation of new resources, for example, tar sands in Canada, shale (tight) oil in the U.S., heavy oil in Venezuela and ultra-deep pre-salt oil in Brazil. In the production of oil there have been temporary ups and downs but no significant (physical) shortages in the last decade.[v] For example, in 2012, production in the U.S. (shale oil), Russia and Saudi Arabia recorded significant increases; Libya and Iraq recovered production; aging fields past their peak in the North Sea (Norway and UK) and Mexico (problems made worse by inadequate investment) continued their decline; and political factors led to decreased production in Syria (civil war) and Iran (sanctions). Consumption in the U.S. and most European countries continued its decline but grew in the Middle East, South and East Asia. Overall, the significant reduction of oil used in the U.S. and Europe has been offset by the increases in the Middle East and Asia-Pacific. Limited spare production capacity, which allows even small cuts by OPEC members or any disruptions (for example, reduced production in Syria and Iran) to have large impacts, has contributed to high prices, which have remained, on average (nominally), above $100/barrel since 2011. Future demand and prices are uncertain in light of the recent dramatic fall in the prices to about $50/barrel between June 2014 and January 2015 due to lower than expected global demand and growth in production of shale oil in the U.S.

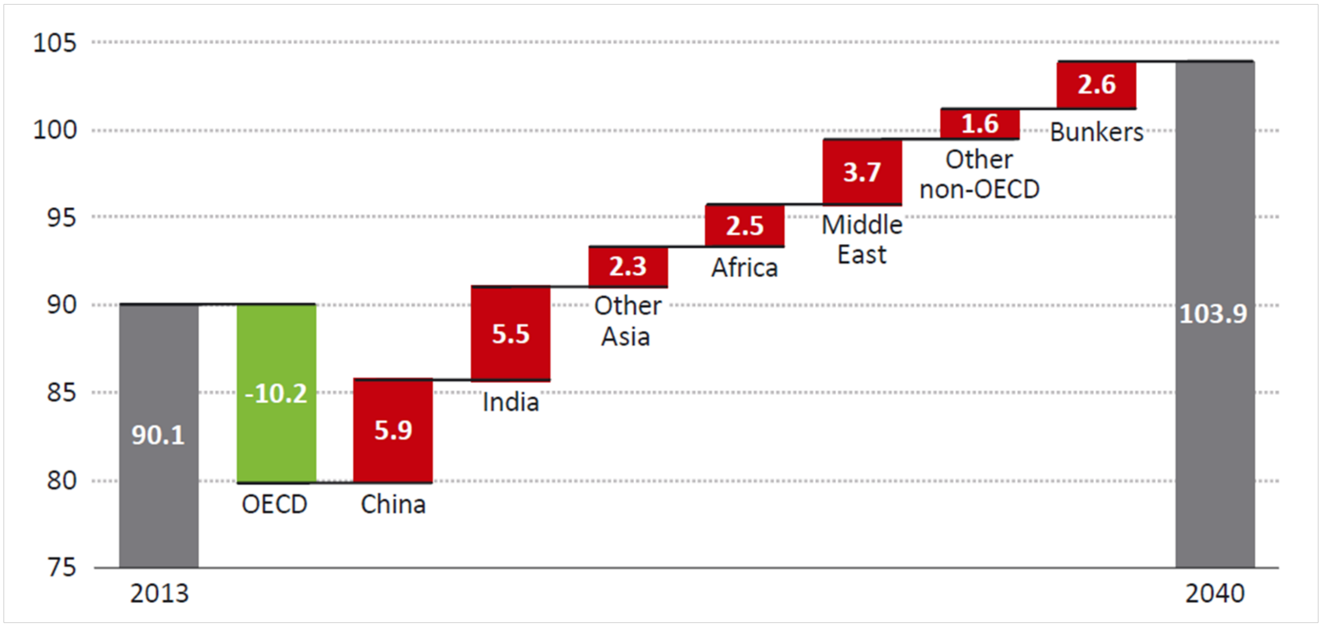


Figure 5: Projected increase in oil demand in the IEA New Policies Scenario in WEO 2014. [Source IEA WEO (2014) p. 100]

To evaluate the potential for switching fuels, a comparison of energy densities of fuels, an important parameter in the transportation sector, is shown in Figure 6 with gasoline and diesel setting the standards. For example, a CNG fueled car requires a tank with three times the volume compared to a gasoline-fueled one for storing the same energy. The only significant alternatives to oil for liquid fuel based technology today are bio-fuels and CNG. Bio-fuels are, however, limited in scope unless there are major breakthroughs in biomass production and conversion technologies, and society is convinced that environmental impacts of growing the bio-crops will not outweigh the benefits. In 2012, bio-fuels provided about 1.2 MMboe/day out of the 88 MMboe/day consumed[vi]. Ethanol production (mostly from corn in the US and sugarcane in Brazil) is expected to saturate at about 25 billion gallons a year (about 2 MMboe/day versus the 100+ MMboe/day oil usage that is projected post 2035). Fuel and power from bio-waste is also limited by the volume of bio-mass that can be collected at reasonable cost even if R&D breakthroughs leading to cost-effective conversion of cellulose to ethanol materialize. All bio-crops will also have to address the growing issue of "food versus fuel" as competition for access to arable land, water and fertilizers grows and the environmental impacts accumulate.[vii] CNG/LNG are effective fuels for light vehicles/trucks, however, growth in their use has been limited by the lack of distribution infrastructure. Europe and the U.S. are currently evaluating the potential of CNG versus LNG for high-mileage heavy-duty trucks.[viii]

On the new technology front, the biggest hope for bio-fuels today is algae.[ix] It remains to be seen if the cost and water needs of algae production and harvesting will be brought down for algal oil (2013 production cost was about $8/liter) to compete with fossil fuels ($1/liter that includes an acceptable carbon tax on fossil fuels) over the next 30 years.[x]

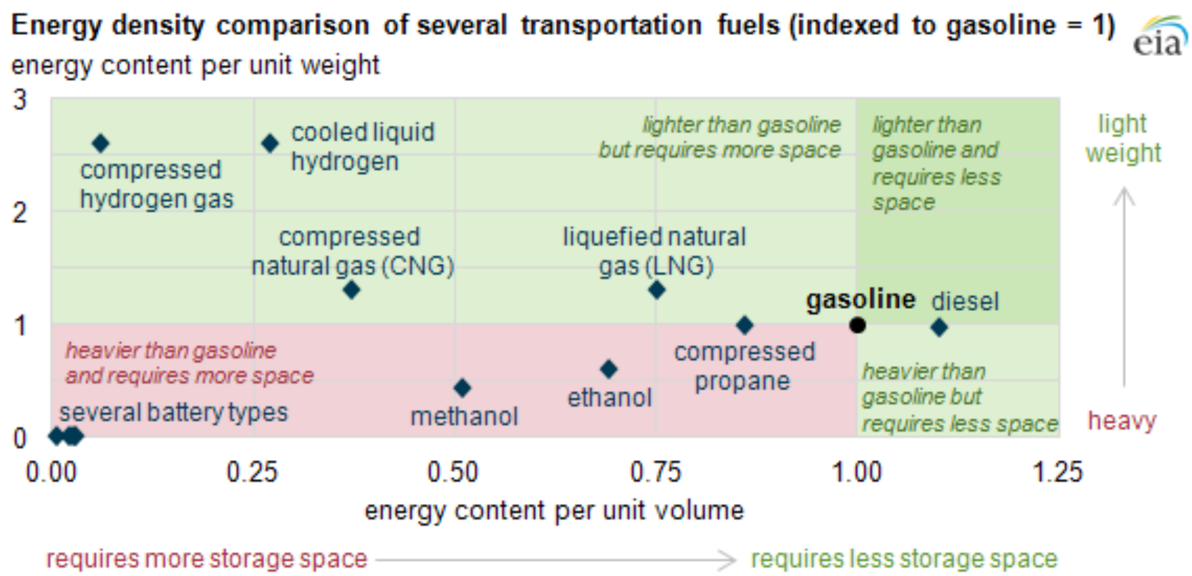


Figure 6: Comparison of energy density of fuels used for transportation by both weight and volume. [Source: http://www.eia.gov/todayinenergy/detail.cfm?id=14451.]

Clouding the future of global trade is the important recent development – the unexpected collapse of the price of oil from $115 to $50/bbl between June 2014 and January 2015. It highlights the volatility of the system and the interplay between stagnant demand due to global financial downturns, increase in unconventional production by the U.S., discord within OPEC and geopolitics. It has given rise to many questions: Will the low price persist? Will it settle at a value that is high enough to allow production of unconventional oil, or will low prices drive out that nascent industry? What hardships will it inflict on countries that rely on oil for a majority of their revenues and are considered belligerent by the West such as Iran, Russia and Venezuela?

On the usage end, large-scale switch to cost-effective electric cars needs major advances in battery technology. Figure 6 highlights the current state of batteries – they sit at the very low end with respect to both energy per unit weight and volume. Based on current trends and the scale of R&D needed, and notwithstanding the large investments, such a transition to electric vehicles is unlikely to occur quickly or soon. As it occurs, it will shift the burden of greenhouse gas emissions from the transportation sector to the electricity generation sector. Meanwhile, the liquid-fuel based automobile industry is improving fuel efficiency by making improvements in engine technologies[xi] and incorporating novel materials to decrease vehicle weight. The result is that the cost-performance bar for electric cars is being raised steadily.

Given the current dominance of oil, slow and uncertain growth of alternatives, it is unlikely that, by 2030, there will be significant transition away from liquid fuels (oil) for individual transportation, or for powering ships and airplanes. Therefore, the global carbon footprint of the transportation sector, which is proportional to the amount of oil combusted, will also continue to grow since it is unlikely that practical methods for capturing greenhouse gas emissions from engines powering vehicles, pumps, ships or planes will emerge any time soon.

II.2 Coal and Electricity Generation

Coal is the dirtiest fossil fuel and used predominantly for electric power generation. Coal production and consumption has grown by over 50% between 2002-2012 worldwide driven by consumption in China (+235%) and India (+97%), and production in Indonesia (+375%).[xii] The global consumption of almost 8 billon tons in 2012 accounted for about 45% of CO_2 emissions from fossil fuels (oil contributed 35% and natural gas the remaining 20%).[xiii] Emissions of greenhouse gases, in addition to environmental impacts and pollution, puts transitioning away from coal on top of the climate change mitigation agenda. While many countries are replacing their older coal-fired units by high efficiency ones with emissions controls, few have reduced their dependence on coal. These few are developed countries with access to inexpensive natural gas; for example, the U.S., Canada, Denmark and Russia. In the next section we will highlight countries that are critically dependent on coal-fired generation, their options for the future and possible impacts of the mounting social pressure vis-à-vis climate change and environmental concerns to transition away from coal.

Analyzing current reserves, production and consumption histories, an important pattern emerges. Post about 2040, imports of coal will be dominated by China and India and only six countries, the U.S., Russia, Australia, South Africa, Ukraine and Kazakhstan will have sufficient reserves left to undertake exports in gigatons. In the absence of large scale carbon capture and sequestration, any internationally binding agreement accepted by these six suppliers (or led by them) in response to the need to mitigate climate change would squeeze coal out as a fuel.

Fortunately, the generation of electricity has significant variations in different parts of the world and there are more options at scale to choose from. Regional variations and opportunities will be examined in more detail in Section III.

II.3 Natural Gas: conventional and unconventional

Natural gas is poised to become the dominant fossil fuel for power generation and transport, and for domestic and industrial use. In addition to being a multi-purpose fuel, it is accepted socially because its end-use combustion produces only CO_2 and H_2O, which are non-toxic and odorless. It has relatively higher energy density by weight and can be transported effectively by pipelines. Its only disadvantages are fugitive emissions during extraction and transport and the added cost of intercontinental shipping as LNG, including the cost of cleaning the gas before liquefaction. Figure 7 shows the historical and projected continued growth in consumption of natural gas in all regions at an average rate of 1.9% until 2035.[ii] Shale gas is projected to contribute 22% of total consumption by 2035 with most of it in the developed countries in the near- and mid-term.

In 2014, the price of natural gas had large regional variations reflecting the difference in cost of transport between shipping as LNG and as gas via pipelines, i.e., the cost in a region depends on the relative fraction supplied as LNG versus via pipelines. The three major price categories were: North America (about $4/MMBtu with no imports), Europe (about $10/MMBtu via pipelines), and Asia-Pacific (usually above $15/MMBtu as LNG in recent years). With new production capacity and construction of export terminals, it is anticipated that the differences will decrease and the price will come closer to the cost of production. Whether Asia-Pacific LNG spot prices can come down to $10/MMBtu and stay there for a long period and whether a unified market for gas emerges remains to be seen.[xiv]

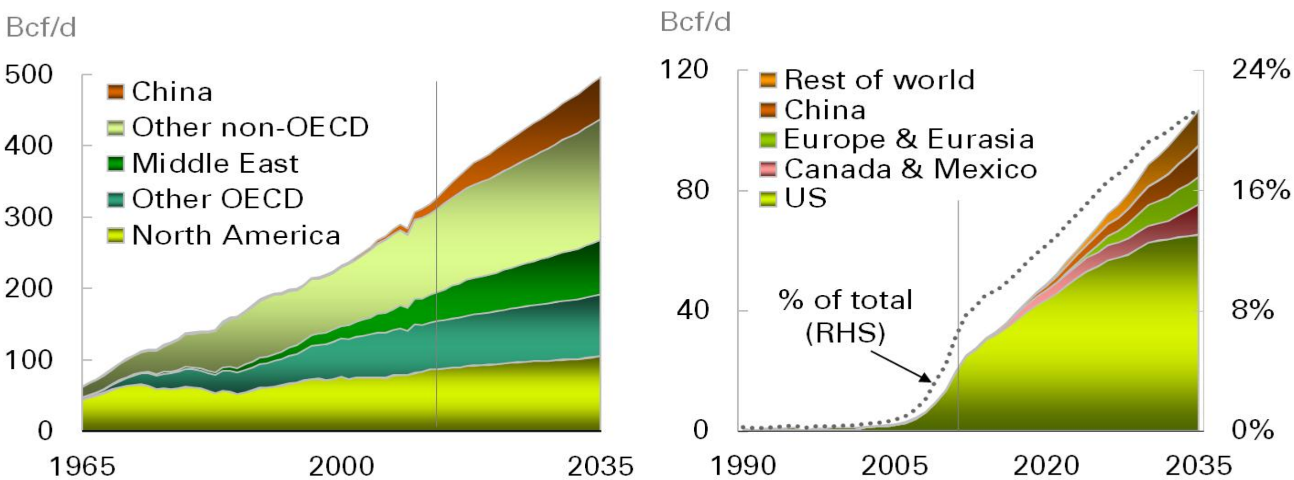


Figure 7: The historical and projected growth in the consumption of natural gas by region. (left) total global consumption and (right) contribution of shale gas to the total.
[Source: BP Energy Outlook 2035 Slides 23 and 25]

Unconventional resources, such as tight oil and shale gas, are widely distributed across the world, but the development of these resources is, today, dominated by U.S. and Canadian companies. Complex and sophisticated resource analysis capabilities and extraction technologies (off-shore, deep and horizontal drilling; hydraulic fracturing; and 3-D reservoir modeling and simulations) are needed to efficiently develop and exploit unconventional resources locked in deep waters, deep underground, harsh arctic environments, shale and tight formations, or as coal-bed methane (CBM). Looking ahead, development of environmentally responsible *in situ* gasification technology would open up huge additional resources locked in deep, narrow or fragmented coal and shale seams. Another large untapped resource is deposits of methane hydrates locked underwater on continental shelves. Japan, devoid of other resources of fossil-fuels, is actively investing in developing the technology for mining these deposits.[xv]

These unconventional resources are widely distributed around the world but even after technological breakthroughs have been established, other developed and developing countries will require very significant investments to exploit them and, at least initially, will need to foster collaborations with multi-national companies with the state-of-the-art technology and experience as the risk of large scale fugitive emissions is high. Governments will, therefore, need to create the right incentives and policies for attracting investments and at the same time convince their citizens that the development of resources will be carried out responsibly and in the nation’s interest. These are non-trivial hurdles, so it remains to be seen how fast these technologies mature and diffuse to other countries and what government policies, industrial partnerships and cooperatives are developed to facilitate timely, efficient and environmentally benign extraction and processing.

The gas turbine industry is reacting to today's opportunity due to increase in gas supply. Gas turbines are and will remain the best near- and medium-term option to provide backup to intermittent solar and wind resources. Manufacturers are designing the new generations of high-efficiency gas turbines (*flexefficient* F and H class turbines and aero-derivative ones) for frequent (250+/year) cold starts and fast ramp up rates (less than 30 minutes to full power from a cold start) to provide both base load generation and backup to intermittent solar and wind.

II.4 Installation and Integration of Solar and Wind Farms

Worldwide, at the end of 2013, wind, solar and geothermal capacity was 318 GW,[xvi] 140 GW[xvii] and 12 GW,[xviii] and annual capacity additions were about 35, 39, 0.6 GW respectively.[v] Wind and solar can, in principle, meet global electricity needs with a small carbon footprint, however, large-scale deployment of wind and solar PV systems require solutions to the intermittency and rapid fluctuations during generation challenges. In the last four years (2010-2014) there has been a dramatic reduction in cost of solar panels – cost came down to about $0.6 per peak watt at the end of 2014 – to the point that installations in new homes with net-metering options and no other subsidies are cost-effective with a less than 20-year payback period. Utility scale installations are still driven by incentives and mandates. Experience with concentrating solar power plants (CSP) is coming mainly from installations in Spain and the U.S., and the price point at which they become competitive is 20-40% higher than solar PV. Utility scale wind farms are a more mature option and have become competitive with fossil-fuel based generation on a simple $/KWh basis. However, on-shore capacity in most countries is limited; for example, the current estimated wind energy potential measured at 80m hub height for India is 102 GW. Fully exploited, 102 GW could contribute about 200 TWh per annum, i.e. about 3% of the total estimated 6000 TWh demand in a developed India by 2050.[xix] In the long-term the highest wind potential is from off-shore farms, which are primarily being developed in North-West European countries (U.K., Denmark, Germany, etc.) and recently in China.

Since wind and solar photovoltaic (PV) plants have no fuel costs, a simple calculation can be done to estimate the tariff at which they become economically viable without subsidy but under favorable regulatory conditions and a guaranteed tariff. If we assume an overnight capital cost of $2/Watt for a solar PV plant;[xx] a 10-year mortgage at 8%; allocate 2.5% of capital cost for annual operation and maintenance; and require 20% profit on the amount of electricity sold, then the capital cost of a 1 MW plant would be $2 million; the annual mortgage payment would be $291,000; O&M costs would be $50,000 and the expected annual profit would need to be $80,000 to achieve a rate of return on investment that investors typically expect. Such a plant in an area of high solar insolation could generate and export about 1.8 GWh per year. Assuming all the electric energy is sold at a guaranteed fixed rate, the tariff paid to the generator would have to be about $0.24/kWh to yield the desired total revenue of $421,000/year. Wind energy, on the other hand, would become economically viable at $0.12/kWh if one assumes a capital cost of $1/Watt, O&M cost at 5%, and all other factors the same. Note that good onshore and offshore wind sites typically produce 15-30% more electricity than good solar sites. The above numbers, summarized in Table 1, are, we believe, underestimates; however, they can easily be scaled as appropriate to obtain actual costs in different regions/countries.

	Assumed Capital Cost $/watt	Overnight Capital Cost 1 MW unit	Yearly Mortgage payment at 8% for 10 years	Operation & Maintenance Cost at 2.5% for PV 5.0% for wind	Energy Generated GWh/year	Profit at ~20% of electricity sold	Price per kWh to recover cost and profit
Solar PV	$2	$2,000, 000	$291,000	$50,000	1.8	$80,000	$0.24/kWh
Wind	$1	$1,000,000	$145,500	$50,000	2.0	$45,000	$0.12/kWh

Table 1: Cost analysis of probable tariff that a generating company would need to charge for a 1 MW solar PV versus wind turbine power plant to be sustainable without any subsidy other than guaranteed fixed tariff.

The cost of electricity will, in practice, be higher if high quality dispatchable power is required since solar and wind systems need backup. Assuming a total additional cost of $0.1/kWh for backup capacity, and distribution, and the profit expected by the backup/distribution company, a retail customer would need to pay over $0.33/kWh for solar and $0.22/kWh for wind energy. To put these numbers in perspective, today, the retail cost of electricity for a domestic customer in the U.S. is between $0.09-$0.11 per kWh, whereas in Europe it is between $0.3-$0.45 per KWh.

To address the main challenges for wind and solar farms, intermittency and rapid fluctuations during productive hours, requires large-scale integrated storage/generation that can be brought on-line on the same timescale as the fluctuations. Today, such backup energy is provided cost-effectively by reservoir based and pumped storage hydroelectric plants or by combustion turbine power plants. To build a balanced integrated system comprising of solar, wind, hydro and gas turbine units requires cooperation between utility companies and an enabling regulatory environment that is still emerging even in the countries leading in the development of “smart grid” technologies.[xxi] One can further combine these with nuclear power plants, which are cost-effective for base load power and have a low-carbon footprint, to build a highly optimized system. To facilitate the growth of such integrated (and more complex) systems, it is equally important to develop and train the human resource needed to operate and maintain them. Such a workforce is lacking in most developing countries.

Large-scale use of solar and wind farms to charge batteries or generate hydrogen by electrolysis is unlikely in the short term as there is little demand for these today: there are very few utility scale storage farms or electric vehicles and cost-effective utility scale electrolysis technology is still in the R&D phase.

As the capital costs come down and as experience with integrating them into the grid accumulates, solar and wind farms will continue to be installed but will not significantly displace fossil-fuel fired capacity (see figure 4) unless the challenge of intermittency (storage) is overcome. An integrated system designed to reduce carbon emissions and provide high quality power would need to maintain large excess capacity in fossil-fuel and hydro plants that operates in backup mode when wind is blowing and/or the sun is shining and meets full demand at other times. Similarly, the grid would need to be enlarged to wheel energy from areas of high wind (or high solar insolation) to demand centers. In practice, maintaining the full complement of fossil-fuel fired capacity to act as backup and for use intermittently is expensive, so the tariff will be higher.

Three scenarios would accelerate this transition:

(i) the capital cost of solar and wind units falls significantly;
(ii) the conversion efficiency of PV cells and wind turbines is improved from current 30% for typical wind turbines towards the Betz limit of 60%[xxii] and for PV from about 17% to demonstrated efficiency of 45% for multiple junction cells.[xxiii] In the near-term, it is unlikely that the combination of overnight capital cost and conversion efficiency will go much below the equivalent of $1/watt with 20% conversion efficiency for either solar or wind.
(iii) A sufficiently high price is put on carbon, for example at the emission trading scheme (ETS) in the EU.

The bottom line is that with current technology and costs, integration of wind and solar capacity to provide (20-40%) of electricity is technically achievable provided the public is willing to pay a much higher price for electricity and allows the building of enabling infrastructure in addition to the power plants (for example, new transmission lines) and/or international agreements mandate it. [xxiv]

II.5 Nuclear Power

Issues of safety and security of nuclear reactors and disposition of spent fuel continue to cast a long shadow on the future of nuclear power. A summary of the timeline of nuclear capacity added by OECD and non-OECD regions is shown in Figure 8. As of December 2014, there were 438 nuclear reactors in operation in more than 32 countries and 71 under construction, mostly in China (26), Russia (10) and India (6). [xxv] Also, there are five major companies that are developing and marketing nuclear power plants – Areva (France), KHNP/KEPCO (South Korea), Rosatom (Russia), GE-Hitachi and Toshiba-Westinghouse (U.S.-Japan mergers). These are no longer integrated companies but obtain components from a range of international suppliers, and often bid for contracts as collaborations. Post Fukushima, only five countries – France, Russia, China, South Korea and India – are promoting large-scale production facilities for enhancing domestic capacity and/or for export. Note that China and India have integrated capacity for manufacture and installation of the full plant, but this capacity has so far served mostly the domestic market. Growth of nuclear power will be driven by China and India as they each have plans for installing over 500 GW of nuclear capacity, with mixed oxide and thorium based fast breeder reactors constituting most of India's planned capacity additions.

For nuclear power to grow in even China and India, which are banking on it for a large fraction of the power needed to achieve the status of developed nations, it is imperative that no major new accidents occur anywhere in the world. The slowdown in the nuclear industry after each accident, the Three-mile Island, Chernobyl and Fukushima, show that negative impacts of nuclear accidents are large, long-term and global. The trend of fragmentation of manufacturing and construction spread over many companies from many countries has exacerbated the problem of liability and responsibility in case of an accident. The public wants a guarantee from the companies who profit from the construction and operations that they will be responsible all the way from construction through the dismantling of the plant and for proper disposition of all the spent fuel. With each accident, the public and the governments are less willing to accept the possibility and consequences of accidents. Furthermore, unlike other types of power plants, after an accident at one plant countries shut down their entire fleet of nuclear reactors for years-long evaluation period. As a result, increasing regulations and multiple safety measures continue to give rise to cost escalation and delays in construction. The Olkiluoto-III (Finland) and Flamanville-III (France) EPR reactors being constructed by Areva are ongoing examples of cost increase and delays in construction. International standardization of nuclear reactor designs would address some of these issues by reducing the overhead of oversight in design, quality control and construction. [xxvi]

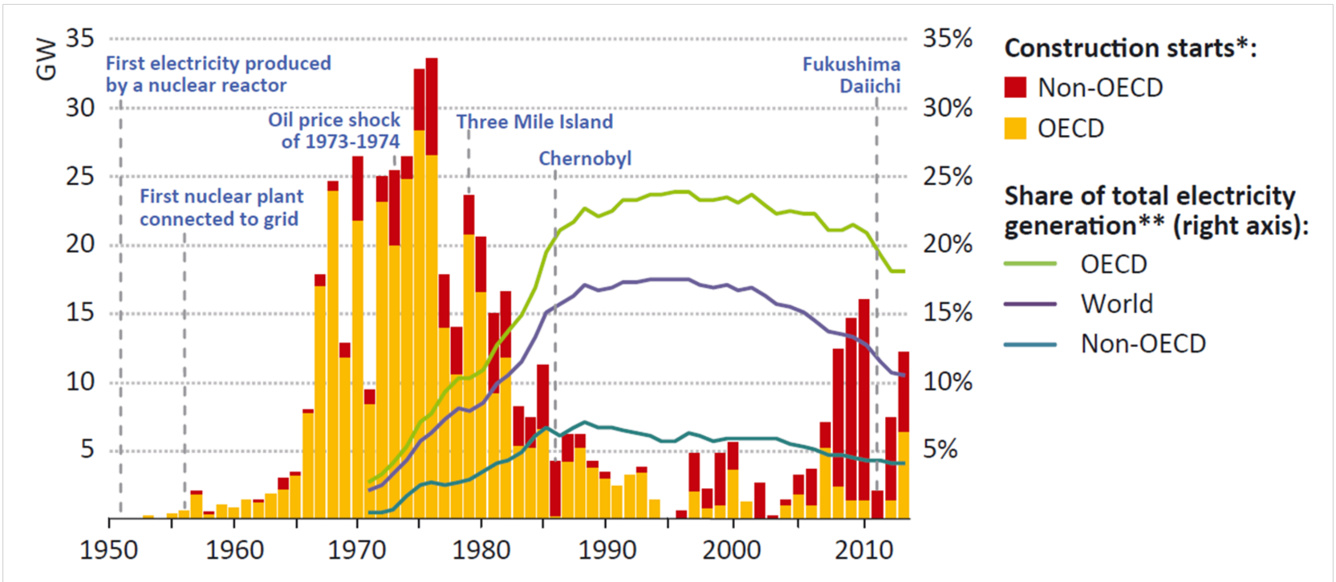


Figure 8: A summary of the timeline of the construction of nuclear power reactors by OECD/non-OECD countries (capacities on left scale) and the share of nuclear in power generation (right scale). [Source: IEA, World Energy Outlook 2014, p. 349]

Replacing coal-fired plants by nuclear is a very effective option to reduce carbon emissions, particularly because most of the countries that have large coal-fired generation (for example, China, USA, Russia, India, Germany, South Korea, South Africa, Japan) also have long experience with nuclear power and have operating nuclear power plants. Strong public opinion against nuclear power in some countries (for example, Germany) is, however, causing the opposite trend: nuclear capacity is being replaced by coal-fired or gas turbines in the near-term.

II. 6 Transmission Grid

The transmission grid in most countries is a patchwork of incremental development that has taken place since the first installations. Large investments are needed to modernize and automate it, and make it more resilient to provide reliable high-quality power to all customers – industry, commercial and residential. For example, the grid will need to be enlarged to wheel energy from areas of high wind and/or high solar insolation to demand centers. Opportunities for trade between countries to balance demand and supply in the larger system will need to be developed. These improvements are increasingly being recognized as necessary, especially in order to integrate intermittent renewable generation.

II. 7 Efficiency

Large savings of energy are possible through efficiency measures and the development of new technologies. Examples include electricity savings in lighting as it evolves from incandescent bulbs to CFL to LEDs to buildings designed to allow in more natural light during the day; more efficient appliances; better-insulated homes and buildings; solar hot water systems; geothermal heat pumps; higher mileage cars; better planned cities; etc.. The technology and the knowledge base for realizing these huge energy savings exist and remarkably they are also cost-effective! Comparing the three scenarios developed for IEA – the 'Efficient World Scenario'[xxvii], the '450 Scenario'[xxviii] and the 'New Policies Scenario'[xxix] – one finds that the 'Efficient World Scenario' is least dependent on new policies or new technology, leads to a more efficient allocation and use of resources and delivers economy-wide cost-effective benefits. Much can be done to implement these known higher efficiency options and further decrease their carbon intensity. The transition can be accelerated (faster and earlier) than the trend shown in Figure 9 through education, regulations and incentives. We do not discuss these opportunities in this paper, not because they are less important but because they are essential and require an independent detailed study. We also stress that inculcating and incentivizing a culture of efficiency must be at the core of all discussions on energy and climate. Furthermore, populations in parts of the world that are poor and don't have adequate energy resources and services need help to incorporate, adopt and benefit from efficiency measures (indigenous and those developed by industrialized countries) so that as they develop they can leap-frog many of the wasteful practices of the developed nations.

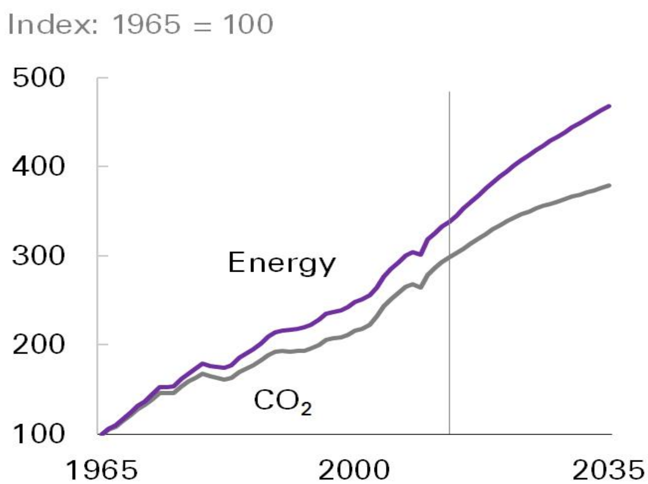


Figure 9: The amount of CO_2 emitted per unit of energy generated has been decreasing steadily. A major change is expected starting around 2020 with increasing conversion efficiency of fossil-fuel fired power plants, generation from renewables and fuel switch from coal to gas.
[Source: BP Energy Outlook 2035, slide 10]

III The future of Energy in different regions of the World

To understand how energy systems are evolving and what opportunities and challenges exist, we examine the energy needs of, and opportunities in, different regions of the world in this section.

South America:

Currently, five countries in this continent - Argentina, Brazil, Columbia, Chile and Venezuela - have large economies. Of these, Argentina, Brazil, Columbia and Venezuela generate most of their electric power from hydroelectric and combined cycle gas turbine (CCGT) power plants and are, on a regional scale, essentially self-sufficient in oil and natural gas.[v] These four countries can, therefore, power their development and sustain growth based on domestic reserves of fossil fuels. Venezuela has the largest oil reserves in the world and is already a major exporter of oil; however, policies of the Chavez and his successor Maduro governments negatively impacted exploration and production. The export of natural gas from Bolivia, Peru and Venezuela is growing. Inter- and intra-region trade in oil and gas can be enhanced and implemented efficiently through pipelines, if and when individual economies require it. Furthermore, these countries can also promote growth of solar and wind farms using their gas turbine and large reservoir based hydroelectric power generation capacity as backup.

Argentina and Brazil have strong demand growth that has recently led to growth in imports of oil and gas. Indigenous resources can, however, meet their growing demand; for example, they have large reserves of shale gas in addition to those of conventional gas. Planned exploitation of new large finds of oil (pre-salt fields in the Santos basin) could make Brazil a net exporter of oil by 2020 and the development of gas fields in the Campos basin and associated production from pre-salt fields could reduce the recent growth in imports from Bolivia and Trinidad and Tobago.[xxx] Similarly, Argentina has incentivized the development of new fields by offering higher tariff. Furthermore, both countries have over 25 years experience in operating nuclear power plants, are adding new capacity, and do not [yet] face strong public opposition against nuclear power. [xxxi] In the transport sector, a significant fraction of their individual transport vehicles are fueled by CNG and/or ethanol. Based on current reserves and predicted growth in energy demand and population over the next forty years, we foresee Chile as the only country in South America that may need to continue to import a significant fraction of the fossil fuels it will consume. It too can install and integrate about 5 GW of wind capacity backed by existing hydro and CCGT power plants, and thereby reduce imports of coal and gas in the short-term.

These five countries have very low population growth and high literacy rates. According to the CIA country factsheets, the fertility rate per woman and the literacy rates are:

- Argentina (2.27/98%),
- Brazil (1.8/89%),
- Chile (1.85/95%),
- Colombia (2.1/90%), and
- Venezuela (2.37/93%).

With stabilizing populations and an educated workforce, the biggest challenges these countries could face in the coming decades are poor governance, corruption and public outcry against inequitable distribution of resources and wealth. The investment and regulatory environment they create for attracting capital and multi-national oil and gas companies to help exploit conventional and unconventional (heavy oil, pre-salt oil and shale gas) reserves will impact development and the timely creation of state-of-the-art indigenous capability.

In short, countries in South America have multiple options for their energy needs, and because of large existing renewable resources (hydro, wind and biofuels) they will continue to have a smaller carbon footprint per capita compared to other regions of the world with similar levels of development. They can provide leadership by further reducing their carbon footprint by investing in improving efficiency – public transport systems, high mileage cars, smart homes, energy efficient cities, etc. – and improving the grid to integrate solar and wind generation.

North America:

Mexico, the U.S. and Canada are rich in natural resources. Canada is a net exporter of oil, gas and coal and gets about 60% of its electricity from hydroelectric power plants. Over the last decade it has significantly reduced its dependence on coal-fired generation by increasing the share of gas-fired CCGT, but the coal saved is increasingly being exported. Mexico has been an exporter of oil since 1975 and most of its gas and coal imports are from the U.S. These patterns will persist especially given the growth in unconventional oil and gas (shale gas, tar sands, tight oil) production in the U.S. and Canada. Over the last decade Mexico's oil production has declined due to insufficient investment in existing fields, incorporating new technologies and in exploration. This could change rapidly with the recently approved reforms that allow foreign investment in the state monopoly PEMEX and nudge it to become more open.[xxxii]

The only significant energy import into the region in 2013 was oil by the U.S. According to the latest projections by BP, IEA and EIA, by 2035 the region will not need to import even oil assuming the pattern of growth in exploitation of unconventional resources (tar sands and shale oil and gas, coal bed methane and tight gas) and reduced consumption of oil continues.[xxxiii] In addition, Canada still has very significant untapped hydroelectric capacity and can further reduce its dependence on fossil fuels. Using their hydroelectric and CCGT resources as backup, both Canada and the U.S. can continue to install utility scale wind and solar farms. Learning from the experience with slow integration of wind farms in Texas due to limitations in the capacity and structure of the transmission grid, they are investing in modernizing the grid to facilitate growth and integration of renewable generation.

All three countries have extensive experience with nuclear power. The U.S. and Canada are leaders in its development; however, over the last 35 years since the accident at the Three Mile Island power plant, negative public opinion has stalled growth. If need arises, they can, however, restart large-scale development of nuclear power plants on short notice. Meanwhile, the focus in the U.S. is on research in (i) small modular reactors (SMR),[xxxiv] (ii) fourth generation reactors that are economical, proliferation resistant and have high fuel burn up rate with reduced waste production,[xxxv] and (iii) very long-term management and disposition of spent fuel. An important issue that SMR are being designed to address is to reduce the high up front capital cost due to the long construction time and changing regulations by standardizing design and manufacturing. Also, capacity can be built up incrementally in sync with increase in demand. In short, SMR are likely to be more acceptable in developed countries while large conventional reactors are favored by developing countries with large unmet and growing demand.

The region has numerous options for meeting its energy needs from a resource perspective as well as for making very significant reductions in per-capita demand from gains in efficiency. Overall, one would characterize the U.S. and Canada as post manufacturing economies, however, prospects of long-term low-cost energy are incentivizing and revitalizing manufacturing. Otherwise, any growth in demand for energy will primarily come from the current rate of population growth of about one percent.[xxxvi]

Given its wealth of resources and many advanced technology options for energy systems, how and when the U.S. reduces its dependence on fossil fuels will depend on government policies and regulations driven by economics and public opinion. The public will have to increasingly weigh in on leading the world in mitigating climate change and environmental impacts of burning fossil fuels, for example, by providing the leadership needed for the revival of nuclear power industry and investment in renewables. Until the U.S. and international policy penalizes greenhouse gas emissions fairly, the likely trend over the coming decades is increasing exploitation of unconventional oil and gas, increasing exports of coal and natural gas (LNG) from the region and shrinking imports of oil.

In the area of exploration and recovery of unconventional oil and gas, technology and experience are essential and the U.S. oil and gas companies are industry leaders. Thus, the U.S. companies will continue to create and develop new opportunities for production, both domestic and international. Today, worldwide, national companies or governments control about 80% of conventional oil and gas reserves. Many of these assets have underperformed or have been damaged (reduced percentage of the resource is being recovered) due to poor management and/or inadequate investment in new technologies and resource analyses. One reason is that western multinational companies have been asked to leave prematurely before indigenous talent is fully trained. Today, many of these national companies are rebuilding relationships with American and European companies having realized the benefits of cooperation and the increasing need for state-of-the-art technology, especially for the exploitation of unconventional resources.

Looking ahead, significant investment is needed in the transmission grid, especially in order to integrate solar and wind generation. The electricity transmission networks of Canada and the United States are integrated along the border, and the United States will remain a net importer of electric energy, along with oil and gas, from Canada.

Lastly, it is worth mentioning that Canada and Russia may see themselves as winners (or perhaps as the least-dramatic losers) in the climate-change game, because they're closest to the Arctic. Under warming scenarios, it will become easier to extract minerals and fossil fuels locked in the Arctic and, assuming soil quality is maintained, their agricultural sectors will become more important as crop zones move towards the poles. Lacking social pressure and possessing large resources, they may not have sufficient incentive to whole-heartedly support international regulations on greenhouse gas emissions or trade in fossil fuels.

Russia:

Russia, rich in natural resources, plans to continue to exploit fossil fuels and remain a major supplier of fossil fuels and nuclear power reactors to the world. It holds the world's largest reserves of conventional natural gas (about 50 trillion cubic meters), the second largest coal reserves (about 150 billion tons) and the eighth largest oil reserves (about 90 billion barrels).[v] A very significant fraction of its export earnings (about 50%) have historically, and continue to, come from the export of all three fossil fuels. These exports constitute about 40-50% of the government revenue. Not surprisingly, there is no indication of introduction of policies to curb their use and/or export, especially since Japan and South Korea to its east, China to its south and Europe to its west have large [unmet] energy needs and can pay international prices for them. The major challenges Russia faces in enhancing supply are geopolitics and the modernization of its existing assets (oil and gas fields and coal mines, oil and gas pipelines, and gas- and coal-fired heat and power plants) and the development of the technology to exploit unconventional oil and gas resources and off-shore fields in the Arctic.

Russian companies (both state and private) were undergoing modernization and creating global alliances. These partnerships were exploring and developing new fields including offshore ones in the Arctic. Similarly, President Putin was campaigning to increase exports of natural gas to Western and Southern Europe (about 27% of EU gas currently comes from Russia) and new pipelines are being developed. In addition to the extensive gas pipeline infrastructure to Europe developed during the Soviet era, the Blue Stream gas pipeline (16 bcm/a) to Turkey[xxxvii] became operational in 2005 and the Nord Stream pipeline (55 bcm/a) to Germany in October 2012.[xxxviii] Construction of the South Stream gas pipeline with design capacity of 63 bcm/a was started in December 2012[xxxix] but was cancelled on December 1, 2014 by President Putin. Considering the uncertainty in growth in demand for gas if prices stay high,[xl] justification for some of the recent capacity additions in Europe (pipelines, LNG terminals, CCGT power plants) may, however, lie in long-term strategic interests rather than a response to growing demand. Unfortunately, the events of 2014 (annexation of Crimea and unrest in Ukraine) and subsequent economic sanctions against Russia and the plunge in world oil prices, make it unclear whether, and how, growth and modernization of the energy infrastructure that depends on international cooperation will take place in the near future.

Russian strategic planning aims to significantly increase the use of nuclear power for cogeneration of electricity and heat and for powering arctic ships. For example, it plans to increase the share of electricity produced by nuclear power from about 17% in 2012 to almost 50% by 2050.[xli] It is also marketing its nuclear reactors to ex-Soviet Eastern European and Central Asian countries, Iran, India, Turkey, Greece, Vietnam and China under very favorable terms.[xlii] With more countries acquiring nuclear reactors and technology from Russia, issues of proliferation, safety, security and safeguards will need to be reassessed.

Some of the decisions that Russia will have to make in the future, from both economic and mitigating climate change perspective, are: (i) whether to replace its aging coal-fired power plants with natural gas fired CCGT or reserve the natural gas for export; (ii) modernize its coal-fired power plants by manufacturing/importing supercritical coal-fired boilers and turbines; (iii) increase the share of nuclear power; and (iv) develop the remaining 80% of its hydropower potential, mostly in Siberia, and export excess power to China. The efficiency and timeliness of these developments will most likely depend on whether its companies are controlled by the state or whether the government creates a favorable investment climate to encourage participation by international companies.

In the short-term, one has to assess the situation in Russia and its relationship with the West which changed dramatically in 2014 following its annexation of Crimea and military intervention in Ukraine. Isolation by Western countries and economic sanctions have replaced cooperation. The collapse of the price of oil has already impacted the economy very significantly and the Ruble fell from about 25 to 60 per dollar in 2014. There are fears of very hard times ahead. It is, therefore, unlikely that Russia will have the resources to continue to modernize its energy infrastructure anytime soon.

Western Europe:

Europe, excluding Russia, will continue to depend on imports to meet its energy needs for both power generation and transportation. Barring Norway and Netherlands (and partially the U.K.), all European countries currently import almost all the oil and natural gas they consume. With their populations having stabilized and the historical trend of the total oil consumed showing a rough plateau over the last forty years, reflecting both improved efficiency in transportation sector and fuel substitution away from oil in power generation and heating sectors, the future burden of oil imports can be estimated to remain constant or decrease slightly.[v] Natural gas' share, on the other hand, is expected to increase somewhat as gas turbines are being used to generate base load electric power and serve as backup to solar and wind.

Europe is geographically well situated to access natural gas reserves in Russia, Caspian Sea basin, North Africa and even Middle East via pipelines. To maintain a diversity of supply, it has also developed LNG ports and significant regasification capacity that would feed into the existing gas pipelines. Public support for natural gas is growing because it is cleaner and has a smaller end-use carbon footprint. The challenge individual countries face is paying for imports of oil and gas if prices stay high. Two examples of the financial hardships imposed by mounting costs of energy imports are Spain and Italy – energy imports are very significant contributors to their recent trade deficits. Overall, high prices of oil and gas during 2010-2014 contributed to the decline of oil and gas consumption in Europe.

The only large reserves of coal in Europe are in Germany (lignite) and Ukraine. So far Ukraine has not significantly exploited its reserves, as its consumption is modest. Germany's coal consumption is about 50% lignite and it imports most of the remaining thermal (hard) coal it consumes. Other significant consumers such as Poland and Czech Republic are self-sufficient. France, Italy, Spain and the UK import most of the coal they consume. From the climate perspective, the opportunity for countries that get a large fraction of electric power from coal-fired power plants is that they also have long experience with nuclear power (Germany, Ukraine, Czech Republic, Spain, The UK) and could, in principle, replace coal by nuclear. The growing public opinion in Western Europe, however, is to phase out both nuclear and coal and predominantly rely on natural gas and renewable resources. While natural gas presents an opportunity for fuel substitution leading to a smaller carbon footprint compared to coal-fired generation, it is more expensive and has to be imported from some unstable regions of the world. Currently, eliminating both nuclear and coal is posing economic challenges for many countries due to the higher price of natural gas and low price of carbon allowances. For example, while phasing out nuclear power plants, Germany in the short-term is installing high-efficiency coal-fired units and a larger fraction of its electricity is coming from coal. Thus, it is not clear whether fuel-switch to gas and renewable technologies is realistic, economically and technically, to eliminate both nuclear and coal in the near- to mid-term. On the other hand, recent legislative initiatives in Germany and at the European Union are aimed at putting the green energy turnaround back on track.

High-efficiency CCGTs are very efficient and effective for both base load power generation and as backup to solar and wind. To implement a fuel switch from nuclear/coal to natural gas, however, requires that each country export enough goods to pay for the gas in addition to what they are already paying for oil – irreplaceable for transportation. Spain is an example of a country that, today, could meet all its electricity needs from the recently installed high-efficiency CCGT power plants supplemented by renewable generation from hydro, wind and solar. The downside of switching to CCGT is that when one examines Spain's trade balance, one finds that its growing deficit is almost totally accounted for by the cost of oil and gas it imports. This economic reality will most probably require it persist with either coal or nuclear or both for base load generation in the near-term unless the cost of gas comes down dramatically.

Germany is also increasing its coal- and gas-fired generation capacity. Its first priority is to phase out nuclear by using existing excess coal and gas-fired capacity and increasing the share of renewables. So far, it exports enough goods to pay for the imported oil and natural gas to prevent accumulating a trade deficit. Nevertheless, the large differential in cost between coal- and gas-fired generation has resulted in a larger use of coal; some of the recently installed high efficiency gas turbine capacity, for example at Irsching, is underutilized and operating as backup. These trends indicate that the new state-of-the-art coal plants coming on line will, in the near-term, replace most of the nuclear base load capacity as it is retired even though they have a larger environmental footprint compared to nuclear or even CCGT if market and/or legislative framework remain unchanged.

France gets about 80% of its electric power from nuclear power plants. The combination of hydroelectric, CCGT, coal-fired and wind provide the rest and meet the peaking load. France is, however, driving forth an energy transition law that intends to reduce the fraction of nuclear to 50% by 2025 while increasing the share of renewable generation.[xliii] It will be interesting to see how France's policy on nuclear power evolves, especially post 2030 when its current fleet of reactors will be between 40–50 years old.[xxv]

Eastern Europe without Russia:

Soviet era power systems (coal and nuclear) still dominate the generation of electric power. EU mandates on emissions have resulted in the closing of old plants and installations of pollution control systems for sulphur and nitrogen oxides on the rest. Because of these mandates, the price of new build coal-fired plants has increased very significantly. Large-scale development of coal-fired plants, which have lifetimes of over forty years, in Eastern Europe, will, therefore, depend on foreign investments, carbon taxes and long-term stability of coal imports, most likely from

Kazakhstan and Russia, once indigenous reserves run out. On the nuclear front, after an almost twenty-year hiatus, Ukraine, Belarus, Slovakia have new reactors under construction, and Poland, Romania and Bulgaria are in advanced stages of planning.[xliv]

Most of the countries of Eastern Europe import the bulk of the oil and gas they consume. Installations of CCGT plants are increasing as a result of capital inflow from, and participation by, international power generating companies, however, they are dependent on Russia for the supply of natural gas. In fact, Russia maintains a strong economic hold on these countries by controlling their access to oil and natural gas (for example, the ongoing struggles with Ukraine on gas pricing and transit fees since 2005, and an increase of 80% in April 2014 due to the political tensions). Thus the technology selected for the power plants being installed since 2000 has depended strongly on the operating company and the financial institutions providing the capital, with Russian and Western-European companies competing for a market share.

Overall, there has been significant reduction in the carbon footprint since 1990 due to gains in efficiency, upgrade of Soviet era plants to modern technologies, fuel substitution and development of wind and solar farms.[xlv] Demand has not increased significantly because of decrease in population, the economic crises and high cost of imported fuels since these countries are no longer subsidized by Russia but have to pay international prices for oil and gas. New fossil-fuel plants are mostly being built with international partnerships. Hydroelectric capacity in many countries is small so large-scale integration of wind or solar will require concomitant growth in CCGT. The good news is that the population in most countries in the region has stabilized (in fact decreasing), so any increase in greenhouse gas emissions in the near-term will be due to very welcome economic development.

North Africa:

The five North African countries (Egypt, Libya, Tunisia, Algeria and Morocco) can power their development for the next thirty years through the use and sale of fossil fuels. Barring political instability, Libya and Algeria have sufficiently large reserves of oil and gas to meet growing domestic needs and export significant quantities. They are currently exporting gas to Spain and Italy through the Maghreb-Europe (12 bcm/a), Medgaz (8 bcm/a), Trans-Mediterranean (30.2 bcm/a) and Greenstream (11 bcm/a) pipelines, and GALSI (10 bcm/a) is being planned. Morocco and Tunisia are earning transit fees from the Maghreb-Europe and Trans-Mediterranean pipelines, respectively. These pipelines also provide a framework for access to gas supplies from Algeria by Morocco and Tunisia and, if necessary, for new pipelines as needs grow. Egypt, too, has significant production of natural gas. As a result it has mostly replaced its oil-fired power plants with CCGT and has developed the infrastructure to export natural gas to Israel (7 bcm/a capacity Arish-Ashkelon pipeline), to Jordan, Syria and Lebanon via the Arab gas pipeline (10.3bcm/a), and to Europe as LNG. Rising domestic consumption, however, has led to oil imports and a decline in export of natural gas since 2009.[xlvi] Furthermore, repeated sabotage of pipelines has disrupted export of gas for long periods. Anticipated fuel shortages and trade deficits in the near-term could significantly worsen the ongoing political instability.

All five countries have large areas of cheap desert land with high solar insolation that provides excellent opportunities for both solar PV and CSP power plants. These can be integrated with the

CCGT and wind plants for providing high quality dispatchable power. Projects such as Desertec-Africa, albeit currently in limbo, are creating options for increasing capacity and training the human resource needed for sustainable development of CSP.[xlvii].

The key issues for future development in these countries and the transition to an increasing share of renewables in the energy portfolio and reduction of greenhouse gas emissions are

(i) governance,
(ii) population stabilization,
(iii) investment in education, and
(iv) broad-based economic growth.

The recent political and social upheavals, starting with the Arab Spring, have left behind lingering instabilities and restive populations. Throughout the region, there is pressing need for the development of infrastructure for manufacturing and service industries that would facilitate job creation and trade over and above that driven by the tourism and the oil and gas industry. The question, post social upheavals in 2011-2012, is whether stable political systems will emerge in the near-term and whether these countries will invest revenues from sale of oil and gas into long-term development, *i.e.*, health care, education and job creation?

Sub-Saharan Africa

Most of sub-Saharan Africa excluding South Africa has highly inadequate electric power generation capacity; the existing capacity consists mainly of hydro and diesel generators. Infrastructure development, in general, has been minimal due to lack of capital. Also, maintenance of many facilities and access to spare parts has been poor, resulting in power plants having short lives, underperforming or remaining under maintenance for extensive periods. Poor governance, civil wars, epidemics (malaria, HIV/AIDS, Ebola, etc.) and widespread corruption continue to stifle development throughout the continent. The primary need is stability and development.

Current consumption of oil and gas is very low. Only five countries have significant oil and/or gas reserves that are being exploited – Nigeria, Angola, Chad, Sudan and Mozambique – and oil exports constitute the majority of the government revenue in the first four countries. Nigeria also exports natural gas as LNG in the world market and via the West-Africa gas pipeline to Benin, Togo and Ghana[xlviii] that is used mainly for power generation. Mozambique exports most of the gas it produces to South Africa via the Sasol Petroleum International Gas Pipeline. New discoveries of large gas fields in Mozambique[xlix] and Tanzania are being developed and LNG exports are expected to start rivaling those from Qatar by 2020 and help reduce global prices. Further discoveries in Uganda and Kenya and the creation of a regional gas distribution system could change the energy landscape in East Africa. Until that happens, the dominant source of electricity for the rest of the countries is hydropower and most of the planned development is also hydro.

South Africa is the only country in sub-Saharan Africa with a significant economy and modern infrastructure. It imports about 70% of the oil and gas it consumes. Domestic oil production relies on coal to oil conversion by Sasol. It has large reserves of coal (about 30 billion tons with an R/P ratio of 116 years), which provide about 95% of the electricity generated. Along with Colombia, it is the fifth largest coal exporter (about 70 mtpa in 2013). Its exports are, however, unlikely to grow rapidly owing to domestic consumption, declining coal recovery grades, depleting easy to get at mine reserves, increasing operating costs and a railway bottleneck to the export port of Richards Bay. It also faces water shortages in the coal belt (Mpumalanga province) that could limit its reliance on coal for power generation. Any significant shift away from coal-fired generation will, however, require exploitation of its shale gas resources or investment in nuclear power. It does have extensive experience operating two nuclear reactors that were commissioned at Koeberg in 1984, however, there are no new ones planned. Without strong economic incentives and international mandates, at present it has little motivation or social pressure to move away from its reliance on cheap coal for power generation and for conversion to liquid fuels.

Central Asia:

Of the countries of Central Asia (Uzbekistan, Tajikistan, Kyrgyzstan and those bordering the Caspian Sea), only Tajikistan and Kyrgyzstan are lacking in fossil fuels and get most of their electric power from hydroelectric systems. Most of the other countries export commodities and could fuel their development through these sales and create a regional economy. The primary challenges for this region are governance, development and an educated workforce that can compete in the international market and grow a non-commodity based economy to create jobs.

China (pipelines and other infrastructure), Russia (thermal and hydro power plants), and the U.S. (gas turbines and oil and gas exploration) are competing for influence in this region. China, with its large monetary reserves and energy needs, is helping build infrastructure in exchange for oil and gas. The development and operation of the Kazakhstan-China oil pipeline and the Central Asia-China gas pipeline (both became operational in 2009) have begun to connect the countries in this region in addition to exporting oil and gas to China. The Trans Adriatic Pipeline (TAP) from Shah Deniz gas fields in Azerbaijan would engage Europe and the TAPI gas pipeline from Turkmenistan, if built, would engage Pakistan and India.

Turkey

Turkey is strategically located at the crossroads between Europe and gas- and oil-rich Russia, Central Asia and the Persian Gulf. It serves as an important transit country for both oil and gas.[l] For domestic consumption, it gets natural gas from Russia via the Blue Stream gas pipeline; Caspian gas via the Bulgaria-Turkey Gas pipeline under construction; from Azerbaijan via the Baku-Tbilisi-Erzurum pipeline[li]; and from Iran via the Tabriz-Ankara Pipeline. (The latter two have recently been blown up repeatedly by Kurdish separatists). Against the backdrop of cancelling the South Stream Pipeline project to Western Europe, Russia has recently reinforced its intention to enlarge its undersea pipeline connection to Turkey by an annual capacity of 63 bcm, more than four times Turkey's annual purchases from Russia. The recent selection of the Trans-Adriatic Pipeline (TAP) by the Shah Deniz Consortium to connect with the Trans Anatolian Pipeline (TANAP) near the Turkish-Greek border at Kipoito to carry gas from the Shah Deniz II field in Azerbaijan via Turkey to Europe will open up a Southern Gas Corridor.[lii]

In Turkey, gas is primarily used for power generation and industrial use. The importance of coal in electricity generation is also increasing and indigenous resources of lignite are already committed to supplying existing lignite-fired power plants. Over the last decade consumption of imported hard coal has grown and in 2013 Turkey imported about 35 million tons, comparable to its consumption of indigenous lignite.

The eastern half of Turkey has large reservoir based hydroelectric generation capacity (both installed and under construction and planning), which it can use to integrate significant generation from wind and solar. The challenge it faces, since its energy demand is projected to grow at 7-8% per year in the near-term (second only to China), is its ability to pay for importing oil, gas and coal if their prices stay high and if its economy continues to struggle. To reduce its dependence on growing imports of fossil-fuels, it views nuclear as a major part of its future power generation system and Russia is offering to finance and build its first four reactors.[liii]

Middle East:

Most of the countries in the Middle East are rich in oil and natural gas and can power their development using revenues generated by exporting them. Only Israel, Jordan, Lebanon and Palestine have significant imports today. Their energy needs are, however, small compared to the export capacity of their Persian Gulf neighbors and can easily be met. In fact, there already exist oil and gas pipelines from Iraq, Saudi Arabia and Egypt to Syria that can be re-commissioned and/or upgraded to meet future demand. There also exist [unused] pipelines from Syria to supply Israel, Jordan, Lebanon and Palestine. The bottom line for sustained development in these four countries is not lack of easy access to energy but political stability, trade and good governance in the region.

The discoveries of gas fields in the Mediterranean and energy efficiency measures have enhanced Israel's water and energy security. Israel has been developing its off shore natural gas reserves in the Mediterranean since 2009. For example, the Tamar gas fields are already operating and the Leviathan fields are projected to come online as early as 2016.[liv] Israel is also a world leader in the use of solar hot water systems and 90% of homes have solar panels; and in the use of state-of-the-art watering harvesting and conservation systems such as drip irrigation for agriculture.

Power generation in all Persian Gulf countries (Iraq, Kuwait, Bahrain, Qatar, Saudi Arabia, UAE, Oman and Iran) will, in future, be fueled mostly by natural gas given the large gas reserves and the economic and logistic advantages of exporting oil and using gas for power generation as shown in Figure 10. In fact, over the last decade, the transition to gas turbines from oil-fired thermal units has already taken place. This has led to very significant increase in domestic consumption of gas and many states (including the Emirate of Fujairah, Bahrain, Jordan, Kuwait and Egypt) may have to start importing LNG in the near-term. To diversify its sources of energy, the region is investing in nuclear power. Bushehr nuclear power plant in Iran is operational, and recently UAE signed a long-term deal with South Korea for four nuclear reactors at Barakah and the construction of these has begun.[lv] Other countries in the region are also considering nuclear power.

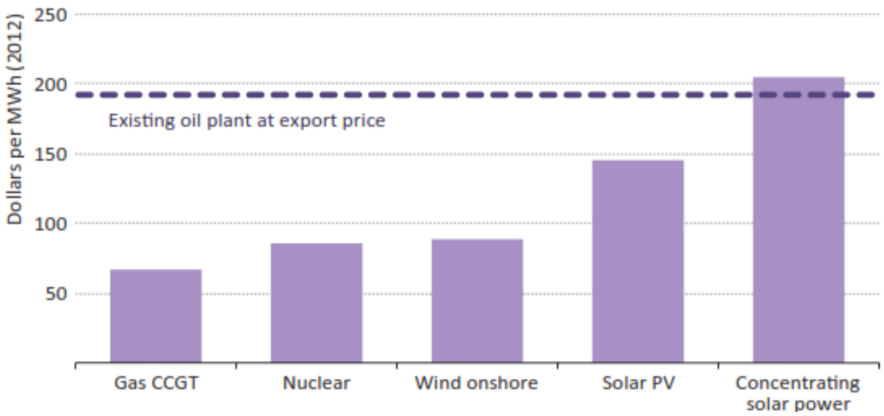


Figure 10: Comparison of electricity generating costs by technology in the Middle East for the year 2015. The current system is dominated by natural gas-fired combustion turbine power plants. [Source IEA WEO (2013), p. 508]

The six members of the Gulf Cooperation Council (Kuwait, Bahrain, Qatar, Saudi Arabia, UAE and Oman) have also undertaken a regional integration of the transmission grid and natural gas pipelines (for example the Dolphin gas pipeline from Qatar through UAE to Oman) to stabilize supply. They are also investing in both the service sector and heavy industry (for example, aluminum smelters) to diversify their economies, nevertheless, oil and gas exports will continue to dominate their economy and revenue generation in the foreseeable future. Needless to say, current (2015) low prices of oil, if they persist, will severely strain government budgets.

As a result of growing populations, economic activity and higher standards of living, the energy consumption in all Persian Gulf countries has been growing rapidly. Since oil, gas and electric power are highly subsidized, the public has little incentive to improve efficiency in end use. As a result, indigenous consumption of oil and gas is growing and these countries have amongst the highest per capita emissions of greenhouse gases. With abundant cheap oil and gas, the biggest challenge these countries face is motivating, educating and training their national populations to create new business opportunities and developing the skilled workforce the private sector needs to diversify the economy beyond fossil fuels.

India:

India continues to have a very large unmet need for electric power. Assuming a development goal of 0.5 kW/person (about 4000 kWh/person/year) and a projected population of over 1.5 billion by 2050, India will need about 6000 TWh of electric energy to attain and sustain the status of a developed nation. This is six times India's 2013 electricity generation. For comparison, these target figures translate into an energy/person goal that is about half of what a German consumed in 2013. Also, China's consumption of electricity in 2012 was about 4000 TWh for a population of 1.35 billion. As will be discussed below, attaining 6000 TWh/year is unlikely based on India's history of development of energy systems, availability of capital for investment and current reserves of fossil fuels. The likely scenarios are either the desired goal of 0.5 kW/person will need to be more than halved or 400-500 GW of nuclear capacity will need to be installed. A detailed discussion of India's energy scenario, constraints and opportunities is given in reference[lvi].

India's population (1.25 billion in 2013) is still growing at about 1.5% p.a., i.e. by about 18 million people per year, and almost all the growth is amongst the poor. Around 2026, at 1.45 billion people, it is projected to overtake China's population and continue growing until about 2050 to about 1.7 billion (see Figure 11). Also, India is just starting its phase of rapid urbanization: in 2013, only 30% of the population lived in urban areas. Its energy needs will, therefore, continue to grow all the way until 2050.

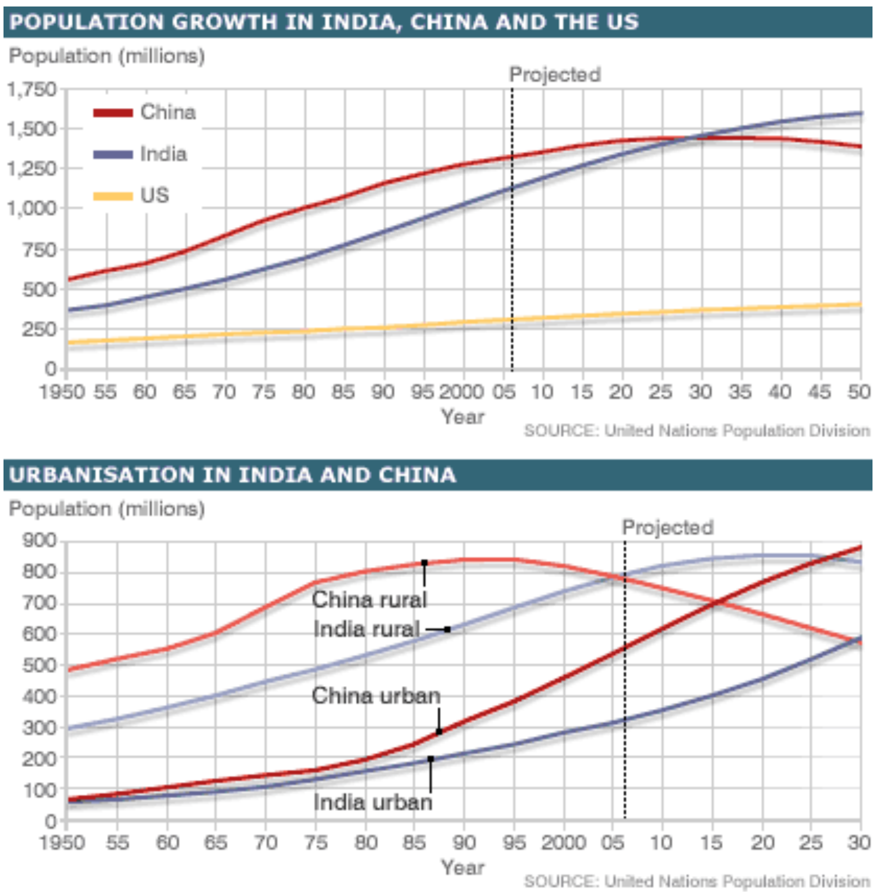


Figure 11: The historic and projected growth of population in the two most populous nations, China, and India. India is projected to overtake China's population by around 2026 at about 1.45 billion and continue growing until about 2050 to about 1.7 billion. The bottom figure compares urbanization in the two countries with India just starting its phase of rapid urbanization.
[Source: http:// www.bbc.news.com].

Considering its size and population, India has limited reserves of fossil fuels to meet this demand, with coal being the most abundant (about 60 billion tons).[v] This reserve can produce about 100,000 TWh of electric energy based on a conversion efficiency of 40% and a caloric value of approximately 3500 Kcal/kg (= $4kWh_{thermal}/kg$ = $1.6kWh_{electric}/kg$). This is the amount of energy that 400 GW of super-critical coal-fired capacity can produce in 30 years, i.e., an annual production of about 3200 TWh. In 2013, 150 GW of coal-fired captive and grid connected plants generated only about 700TWh due to the low conversion efficiency of the older sub-critical units. To reach the 3200 TWh/year mark by 2025, India will have to build over 300 GW of supercritical units to achieve 40% efficiency, increase investment in coal mining and transport infrastructure to provide one gigaton/year of indigenous coal for plants near the mines and in the interior of the country, import about 500 million tons/year for coastal plants, and develop in situ gasification technology as easy to access coal seams close to the surface (0-300 meters) get exhausted. This expansion is non-trivial and India will face increasing international pressure to reduce carbon emissions and domestic societal resistance due to pollution, water rights and land acquisitions. If this mark of 400 GW of super-critical coal-fired capacity is achieved, it will provide a window of opportunity of 3200 TWh/year until about 2050 when current estimates of conventional and unconventional coal reserves will be exhausted and uncharted resources are expensive to mine.

The consumption of oil has been increasing at roughly 120,000 bbl/day each year since 1994, much faster than the total growth in domestic production of about 200,000 bbl/day over the same 19-year period, 1994-2013. Of the total oil consumption, about 3.7 Mbbl/day in 2013, imports constituted about 2.8 Mbbl/day and the demand is projected to continue growing: for example, in the individual transport sector alone, approximately 2 million new cars (18 million total vehicles including commercial and 2 and 3 wheelers) were sold in 2012 and in 2013.[lvii]

To keep up with the increase in demand for oil and electricity, the fraction of imported coal, gas and crude oil has also been increasing. In 2013, these fractions were about 30%, 34% and 76% respectively as shown in Figure 12.[lviii] It is important to note that India is importing significant quantities of all three fuels at a much earlier stage in its development compared to China, and these imports are creating economic challenges. As stated above, to support 300+ GW of coal-fired capacity beyond 2025, India's coal imports would increase to over 50% of the consumption, i.e., about a billion tons per year. At this rate of growth in demand for coal, gas and oil, will India be able to continue to afford to import all the fossil fuels it needs? High cost of imported oil, gas and coal are already leading to an increasing annual trade deficit that has become a major national concern. Unless India's manufacturing capacity, services and exports keep pace with the cost of importing fossil fuels, growing trade deficits may start to limit the capacity to import them and curtail overall development.

India's industrial competitiveness is handicapped by, among many reasons, severe shortages in electric power supply and rolling blackouts due to inadequate generating capacity, aging grid and disruptions in supply of coal and gas to power producers. Also, bankrupt utility companies prefer to cut off supply to all their customers rather than buy power on the spot market that they then have to sell at prescribed lower rates.

The majority of 88.5 GW of capacity addition under construction and with anticipated completion date during India's twelfth five-year plan, 2012-2017, is thermal (72.3 GW), Hydro (10.9 GW) and nuclear (3.9 GW).[lix] Most of the thermal addition is coal-fired, which requires the associated infrastructure (coal-ports, mines, railways, roads and transmission lines) be developed in sync. Past experience, even that during the last decade, shows that growth in the needed associated infrastructure has not kept pace. Also, the growing social opposition to coal-fired power plants as a result of displacement of people due to land acquisition, dwindling water resources and growing pollution is likely to limit growth.

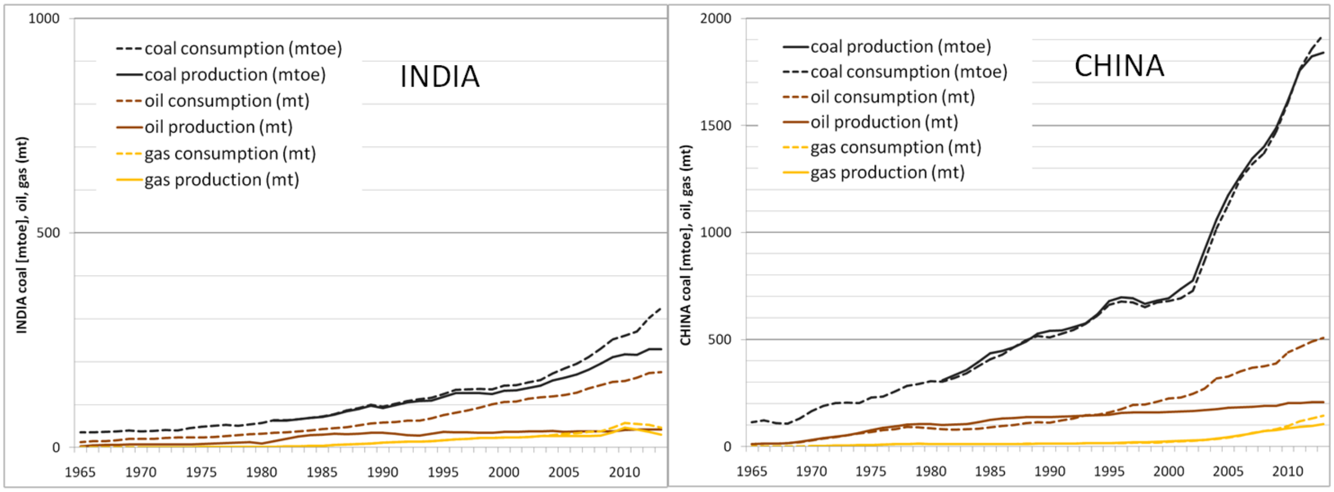


Figure 12: A comparison of the production (solid lines) and consumption (dashed lines) of coal, oil and gas by India and China. Note that the y-scale is larger by a factor of 2 for China and that India has to rely on imports of all three fuels at a much earlier stage in its development.
[Source: BP Statistical data workbook 2014.]

India's hydroelectric and on-shore wind resources are also limited. Current estimates are about 120 GW of economically feasible hydroelectric potential (40 GW has been developed and is operating) and 102 GW of on-shore wind (about 20 GW is operating).[lx] The historic trend is that India has been adding about 1 GW of hydro and about 2 GW of wind turbine capacity each year. Even when the current economically feasible potential has been fully developed, these hydro and wind resources would produce, per year, only about 440 and 200 TWh of electric energy respectively. This, eventual, 200 TWh of wind generated energy could be integrated with reservoir based hydro and existing (plus anticipated) CCGT capacity to provide about 1000 TWh of dispatchable supply. Such integration will, however, require a highly instrumented and automated grid (smart grid) and unprecedented coordination between the producers, transmission and distribution companies and state and central governments.

The only known abundant sources of energy in India are solar and thorium. Today, most of the recently installed 2 GW solar capacity is the result of incentives and tax credits as part of the Jawaharlal Nehru National Solar Mission.[lxi] Since utility scale plants have been operating starting only in 2011 as part of this initiative, it is not yet clear how much solar generation will be realized in the coming decades, but it is unlikely to be more than a few 100 TWh by 2050, a very optimistic number when compared to the approximately 2 TWh generated in 2013. Nevertheless the ministry of new and renewable energy (MNRE) recently announced big-ticket projects and set very ambitious targets for solar power capacity additions, *i.e.*, a massive scale-up to 100 GW by 2019.

Progress in the development of nuclear power has been slow; only 5.3 GW of nuclear capacity existed at the end of 2014 and six reactors with a total net capacity of 3.9 GW were under construction.[lxii] Historically, international sanctions and shortage of indigenous uranium mining capacity limited growth. The US-India civilian nuclear deal[lxiii] has impacted the nuclear landscape very positively for India by allowing it to buy reactors and fuel from the Nuclear Suppliers Group.

For example, in an agreement signed in December 2014, Russia agreed to help India build at least 10 new reactors over the next twenty years. Looking ahead, mixed oxide (uranium and plutonium oxides) and thorium-based breeder reactors that are an essential part of India's three stage nuclear plan,[lxiv] are still in the development phase. Given the investment cost, social opposition and history of very slow growth, it is unlikely that even 100 GW of nuclear power will be in operation by 2050.

To summarize, even a highly optimistic exploitation of coal, gas, hydroelectric and on-shore wind resources will provide about 4000 TWh/year, much less than the 6000TWh development goal. Unless India can pay for importing huge quantities of additional coal and gas, its only option for achieving 0.5kW/person is 400-500 GW of nuclear power. In fact, analyses, such as the one presented here, led Indian planners to promote, as early as the 1950s when the three stage nuclear plan was first proposed, the need for 500 GW of nuclear power as the only viable option. If India were to build 500 GW of nuclear capacity, it would need to address issues of quality, safety and security at all levels of the construction and operations chain at an unprecedented scale. A workforce of over 20,000 people, steeped in a culture of safety and security, would be required to operate and maintain just these reactors; a nuclear capacity larger than the cumulative global capacity to date. Recruiting, training and maintaining such a workforce represents a challenge that is at least as daunting as the very building of these nuclear power plants. If, instead, India is to cover the shortfall using coal-fired generation, then it needs to import coal and develop CCS at an equally large scale to mitigate growth in emissions of greenhouse gases in a carbon-constrained world.

In an optimistic, business-as-usual scenario, short of technology miracles, India would achieve only about 0.25kW/per person by 2050. Since this resource would not be equitably distributed, a large fraction of India's population would remain under-developed and poor.

A detailed discussion of the opportunities for development and energy trade between countries of South Asia is given in reference.[lxv] That analysis shows that (i) India, Bangladesh, Sri Lanka and Pakistan need to import fossil fuels in the short term to develop, whereas Nepal, Bhutan and Myanmar can develop using indigenous hydroelectric resources; and (ii) Pakistan can benefit economically by facilitating the transmission of natural gas from Iran and/or Turkmenistan to India via pipelines. It is in India's long-term interests to foster such cooperation as it would reduce tensions in the region and allow all eight (including Afghanistan and Myanmar) countries to focus on trade and development.

China:

China's economic growth since 2000 has been unprecedented, as has been its use of fossil fuels. Its consumption of energy and its carbon-footprint doubled between 1990-2000 and has more than doubled again between 2000-2011 as shown in Figure 12. During the period 2004-2011, it installed over 100 GW of new electricity generation capacity each year, most of it super-critical coal-fired. China paid for this growth by becoming the manufacturing center of the world and creating an export driven economy, which by 2014 had generated about $4 trillion in reserves in foreign exchange and gold. By 2014, it has the largest installed capacity of coal-fired (over 700 GW), hydroelectric (about 250 GW) and wind turbine power plants (about 90 GW). It had 23 operating nuclear reactors and 26 under construction. It continues to install more capacity of each technology with little evidence of a slowing down in the investment into, and growth of, its generation and transmission infrastructure. It has also become the largest manufacturer of thermal, hydro, solar PV and wind energy generation systems. So far this manufacturing capacity has mostly been used to satisfy the domestic market, but as its domestic market saturates it will look to export these systems.

China's population, 1.36 billion in 2013, is projected to peak around 2026 at about 1.45 billion and is expected to decrease steadily thereafter. The Chinese government can now, therefore, start to concentrate on issues of economic development and equitable distribution of resources similar to those faced by other developed countries. To maintain the overall growth of its economy and provide higher paying and better jobs to a larger population, which the current political leadership deems necessary to preserve the one-party system, China needs to continue economic growth at a high rate (~ 10%) over the next two decades. This growth in manufacturing and infrastructure and job creation requires that it ensure a guaranteed long-term supply of all the raw materials it needs, including coal, oil and natural gas.

China is geographically very well located to access the oil and gas reserves in Russia, Central Asia and even the Middle East through pipelines. The Kazakhstan-China oil pipeline has been operational since 2009, as has been the Central Asia-China gas pipeline (40 bcm/a, with planned increase to 55 bcm/a by 2015) that brings gas from Turkmenistan and Kazakhstan. In mid 2014, China and Russia sealed a $400 billion gas deal for the supply of up to 38 bcm/a for 30 years, beginning in 2018. Most of its coal imports are by sea from Indonesia, Australia and recently from North America. To ensure long-term supply it has developed bi-lateral relations with exporting countries all over the world, is acquiring shares in mines, pipelines and ports, and is investing in all aspects of the infrastructure required for extracting the needed commodities and transporting them to China.

China has about 115 billion tons of coal reserves that can fuel the existing over 700 GW of coal-fired plants for about 30 years. To supplement coal-fired generation, China is pursuing both nuclear power and CCGT as the next phase of large-scale development. In December 2014, there were 23 operating reactors (the first nuclear reactor was commissioned in 1991), 26 under construction and many more under planning.[lxvi] In the near-term, its development of nuclear capacity will be based on the almost fully indigenized manufacturing chain for the Chinese version of the Westinghouse AP1000 (CAP-1000) and Framatome M310 derived (ACPR-1000) reactors. It has installed and is also gaining experience and expertise with most other designs (for example EPR, VVER, Candu) and commercial fast breeder reactors starting with the Russian BN-800 technology.[lxvii]

China surpassed the U.S. as the largest car market in 2009 and about 20 million new vehicles were sold in China in 2012.[lxviii] It is the second largest consumer and importer of crude oil after the U.S. and is projected to overtake the U.S. in 2027 (and Russia in natural gas consumption in 2025).[lxix] Over the last two decades China has demonstrated that, as long as its economy keeps growing, it will buy the fuels and other commodities it needs.

China has one of the world's largest reserves of shale gas and oil and is starting to develop these. Shale gas, combined with imported LNG, indigenous conventional and tight gas production and gas from Turkmenistan and Kazakhstan, etc., via pipelines, will facilitate a large increase in CCGT capacity and industrial use of natural gas. However, in spite of the growth in nuclear, hydroelectric and CCGT capacity, the bottom line is that, at least, over the next couple of decades the utilization of coal-fired plants, which currently contribute 78% of the total electricity generated, will not diminish significantly because of easy availability of coal, lower cost and growing demand for electric power. With growing use of coal, oil and natural gas (see Figure 2), its carbon footprint is expected to continue to grow for at least the next two decades as shown in Figure 1.

Asian Tigers:

Japan, Korea, Taiwan and Singapore have essentially no fossil fuels reserves and need to import all the coal, gas and oil they consume. They also do not have adequate hydroelectric or on-shore wind potential to meet a significant fraction of their needs, leaving solar, off-shore wind and nuclear as their main non-fossil options. Post Fukushima 2011, the future of nuclear power in Japan and Taiwan is uncertain whereas South Korea plans to increase the share of electricity generated by nuclear power from the current 33% to 59% by 2030.[lxx] Fossil fuel based generation (coal and gas) will have to provide most of the rest in the near to mid-term.

Natural gas fired CCGT power plants are the main source of electric power in Singapore and have mostly replaced oil-fired plants for base load. Singapore will continue to depend on imported fossil fuels for its energy needs unless it transitions to nuclear power.

South East Asia:

South-East Asia, along with China and India, is now the center of growth of energy systems. This region has significant reserves of oil, gas and coal and in 2013 was a net exporter of all three. Energy resources are also sufficiently well distributed while development is highly variable and no single country (other than Singapore and the Philippines) has significant net fuel import costs.[lxxi] Domestic energy resources have allowed Indonesia, Malaysia, Thailand and Vietnam to grow economically and create a strong manufacturing economy that provides sufficient revenue to pay for the needed imports and to withstand fluctuations in the prices of fossil fuels. With continued economic development and growing demand for energy, this situation of regional self-sufficiency is, however, expected to change resulting in imports starting with oil, especially as domestic reserves are exhausted.

We expect a major shift in Indonesia's coal exports in the near-term. Over the last decade it expanded its coal production by 375% and become the largest exporter of thermal coal in 2005.[v] Unless new reserves are discovered and developed, the current volume of export is not sustainable because the reserve to production ratio is low and domestic consumption continues to grow as more coal-fired power plants are built.[v] Its gas exports are also shrinking and it may become a net importer in the medium-term.

Australia:

Australia has large reserves of coal, oil, and conventional and unconventional gas (coal bed methane and shale gas). Its coal and LNG exports are growing and the revenues they bring more than compensate for the cost of oil imports. In the near- and mid-term, planned investment in gas exploration and production indicate it will continue to be a major exporter of coal and LNG.[lxxii] The volume and price will depend on how the global market responds to the 2014 plunge in crude oil prices and the future of Asian LNG prices.

Historically, over 75% of its electricity has been generated by coal-fired power plants. With the discovery and growing exploitation of gas reserves there has been significant growth in gas-fired CCGT that are primarily being used for peak load. These gas-fired facilities are also enabling the growth of wind capacity, however, due to growing demand for electricity, there has been no decrease in Australia's coal-fired generation or its carbon footprint.

A major game changer, that will significantly reduce Australia's carbon footprint, will be the switch from coal to natural gas for base load power generation. This will require overcoming the coal mining and coal-fired power plant lobby and require the construction of gas pipelines connecting gas production sites in the North-West Shelf and the Surat and Bowen basins in Queensland with economic activity centers (and power plants) in the South-East of the country.

Countries/Regions that will remain dependent on imports for meeting their energy needs:

Having surveyed the use of fossil fuels and evolving trends in different regions of the world, it becomes clear that regions that will remain dependent on importing the majority of the primary energy they use, in particular fossil fuels, are the Asian Tigers (Japan, Korea, Taiwan, Singapore), South Asia, Europe and increasingly China. These regions fall roughly into three groups. The Asian Tigers, Western Europe and China have highly trained labor pools and a large export oriented manufacturing capability and capacity with established global markets and revenue generation chain to pay for the fuel imports. Their populations and energy use are not growing in size (except China's until about 2026); therefore they can plan technology diversification and fuel substitution and move towards a stable sustainable supply that is increasingly carbon-neutral.

Four countries in South Asia (India, Pakistan, Bangladesh and Sri Lanka) form the second group. They have large growing populations, the majority of which remain un-empowered. These countries face social unrest, violence and civil wars, and there is a chronic shortage of resources and infrastructure. Their development continues to be hampered by poor governance and lack of capital and infrastructure, so their first priority has to be economic development using the cheapest, most readily available fuels. They need international assistance not just in installing a modern sustainable energy infrastructure but also in education, health care and job creation. Only India has a significant manufacturing capacity and a sufficiently large technically trained population that is highly integrated globally. On the other hand political, social, demographic and economic challenges cloud the horizon and it remains uncertain whether even India will be able to overcome poverty and provide 21st century opportunities to the majority of its population by 2050. It needs to enhance its manufacturing and service industry to generate more jobs and revenue and decrease the trade deficit that has grown significantly in the last four years due to high oil and gas prices. The fall in oil prices in 2014 provides very welcome relief, especially if they stabilize at below $60/barrel for a long period.

A third group consists of the energy deprived sub-Saharan African countries that have large and growing populations and continue to rely on grossly inadequate hydroelectric systems. Without assistance they will have to wait until they can develop large enough economies (over and beyond the sale of commodities) to pay for the infrastructure and fossil fuels or develop strategically placed renewable systems. Since 2000, China has been investing significantly in these countries to build infrastructure with a long-term view of building favorable relations to exploit reserves of commodities it needs and to create a market for its goods and services. According to BP Energy Outlook 2035, "Africa will experience the world's fastest regional energy demand growth – driven by urbanization, rising populations and strong GDP growth. Africa will remain a significant exporter of oil and gas."[lxxiii]

Overall, our conclusion for both South Asian and Sub-Saharan countries is that poor governance and the possibility of conflict will continue to deter and undermine investment in development. Also, considering their long road to development and the many threats faced by them, it is not clear whether the much-needed access to energy will be secure or sustainable over the period to 2050.

Having reviewed most regions of the world, we next discuss some key societal changes and technological innovations that will significantly change the existing energy portfolio/landscape and reduce the emission of greenhouse gases.

IV: Examples of technology breakthroughs that would change the energy and emissions landscape

The analysis so far has viewed the global system as continuing to be dominated by fossil-fuels and evolving incrementally. The significant features and evolutionary changes worth summarizing are:

(i) Fossil oil will remain essential in the transportation and petrochemical industry.

(ii) Countries are maintaining a diverse portfolio of coal and gas based generation and tuning the relative usage of each depending on the relative cost of fuel. According to a 2010 study by EIA, almost 76% of the proposed coal-fired capacity addition was by China and India.[lxxiv] While these two countries will be the primary determinants of long-term coal use, it is unlikely that coal usage in other countries not rich in natural gas or hydropower will reduce substantially unless there is fuel substitution to nuclear power or a storage solution to overcome the intermittency in solar and wind power generation is found.

(iii) Wind turbines are a mature technology and wind energy is being successfully integrated into the grid at grid-parity in many countries that can use hydro and gas turbines as backup. Also, experience with offshore wind installations is growing.

(iv) Cost of Tier I solar PV panels continues to drop (about $0.60/Watt in 2014) and both utility scale and residential installations continue to grow.

(v) Growth of nuclear power remains slow with three countries, China, India and Russia, accounting for the majority of the reactors under construction. A number of countries such as UAE, Turkey and Vietnam are starting investment in nuclear power raising new concerns regarding safety, security and proliferation.

(vi) Annual primary energy consumption and carbon emissions are projected to continue to grow at about 1.8% and 1.4% respectively until 2025.[v]

(vii) Carbon intensity is projected to decrease by about 0.3% per year from 2012 to 2035 and there remains very significant scope for improvements in energy efficiency globally.[v]

To accelerate the transition to low-carbon systems, breakthroughs in storage technology are essential for large-scale integration of wind and solar, i.e., to contribute more than 20-30% of total annual generation of electricity. Backup systems need to have fast ramp rates that match the timescale of the fluctuations. The best large-scale low-carbon option for utility scale energy storage in the near- and medium-term is reservoir based or pumped storage hydroelectric systems. The next best option, including the need to minimize greenhouse gas emissions, is gas turbines. Developed countries, especially, are investing in increasing their pumped storage capacity and turbine manufacturers are developing combustion turbines with fast ramp rates and improving their durability under frequent (daily) cold starts.

Progress in the development and deployment of a number of potential game changing technologies has been slow in spite of considerable investment and many ideas. These include batteries for cars and carbon capture and storage (CCS).[lxxv] A factor of 3-5 in battery performance that is a combination of cost, energy density (kWh/kg), power density, safety and lifetime would accelerate the growth of electric vehicles from the current boutique industry.[lxxvi] The Tesla Roadster runs on a 53 kWh Lithium-ion battery (117 Wh/kg) with a range of 393 kilometers (244 miles) but costs over $100,000, most of which is the cost of the battery pack.[lxxvii] The new BMW i3 car has an 18.8 KWh Lithium-ion battery with a range of 130-160 kilometers.[lxxviii] A range extender model (240-300 km) is also available. It has a small 647 cc two-cylinder gasoline engine with a 9-liter fuel tank that acts as an electricity generator. The list prices for these cars start at $42,000 and $46,000 respectively. The Chevrolet Volt, a plug-in hybrid with a 16.5 kWh lithium-ion battery pack and an electric only range of 61 km (38 miles), lists starting at $39,000.[lxxix] With these and the many other hybrids such as Toyota Prius, Nissan Leaf, Ford Fusion, etc., mass produced affordable hybrids and electric vehicles are getting closer to reality.[lxxx] Needless to say, the payoffs of an affordable battery are so large that venture capital is supporting many start-ups investigating a whole range of technologies but the technological challenges remain equally large.[lxxxi]

Cost-effective carbon capture from large point sources (power plants, industry and petrochemical units) followed by permanent storage would extend the use of coal- and gas-fired power plants in a carbon-constrained world.[lxxv] The scale of CCS required from just the power generation sector to stabilize CO_2 concentrations in the atmosphere is enormous – about 15 gigatons of CO_2 per year, whereas most demonstration projects sequester on the order of a million tons a year. Areas of research include more cost effective methods for separation of CO_2 from pre- and post-combustion gases and characterization of storage reservoirs (capacity, risks of subterranean migration of stored CO_2 and possible leakage back into the atmosphere). In addition, countries will need to build the pipeline infrastructure from power plants to storage sites that might be thousands of miles away. Since CCS would add significant cost to the electricity generated, there has been little incentive for large-scale deployment in the absence of a price on carbon. Most projects have, therefore, not progressed beyond demonstration stage. The handful of plants that have operated for over 5 years sequestered a total of about 5 mtpa. The 2013 WEO by the IEA projects that only 1% of global fossil-fuel fired power plants will be equipped with CCS by 2035.[iii]

Prospects for conventional bio-fuels (ethanol from corn and sugarcane and bio-diesel) to exceed 2 Mbbl/day remain low. The promise for future growth lies in cost-effective production of cellulosic ethanol[lxxxii] and algal oil.[lxxxiii] If the world is successful in reducing their cost to make them competitive with fossil oil, industrial scale production of cellulosic ethanol could begin by 2020 while that of algal oil is expected only around 2030. We contend that even when bio-fuels are price competitive, their production will face increasing public scrutiny regarding lifetime environmental impacts, water needs and competition with food supplies that may limit their growth.

There has been much discussion and speculation about a hydrogen economy. Today, most of the hydrogen produced is by steam reformatting of hydrocarbons. Such hydrogen, if used to replace gasoline, would have emitted more CO_2 than would be emitted by the gasoline it would replace. Hydrogen from hydrocarbons is a more costly source of energy and of no help in reducing greenhouse gas emissions unless production from hydrocarbons is combined with carbon capture and sequestration.[lxxxiv] Alternately, production via electrolysis is expensive. Large-scale application would require (i) the electricity used for electrolysis is generated using low-carbon options of which wind is considered the most cost-effective and (ii) development of durable electrodes that have low over-potential for efficiency and are not made of rare metals such as platinum or palladium. The most seductive possibility, still in very early stages of research, is photocatalytic splitting of water to produce hydrogen or hydrocarbons, i.e., mimicking the process of photosynthesis carried out by plants.[lxxxv]

Lastly, based on current trends, it is unlikely that wave, tidal, geothermal and bio-mass fired power plant capacity will scale to the terawatt scale by 2050. These will continue to present a very important but a local and limited opportunity.

Converging interests: Energy Security and Climate Change Mitigation

The countries for which energy security and climate change mitigation are synergistic goals are the countries without significant fossil fuel resources. Transitioning to nuclear, hydro, wind and solar power systems addresses both issues simultaneously. The questions on how the energy portfolio of any given country will evolve towards renewable generation are (i) the ability to pay for the capital costs of building these power plants; (ii) simultaneous development of supporting/ enabling infrastructure (for example, the transmission grid, pipelines, ports, etc.), (iii) the human resource needed to operate and maintain these systems; (iv) experience with operating nuclear reactors and a culture of safety and security to minimize risk of accidents to acceptable levels; and (v) low-carbon backup systems to provide all the power needed that cannot be met with the sum total of nuclear, hydro and renewable generation. As discussed above, these countries form five regions: The Asian Tigers, China, South Asia, Europe and Sub-Saharan Africa excluding South Africa. Of these, Sub-Saharan countries are still too poor to make large investments in innovation, power infrastructure and concomitant fuel costs. As a result, they rely mostly on renewable sources of energy and foreign investments. It remains to be seen if the other four regions and the U.S. will continue to drive innovation and develop credible options, bring down the cost of renewable systems, become role models and influence the transition globally. Because countries in these regions will dominate imports and use of fossil fuels, they will drive the future evolution of supply and demand. Volatility of prices and constraints on supply will depend on how they manage their energy and development needs. Some of the other important variables that will influence their access to fossil-fuels are political stability, environmental concerns and public opinion in exporting countries.

Resource Curse?

In four regions of the world, government revenues and the national economies are dominated by the sale of commodities. These are the Persian Gulf and Central Asian countries, Russia and Africa. Of these, only Russia has a long tradition of higher education and of innovation in science and technology, however, so far, its political system has inhibited the diversification of the economy from large state controlled enterprises. The Persian Gulf countries are closed hereditary oligarchies. Exports of oil and gas sustain their economies and the government subsidizes most of the services, including those in the energy sector. Work is predominately carried out by foreign guest workers. The majority of their nationals lacks the education, technical skills and drive the private sector needs for a diversification of the economy. There is now growing realization that to diversify their economy and provide employment to their restive populations, they need to train indigenous talent. Qatar and Saudi Arabia have taken the lead by establishing world-class universities and are creating the infrastructure needed to advance economic and human resource development. Qatar and UAE have developed a strong banking and financial sector that serves the region. In spite of these developments, the employment rate amongst the youth remains low. Political and social instabilities are their biggest threats.

The development of a highly educated and trained workforce is essential for innovation and performance in technological societies. Planning, policy and execution depend not just on an elite at the top of the pyramid but require competency and shared responsibility at every level. Without good project management, the likelihood of poor execution, overruns and delays increases. Thus, any country not investing in the development of its human resource is handicapping itself for generations to come. For countries that (can) generate a significant fraction of their revenues by the sale of commodities to not invest in its human capital and promote a diverse portfolio of economic activity is inexcusable. The fact that most countries rich in resources are failing to do so is a tragedy – the resource curse.

The Central Asian and African countries are the most glaring and painful examples. They have low standards of health and education and the majority of their populations are poor. They have a unique opportunity to use revenues from export of commodities to implement broad based development. Despotic governments, violence and civil wars, however, continue to impede development. Corruption is very high and a small sector of the society dominates economic activity. The rest of the world is unlikely, unable and not sufficiently motivated to help change the status quo. As a result, transition to a more educated and equitable society continues to be slow.

Growing public concerns and social activism

The public is slowly beginning to realize that there is no free lunch with respect to energy and climate security. All energy sources have their advantages, disadvantages and limitations. For example, electricity from coal-fired power plants is inexpensive but the environmental and greenhouse gas footprint is large whereas solar PV is clean but intermittent and expensive. The public is also becoming increasingly aware of the need to assess relative lifecycle costs, environmental and climate impacts, air and water pollution and their health impacts, water scarcity, nuclear accidents and long-term storage of spent fuel, displacement of people from ancestral lands for mines, roads, railroads, water reservoirs and power plants, truck traffic for hydrofracturing operations, the infrastructure for electricity transmission and oil and gas pipelines, etc. New builds face growing public scrutiny and any realistic/perceived environmental impact often invokes severe opposition. In China, India and many other industrializing countries, the air quality in major cities has degraded to far above limits specified by the WHO primarily due to emissions from coal fired power plants and vehicles. The public is demanding action. Continued lack of oversight and adequate regulations has eroded public trust in the utility companies and the government. The growing social activism requires that planners make serious and transparent efforts to eliminate/minimize environmental impacts and risks of accidents and take into account public opinion to prevent the development of a hostile environment that can cause cancellations or long delays in the construction and completion of projects.

V. Conclusions:

The economic future of all countries that do not have adequate indigenous supplies of energy for power and transport will depend heavily on whether they can pay for imports of fuels and for the infrastructure needed to exploit indigenous resources and build the distribution system. To prevent large trade deficits resulting from fuel imports, it is imperative they examine what goods they can manufacture and export, and what services they can provide in the international arena to earn enough foreign exchange to pay for imports.

Fossil fuel based systems will not just go away. Fossil fuels are easy to use, readily available and dominate the current global energy system. They are relatively inexpensive as long as externalities such as environmental impacts and climate change are not factored in. Their disadvantages are that their extraction, refinement and combustion are the major sources of greenhouse gas emissions and they have large environmental impacts. Transition away from fossil fuels, especially in developing countries, will need cost-effective options that scale and provide a reliable roadmap to development similar to what fossil fuels provided over the last hundred years.

Countries will continue to use their indigenous fossil-fuel resources (or import the fuels) to maintain energy security as long as needed while making the transition to renewable sources. Even in a carbon-constrained world their highest priority will be development.

The two regions of the world that lack sufficient indigenous energy resources and infrastructure for development, and have large and growing populations, political instability and wide spread poverty are sub-Saharan Africa and South Asia. Climate change, environmental degradation, water shortages and volatility in fuel prices could have severe impacts. In a recent analysis of 17 countries, the Earth Security Initiative found that Tanzania, Nigeria and India face multiple risks with respect to land, population, fiscal, energy, water, food, crops and climate.[lxxxvi] That study illustrates a worrisome possibility that the combined effects of the many challenges these (such) countries face could create a "perfect storm" that stalls, or even worse, reverses development in many regions of the world.

The major advantages of renewable generation systems (hydro, wind, solar, geothermal, etc.) are the very small fuel costs and low emissions over the lifetime of the plant. Their disadvantage is that hydro generation is seasonal; solar and wind generation is intermittent and can have fluctuations on the scale of minutes; and geothermal is small in capacity and has a significant environmental footprint. They require backup systems that need to be large enough to meet the entire demand when these intermittent resources are not available. The backup systems also need to have fast response times and their control systems need to be flexible and sophisticated enough to compensate for large fluctuations in wind and solar generation. This requires a well-instrumented grid and the system operated and maintained by a highly trained workforce.

Energy systems are large and complex. With the growing exploitation of unconventional resources and integration of intermittent solar and wind systems into the grid the complexity will increase very significantly. To exploit new opportunities, build and maintain state-of-the-art systems, each country needs to continually educate and train the necessary workforce, i.e., for exploration and production of fuels, management of integrated power systems and the grid and their evolution towards a smart grid. It is important to bear in mind that any investment in technology, capacity development and grid integration of renewables, control systems and improvements in efficiency will bear fruit as long as the sun shines.

There will continue to be developments in technology that will improve the ways in which we produce useful fuels and electricity but no fundamental transformations in the energy systems are anticipated over the next twenty years (near- and mid-term). Very significant savings in resources can be realized by incorporating the many known improvements in efficiency in manufacturing and use of energy. The world must, therefore, focus on both innovations and implementation of known and demonstrated energy efficiency options.

The long-term goal of all countries should be to create an educated populace that is able to use emerging technologies to produce goods cost-effectively and with minimal environmental impacts. People want jobs that provide a decent standard of living and opportunities for growth. The challenges we face are broad and complex – one of sustainable development. How this will be achieved with the many changes anticipated over the next four decades such as growing populations in poor countries; aging populations in developed countries; mechanization in manufacturing and service industry and increase in robotic processing that are reducing the number of jobs needed; climate change and growing scarcity of many natural resources remains to be determined.

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