Supply Side Economics and the Need for Energy Diversification

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Introduction

In order to understand supply-side economics of energy resources, diversification by both suppliers and consumers, and trade, the following issues will be examined in this paper:

- Current status of global resources and how they are evolving. This part will include estimating which countries will have significant resources left by 2050 based on an understanding of reserves and production trends. Based on such an analysis, projections will be made, in cases where trends are relatively robust, about which countries will control significant resources by 2050 or earlier.
- How the supply side will evolve, driven by technology, economic, political, social and environmental considerations, and what changes this will force on the consumers.
- What options and opportunities for diversification are likely to become available over time for both suppliers and consumers and what their likely drivers and long-term consequences are.

At different points in this paper specific countries will be used to highlight and exemplify the points made. The discussion is informed by four trends that stand out throughout the history of energy use:

- The amount of energy used per person and social and economic development have been studied extensively, and a strong correlation is observed between the two.[1] Access to energy has been a primary enabling factor in human development.
- Humankind has simultaneously exploited all possible forms of energy sources available, often using each for multiple purposes.
- New fuels and sources of power have been integrated into existing energy mixes depending on the ease of recovery, distribution and use, and the technology available for using them. For example, the overlapping use of human muscle power, wind, wood, coal, diesel and nuclear for the propulsion of ships, and the evolution from coal to first diesel and then to electricity for powering trains.
- A fuel switch has taken place when a cleaner, cheaper or more convenient-to-use fuel or power source has become available. Examples include cooking fuels that evolved from wood, peat, coal char and animal dung found naturally on earth's surface to coal to oil to natural gas and propane. Today, many cooking appliances run on electric power.

The contention is that these trends will continue. For example, bio-mass from forests and all other burnable waste, historically collected and used for heating and cooking or put into landfills, is now being combusted in thermal power plants and classified as renewable fuel. In the future, once the conversion of lignocellulose to ethanol (cellulosic ethanol) becomes economical, these resources might also be used to produce high-value biofuels. Animal dung, which was used as fertiliser and cooking fuel, is now also being used to produce bio-gas.

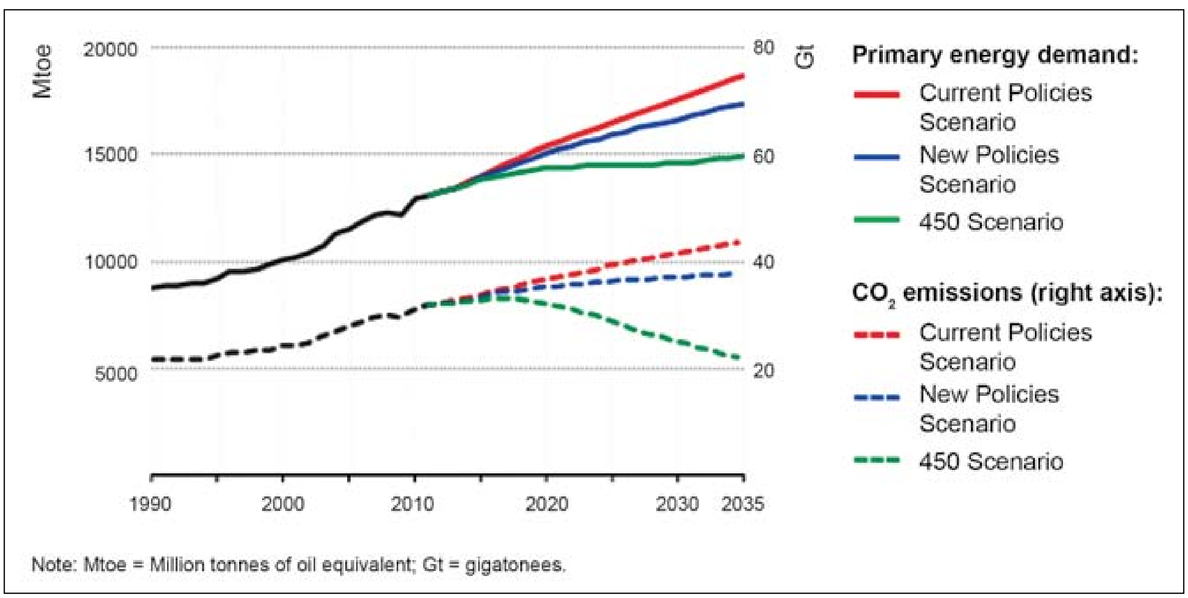
It is also maintained that the drivers of change will continue to be technological innovations, cost, access, and ease of distribution and use. Social and international political pressure, driven by considerations of climate change and environmental pollution, will play an increasing role and could significantly change the picture, particularly as technological innovations provide new options for non-fossil fuel-based dispatchable electricity generation and efficient transportation.

To mitigate climate change, emissions of greenhouse gases have to be reduced drastically. The last time in history that CO_2 concentrations in the atmosphere were stable was pre-industrialisation at about 280 ppm. Pre-industrial annual emissions of CO_2 are estimated at 2-3 Gt, whereas today they have reached around 33 Gt (this estimate does not include contributions from other greenhouse gases) as shown in Figure 1. To stabilise CO_2 levels at current levels (400 ppm in 2013), emissions have to be reduced by over 90 percent overnight. Stabilising at even 450 ppm ('450 Scenario' in Figure 1) is a daunting challenge, which will require international agreements on emissions of greenhouse gases that are far more restrictive and effective than the Kyoto Protocol.[2] On the other hand, mitigation measures will have to take into account economic realities and the development needs of both developing and developed countries. Also, based on recent examples of public discussions and rejection of energy from biofuels, fracking and nuclear power in many parts of the world, one should expect all future fuel and power options to face public scrutiny regarding cost-effectiveness, safety and lifetime environmental impacts. Transitioning away from the status-quo, i.e., energy systems based on fossil fuels, will therefore not be achieved easily.

Global Demand and Supply

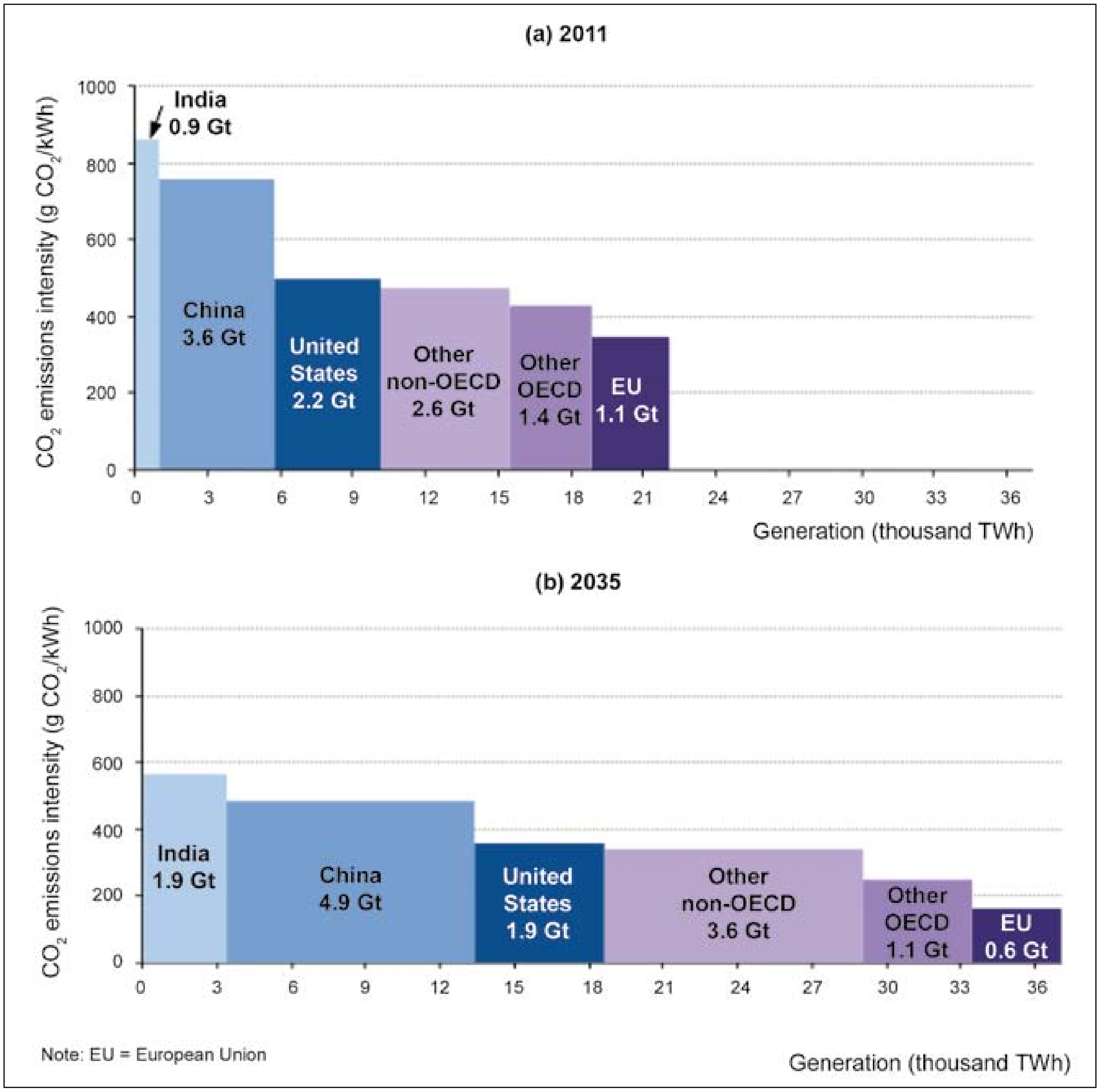
Global energy needs are staggering. In 2011, about five TW of installed power capacity generated about 22,000 TWh of electricity as shown in Figure 2. By 2050, an anticipated population of nine to 10 billion (according to United Nations Population Division) will require twice this – about 10 TW supplying about 45,000 TWh per year. This doubling represents an annual 1.8 percent growth in energy demand over 37 years and includes the one percent business-as-usual decrease in energy intensity due to increased efficiency. It is anticipated that the 10 TW generation capacity will be composed of roughly the following wedges: Coal (two TW at 80 percent plant load factor (PLF)), natural gas (two TW at 65 percent PLF), nuclear (one TW at 90 percent PLF), hydro (1.5 TW at 45 percent PLF), wind (three TW at 30 percent PLF), solar (one TW at 20 percent PLF) and "others" (0.5 TW at 50 percent PLF). During this period, CO_2 emissions are projected to grow by only 30 percent due to fuel switching, increased

Figure 1: Historic Annual Primary Energy Demand (Mtoe) and CO_2 emissions (Gt) with Projection up to 2035*



**These are based on three IEA scenarios: (i) 'Current Policies Scenario,' with PED growing at 1.6% per year; (ii) 'New Policies Scenario,' with PED growing at 1.2% per year; and (iii) '450 scenario' that would stabilise CO_2 concentration at 450 ppm.*
Source: IEA WEO 2013

Figure 2: Global Electricity Usage, CO_2 Emissions Intensity (grams CO_2/kWh) and Total CO_2 Emissions from Electricity Generation (Gt of carbon)* (2011, 2035)

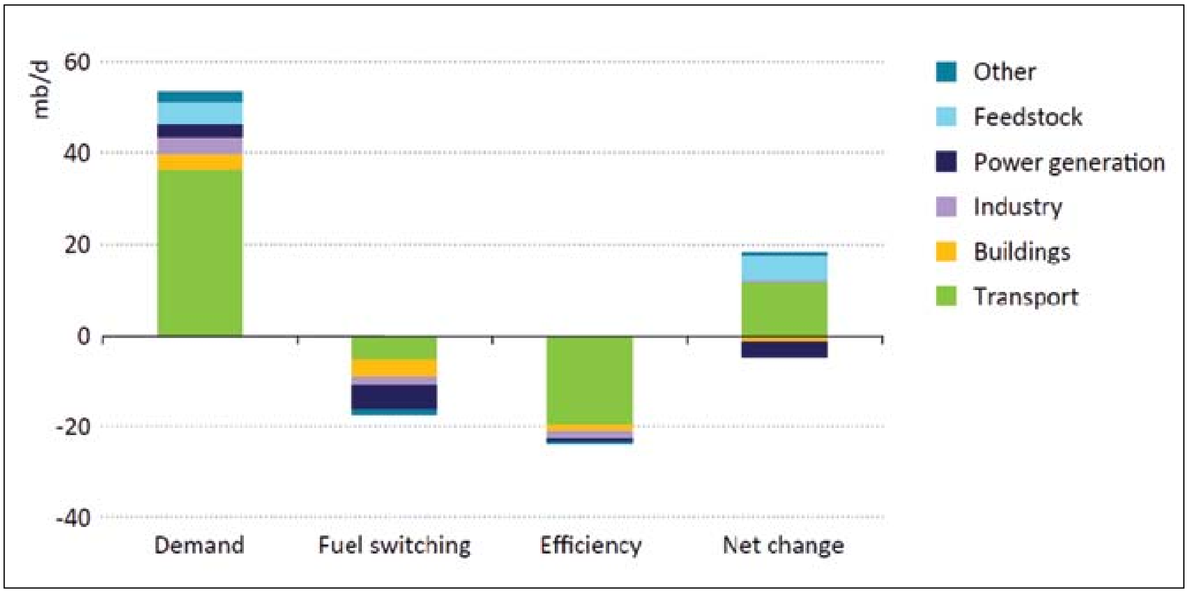


**1 Gt of carbon = 3.667 Gt of CO_2.*
Source: IEA WEO (2013), p. 191

efficiency and growth in renewable generation by OECD countries as also shown in Figure 2.

Similarly, for liquid fuels the WEO projections are 104 mbpd by 2040 as shown in Figure 3 (BP's projection in the Energy Outlook 2035 is 108 mbpd).[3] Unfortunately, there is no alternative to oil at the scale of an oil-wedge (an oil-wedge has been taken to be equivalent to 10 mbpd), and from present perspective it is unlikely that one will emerge by 2035. The total sum of all biofuels may reach five mbpd, as shown in

Figure 3: Projected Demand of 104 mbpd of Oil in 2040*



** Includes impacts of fuel switching and efficiency gains.*
Source: IEA WEO (2014), p. 102

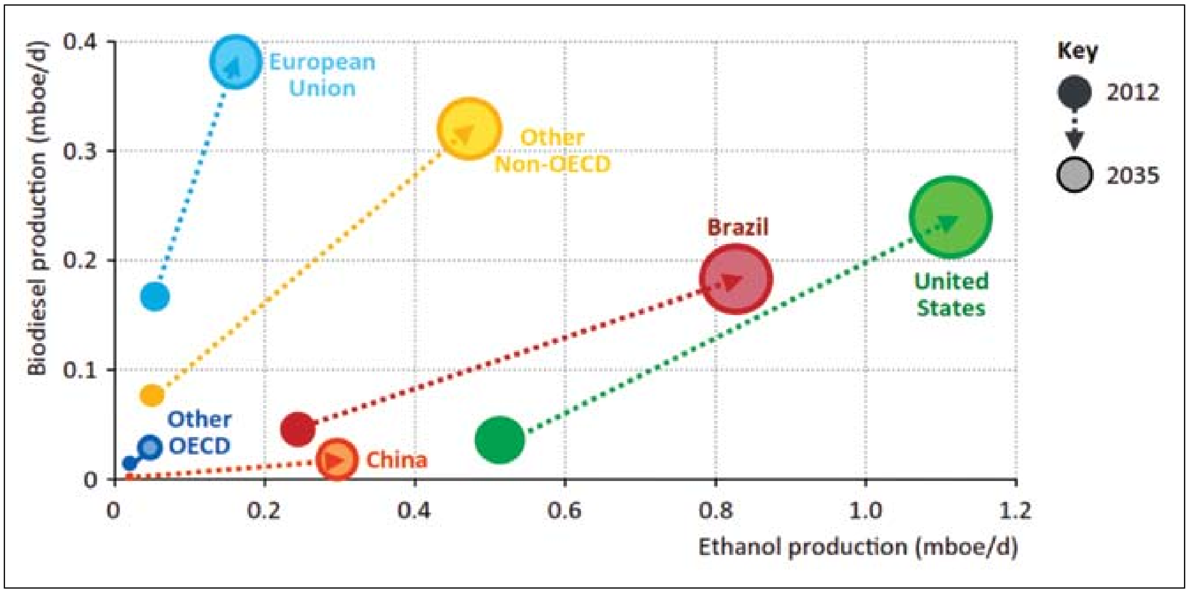
Figure 4, if production cost of production of cellulosic ethanol and algal oil becomes competitive with fossil oil as projected by the IEA in WEO 2013. Dwindling water resources, competition with food and environmental impacts will be major factors limiting the amount of biofuels that can/will be produced. The best option for eliminating greenhouse gas emissions from the transport sector is a transition to electric vehicles. In this eventuality, additional electricity will have to be generated by non-fossil sources to cut greenhouse gas emissions, and only the demands of the petrochemical industry will need to be met by fossil oil and gas.

Today, petroleum products dominate fuels used for transportation (light vehicles, trucks, airplanes and ships). Significant reduction in usage of oil is possible by gains in efficiency and fuel switching. Future fossil fuel-based options with lower emissions include cars, train engines and long-haul trucks fuelled by compressed/liquefied natural gas (CNG/LNG); hybrid/electric vehicles; and more efficient, safe and effective public transport systems.

Electric power generation is currently dominated by coal, natural gas, nuclear and hydroelectric systems. These are likely to grow until all countries achieve adequate total capacity and energy security. Of these, nuclear and hydroelectric are essentially carbon neutral, at least during production. Wind and solar present the largest opportunity for growth amongst renewable systems. It is unlikely that the total capacity of other low-carbon systems such as geothermal, biomass-fired power plants, and tidal and wave energy systems will scale to more than a few hundred gigawatts by 2050. Their contribution will be important and will constitute part of the last wedge called “others.” Current trends in their growth rate indicate that these will continue to present a local and limited opportunity in the near to mid-term. Similarly, the probability of commercial fusion reactors operating by 2050 is small.

The greatest challenge for countries that import a significant fraction of the fossil fuels they consume is the ability to pay for the imports if

Figure 4: Biofuel Production (Ethanol and Biodiesel) in Selected Regions of the World (2012, 2035)



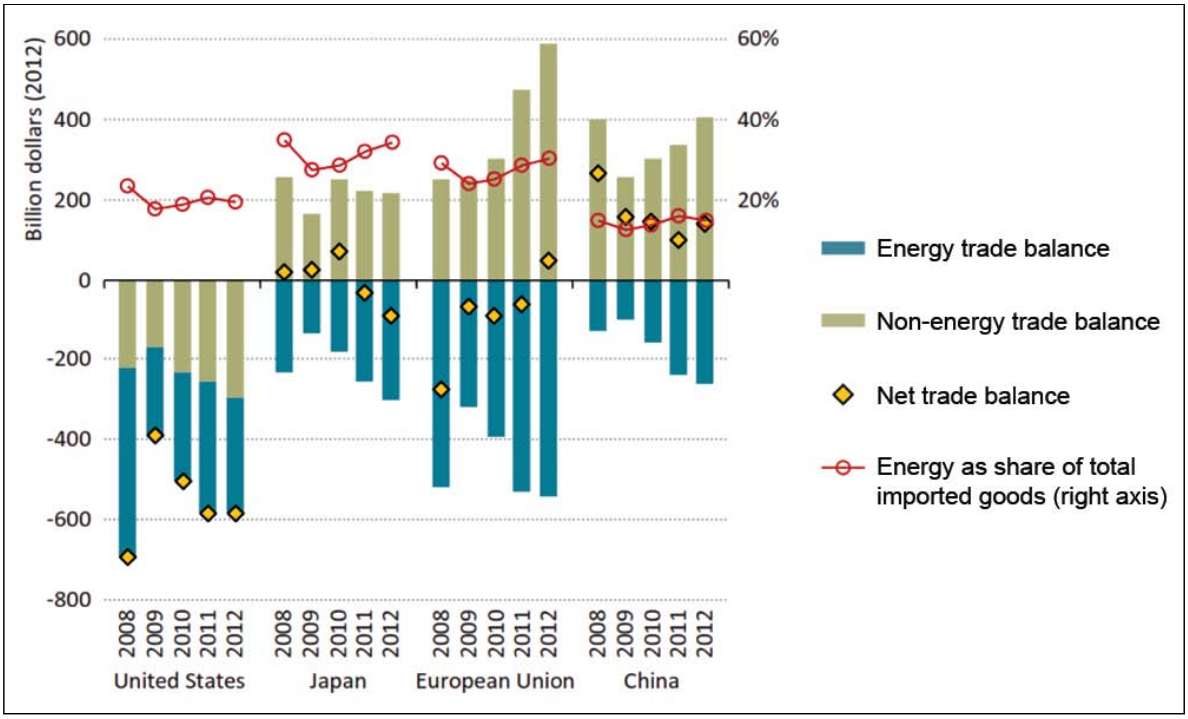
Source: IEA WEO (2013), p. 388

prices remain high and volatile. Many countries are already accumulating large trade deficits driven mostly by the cost of importing fossil fuels as shown in Figure 5 (other prominent examples not shown in the figure include India, Spain and Italy). Such a foreseeable financial burden suggests that all countries without adequate reserves of fossil fuels would have compelling economic incentives to make the transition to renewables independent of considerations of climate change. Three major reasons why this is not happening fast enough are: (i) the enormous existing energy and transportation infrastructure and investment in fossil fuels; (ii) easily accessible fossil fuels continue to provide the fastest and surest path of development; and (iii) solar and wind are more expensive and do not, on their own, provide baseload generation. As a result, the business-as-usual scenario is persisting even under the threat of global warming, and the transition to low-carbon options is proving to be slow and challenging, especially with nuclear power generation capacity not growing significantly.

Low-Carbon Options for Baseload Power Generation

Hydro: Technically and economically feasible, hydroelectric capacity worldwide is estimated at about two TW, of which about one TW has already been developed and generated 3566 TWh in 2011. Since the average plant load factor for hydroelectric units is about 45 percent[4] and generation is seasonal at most sites, the two TW is effectively equal to one TW of nuclear or coal-fired capacity. One must keep in mind that hydroelectric generation already has significant annual variation due to natural weather patterns and climate change is expected to have additional severe impacts in many regions. Thus, hydroelectric by itself or in combination with solar and wind is not sufficient to constitute a reliable dispatchable system. A great advantage of hydro turbines and systems is their fast start and ramp up rates. These characteristics suggest that in the future, the most effective use of reservoir- and pumped storage-based hydroelectric plants will be as backups to solar and wind farms rather than for

Figure 5: Energy and Non-Energy Trade Balance of Selected Regions (2008-2012)

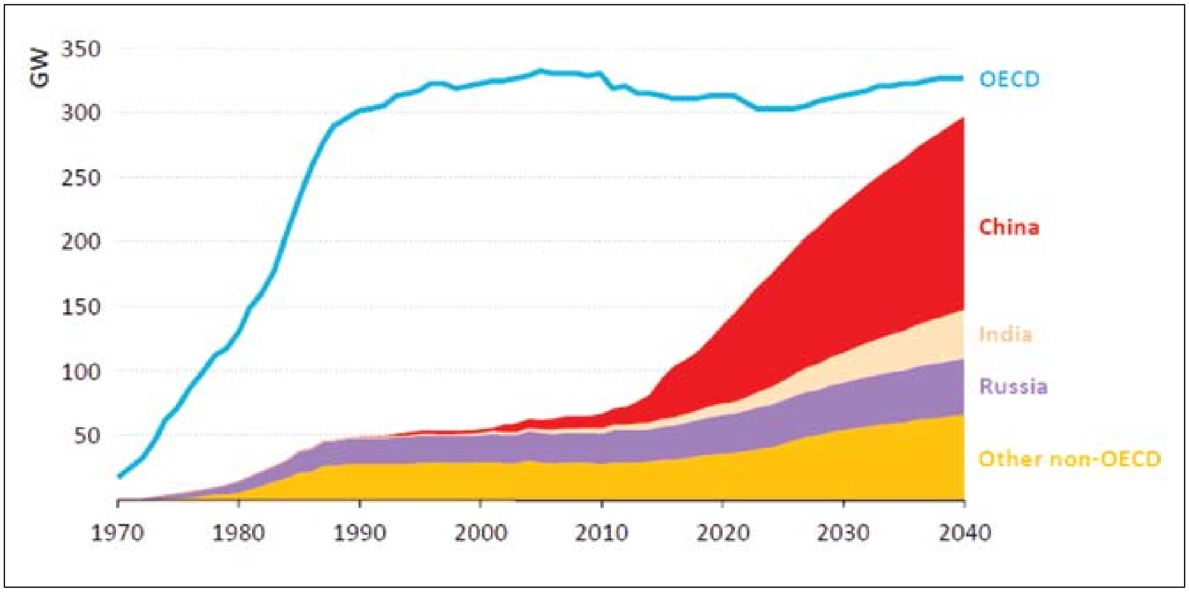


Source: IEA WEO (2013), p. 294

baseload, i.e., integrated systems of hydro, wind and solar plants can provide a large fraction of dispatchable low-carbon electricity.

Nuclear Power: Worldwide, there are 434 operating nuclear reactors with a total capacity of 392 GW that generated about 2,500 TWh/year during 2001-2013.[5] Significant growth of nuclear power (to even reach a wedge of one TW by 2050) is, however, very uncertain due to issues of safety, security, waste management and economics. Projected growth is about 300 GW by 2040 in the 'New Policies Scenario' by IEA as shown in Figure 6. Issues of safety and security, however, continue to trump the advantages: The cost of fuel, uranium, is a very small fraction of the operating cost, so volatility in its price has a minimal impact on the cost of electricity; adequate conventional reserves of uranium exist to serve demand for this century; the fuel is compact (about 150 tonnes/year/GW) and has been moved safely and securely around the world; and nuclear reactors do not emit greenhouse gases during operation. Without significant additional growth in nuclear generation, the world, in addition to improvements in energy efficiency, will have to rely heavily on solar and wind systems, which in 2013 provided a few percent of the world's electricity from 318 GW of wind and 137 GW of solar installed capacity. The timeline of how they can or will scale up to multi-terrawatt capacity, overcome the intermittency challenge, and significantly displace coal and natural gas for baseload generation is uncertain. To seriously address climate change starting today, fostering the growth of nuclear power and integrated renewable systems has to be a key part of all credible long-term solutions. The challenge is to design realistic roadmaps of growth of such integrated systems applicable to countries at different stages of development that address both energy and climate security.

Figure 6: Historical and Projected Nuclear Installed Capacity in IEA's 'New Policies Scenario' (1970-2040)



Source: IEA WEO (2014), p. 387

Diversification/Growth of Fuel Supply

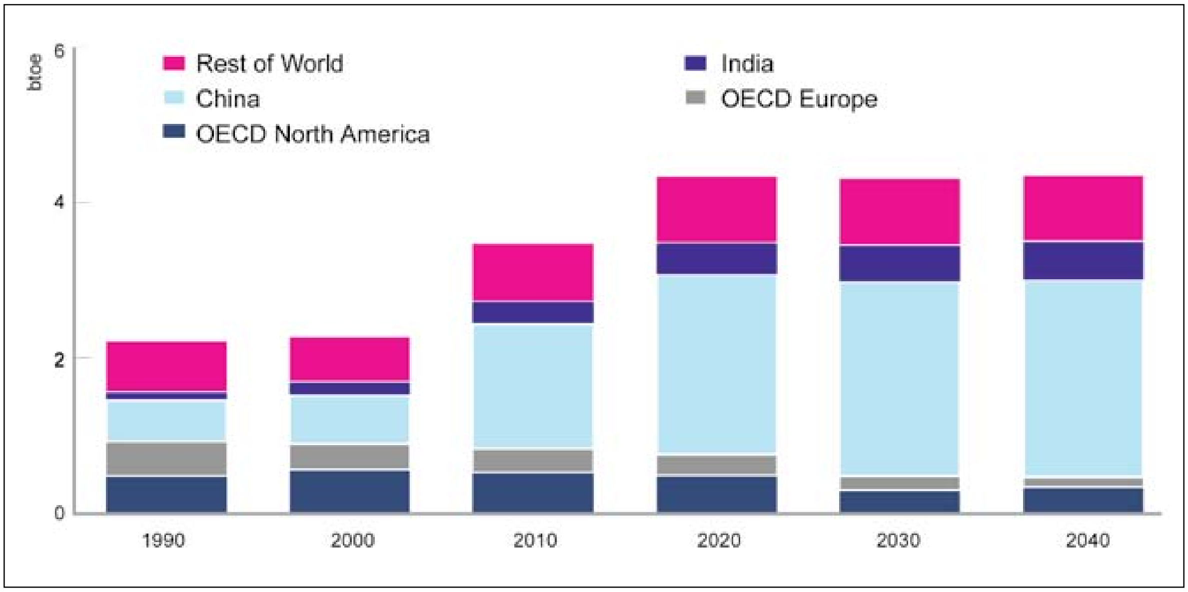
In this paper, three overall trends in the diversification of energy supply are examined: The future evolution of fossil fuel supply and its use, growth in renewable sources of energy, and the opportunities for accelerating the transition to a world with a smaller carbon footprint. Three time frames are considered: Near term, implying up to 2025; medium term, from 2025 to 2040; and long term, the period beyond 2040. The total time horizon in question is up to 2050.

The rest of the paper is organised as follows. It first reviews the supply of fossil-fuels – coal, oil and natural gas. It then examines diversification in power generation and how it will impact the cost of electricity. The paper ends with an enumeration of key conclusions.

Coal

Coal has been mined and used extensively in all forms for over two hundred years. Overall, growth in demand for coal is projected to increase until about 2020 and then stay steady until at least 2040 as shown in Figure 7a.[6] The technology to extract coal from both near surface (open pit mining) and deep seams (underground mining) is mature. Similarly, developments in boiler technology and scrubbers for removing toxic and polluting emissions have facilitated usage of coal with different caloric and water content and toxic impurities (heavy metals, sulphur, etc.). As a result, all varieties of coal are being exploited. Significant improvements have also been made in coal-fired power plant technology. Today's ultra-supercritical steam cycle units achieve 42-46 percent fuel efficiency, have smaller emissions and are much more flexible, i.e., they can withstand faster ramp up rates and more frequent starts.

Figure 7a: Regional Composition of Demand for Coal, Historic and Projected till 2040 (btoe)

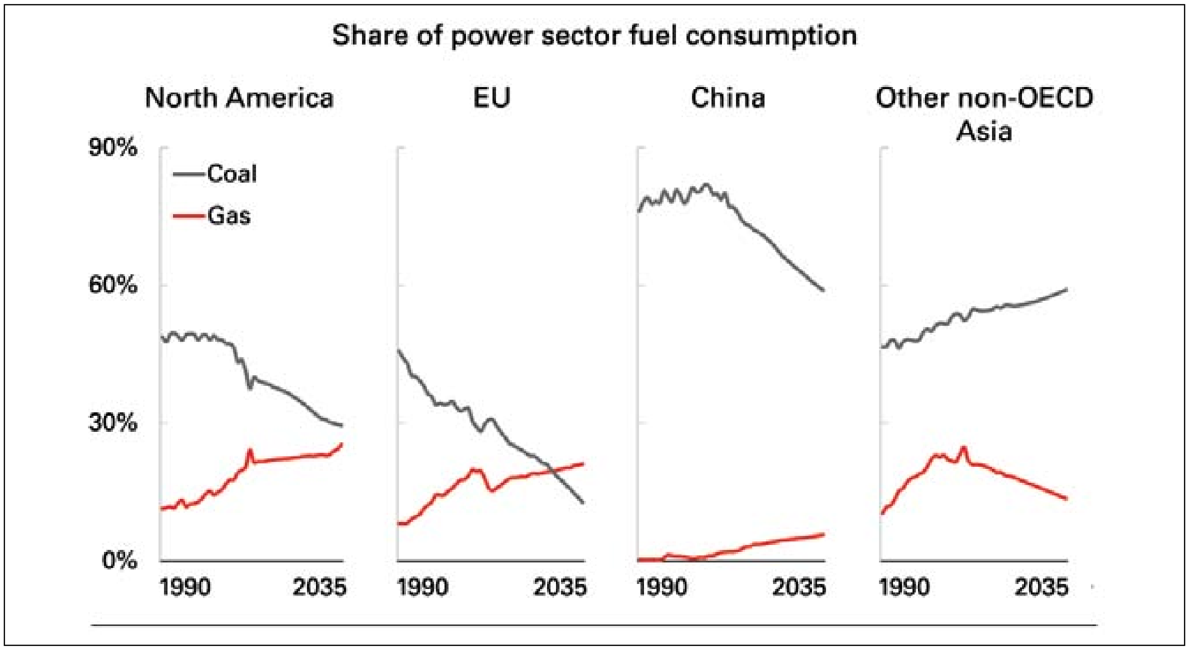


Source: Statoil Energy Perspectives (2013), p. 29

Figure 7b offers a comparison of the share of coal and gas in the power sector for four major economies. In North America and the EU, natural gas has been displacing coal to a certain extent. This pattern is projected to continue to increase as long as gas prices stay low. In China too, the share of coal-fired generation will start to decrease as nuclear, combined cycle gas turbine (CCGT) and renewable generation increases even though the total amount of coal consumed will stay constant between 2020 and 2040 (Figure 7a). In other non-OECD Asian countries (Figure 7b), the share of coal is projected to grow, since it will remain the cheapest fuel, and that of gas decrease as indigenous reserves are exhausted and because the projected price of traded gas is high.

China is the largest producer and consumer of coal (about 4.0 billion tonnes in 2012) with imports meeting around six percent of total demand. China's marginal cost of production for thermal coal, around $80-$100 a tonne, is driving international spot prices (at least the cost of seaborne coal in Asia) as Chinese importers opportunistically switch between domestic and imported coal. This cost and fraction of imported coal is likely to change as the need to mine deeper mines and exploit deposits in western provinces of China grows, which only further add to costs because an extensive transportation infrastructure will need to be built. Given the current consumption, installed coal-fired power generation capacity (about 700 GW, most of which uses super-critical technology and was installed after 2006) and continued increase in demand of electric power, China will most likely continue to consume at least four Gt of coal per year over the next thirty years – until about 2040,as shown in Figure 7a, the earliest timeframe by which growth of installed renewable, combined cycle gas turbine and nuclear generation capacity could exceed growth in demand and significantly reduce dependence on coal. Maintaining four Gt/year during this period already takes into account a decrease in demand growth due to a projected transition from a manufacturing economy to a larger service sector. This scenario is remarkable in that the cumulative consumption at four Gt per year for 30

Figure 7b: Historical and Projected Share* of Coal and Natural Gas in the Power Sector (1990-2035)



**The projected changes in fuel mix have regional drivers: Cheap gas in the US, environmental and climate change policies in EU, rising incomes giving rise to environmental concerns and development of nuclear and gas in China, and economic factors in other non-OECD Asia.*
Source: BP Energy Outlook 2035, p. 86

years amounts to China's total estimated reserves of about 115 Gt. If this scenario unfolds, then China's imports of coal will continue to increase as its domestic reserves, particularly those easier to access, are exhausted and remaining reserves/resources (particularly those in western China) become more expensive to produce.

The second country that will significantly impact the price and volume of internationally traded coal is India. The growth in its coal-fired generation capacity has been accelerating since 2006, and in 2013 there was about 150 GW of captive and grid-connected coal-fired generating capacity but with an average energy conversion efficiency of only about 25 percent. Unfortunately, the enabling infrastructure (coal mining and transport and the electric grid) has not kept pace and the supply of domestic coal is already falling short due to inadequate mining and transport capacity. Because of the low caloric value (about 3,500 Kcal/kg), India's reserves of about 60 Gt can sustain 400 GW of supercritical generation capacity for about 30 years if mining and distribution capacity can be ramped up to 1.5 Gt per year. In addition, many large (called mega and ultra) coal-fired power plants are being developed along coastal areas that have been designed to consume only imported coal. Thus, if India's power generation stays reliant on coal, then the most likely scenario is that it will need to import over one Gtper year by 2040.

In short, China's and India's reserves of 115 and 60 Gt respectively imply that domestic coal can provide them with a thirty-year window of opportunity for coal-fired generation capacity of 700 and 400 GW operating at 80 percent PLF. Highlighting this as a 30-year window of opportunity for China and India ignores many factors such as evolving cost of coal, technological breakthroughs facilitating resource-to-reserves conversion opportunities, of pollution and environmental impacts, and international mandates on mitigating global climate change.

Essentially, domestic reserves are finite and the existence of large global reserves should not lead to complacency. Any given consumer country relying on large-scale imports may not be able to afford them and suppliers may choose not to export in a carbon-constrained world. In a scenario where coal remains a major fuel for power generation in China and India, one can conservatively assume that together they will need to import over two Gt of coal per year by 2040. Only a handful of countries have large enough reserves to meet this kind of demand, and even these countries will need to significantly ramp up production and the associated infrastructure for exporting coal.

Analysing historic trends and projected growth in coal usage and exports, and assuming that no significant new reserves are brought online, current estimates[7] show that only seven countries will have significant reserves remaining post 2040 (countries with more than 10 Gt in reserves in 2012) to supply a significant fraction of the over two Gt per year of thermal coal needed by just China and India. (As discussed above, in this scenario, China and India will have largely depleted their indigenous reserves by 2040). These seven countries are the US, Russia, Australia, Germany, Ukraine, Kazakhstan and South Africa. Since German reserves are mostly lignite, in which there has not been significant international trade, the other six countries will have to be the major suppliers. With so few suppliers, the coal outlook can range from a no-coal economy in compliance with a carbon-constrained world to a market-driven one with high prices correlated with the price of natural gas or a high marginal price of mining unconventional coal (including or even excluding external costs).

If large-scale import is not an option, then to guarantee long-term energy security based on coal-fired generation, China and India in particular will increasingly need to develop cost-effective capacity to mine thinner and/or deeper seams. One promising but yet to be demonstrated at scale technology to exploit thin and/or deep seams is in situ gasification. However, its environmental impacts could be large and cost-effective methods to mitigate them also need to be developed.

An interesting test case of how the market will adjust to depleting reserves will arise in the near term when Indonesia can no longer export significant quantities of thermal coal. It has increased production by 375 percent between 2002 and2012 and is currently the largest exporter of thermal coal. Unless new reserves are confirmed, it is not clear whether it can continue to increase production at current rates.

Geography too will play an important role in determining the supply chain. Coal from Russia, Ukraine and Kazakhstan will most likely go to countries connected to them by railways, i.e., Eastern Europe and China. The rest of the world will therefore have to rely on the US, Australia and South Africa for coal. In a carbon-constrained world, it is very unlikely that these three democratic countries with environmentally enlightened publics could justify exporting large amounts of coal. For example, will the public in the US, which today mines and consumes about one Gt of coal per year and has 243 Gt in reserves, allow companies to build railway and port capacity to export one Gt or more of coal per year as their own consumption decreases? One should note that the US exported only about 40 Mt of steam coal in 2012 and 2013[8] and the public opposition to building new export infrastructure is growing. In a CO_2-constrained world, as domestic supplies of coal dwindle in most countries, there will be severe constraints in supply leading to high volatility in prices. At that point, international bodies regulating greenhouse gas emissions would need the support of only a few exporting countries to force major coal importing countries to transition to other forms of power generation. Such a CO_2-constrained world is the more likely scenario; therefore, countries dependent on imports for coal-fired generation must develop a roadmap to complete the transition to other sources of power by 2050.

In this carbon-constrained scenario, the two ways in which coal would remain a defensible fuel for power generation are: One, Carbon Capture and Storage (CCS) is scaled up from current demonstration projects to sequestering over 10 Gt of CO_2 per year. In addition to the cost of building the infrastructure, large-scale deployment of CCS will require the public to be convinced that risks of leakage and subterranean migration of CO_2 and toxins are small and that the environmental impacts of the associated infrastructure such as pipelines are acceptable. And two, in situ coal gasification technology becomes cost-effective and its environmental impacts are understood and mitigated.

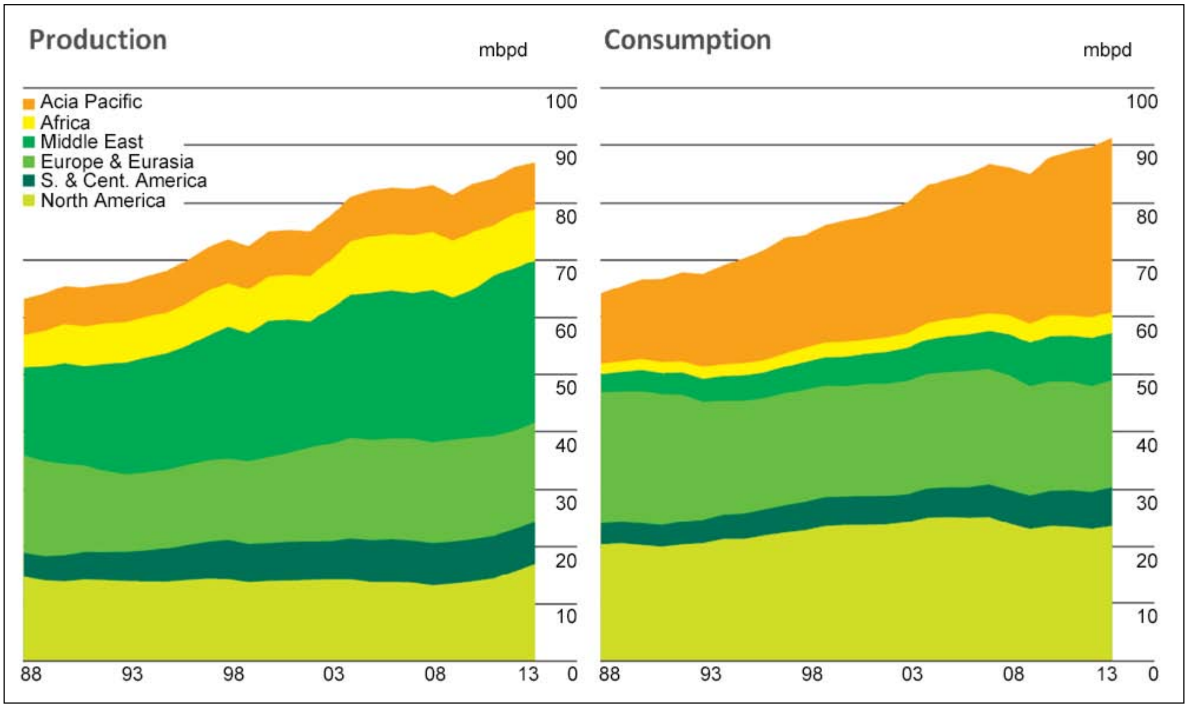
Almost all developed countries have already crossed the peak of their coal-fired generation capacity and thus annual coal usage. Over the coming decades they can start reducing CO_2 emissions by increasing the efficiency of their coal-fired plants and by replacing the least efficient ones by a combination of CCGT, nuclear, hydro, solar and wind systems. All such countries at or past the peak in their installed coal-fired capacity can therefore afford to agree to international agreements capping CO_2 emissions at current levels. Even China, having already reached close to the anticipated maximum sustainable usage of about four Gt of coal per year, is in a position to participate in such agreements as the recent US-China climate agreement (as per this agreement, China will achieve its peak CO_2 emissions around 2030). Only countries such as India, that are still in early stages of using coal to facilitate development, will have a very difficult time agreeing to cap CO_2 emissions at current levels. However, as they get increasingly isolated in the international arena, they may be forced to comply with caps on total emissions at current levels. As a result, they may face very serious impediments to development since it is highly unlikely that they can bring alternative sources – CCGT, nuclear, hydro, solar and wind systems – online fast enough to keep pace with the growth in demand. Such countries face a tough uphill battle. They need to develop a detailed and realistic backup roadmap that provides needed growth in power generation capacity to address development needs which, at the same time, is also accepted by the international community in a carbon-constrained world and by local populations rebelling against environmental pollution and water shortages.

Oil

Fossil oil is used primarily for transportation driven by internal combustion engines and for petrochemicals. Eighty-six of the roughly 88 mbpd of oil used worldwide in 2012 (i.e. 98 percent) came from fossil fuels, and the rest, used for transportation, is either bio-ethanol or biodiesel. These biofuels are unlikely to grow to more than three mboe in the next two to three decades (Figure 3).[9] Thus, the primary emphasis of planners and policymakers for reduction of oil use has been on efficiency, including transitioning to hybrid and/or electric cars and building public transport systems. On the other hand, over the coming decades, as more people are able to afford individual transport vehicles,[10] demand for oil is generally anticipated to continue to increase, especially in developing and emerging economies as shown in Figure 8.

Supplying countries have an incentive to keep the price of oil affordable to encourage this growth in demand. To counter this growth in demand is the rising burden of importing oil leading to trade deficits and the high cost to consumers. Thus, both governments and individuals in importing countries have an incentive to promote efficiency and reduce consumption. Trends in these two counter currents can change rapidly as evident after the 2008 recession. Furthermore, with the price of oil on average staying at about $100/barrel from 2011 till 2014 there has been a sustained decrease in consumption of oil in many countries. Consequently, predictions of growth

Figure 8: History of Oil Production (left) and Consumption (right) by Region (mbpd) (1988-2013)



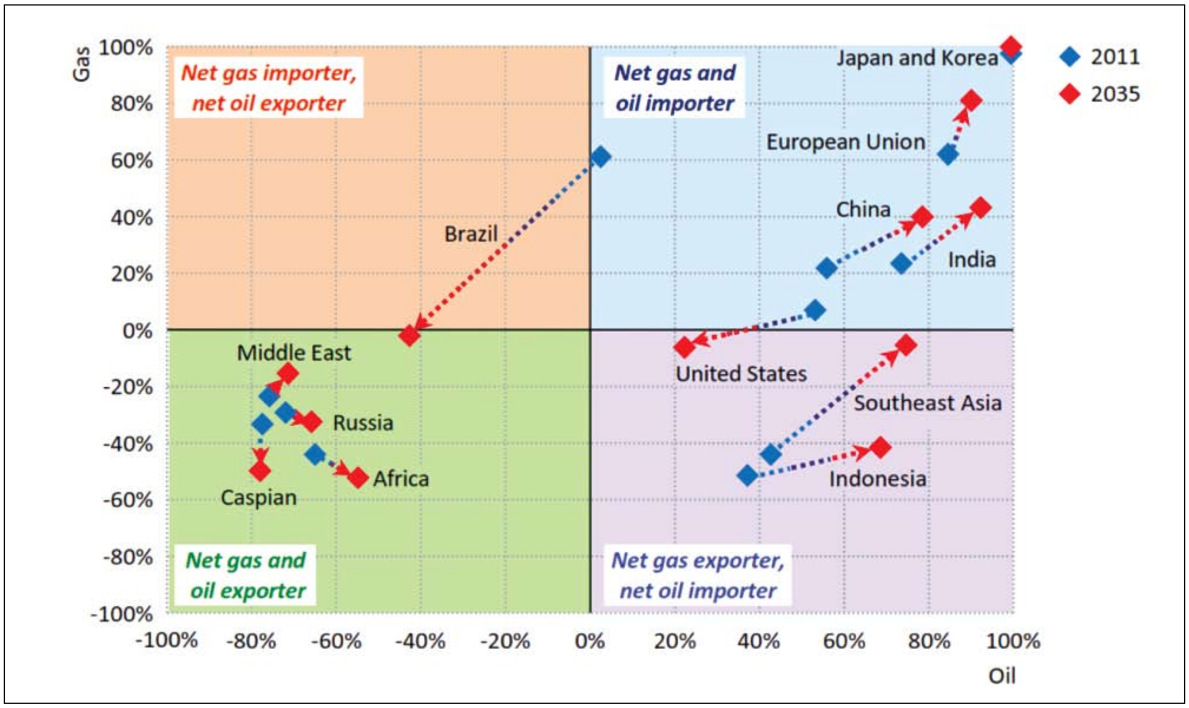
Source: BP Statistical Review 2014, p. 12

in demand have large uncertainties; however, most agencies (IEA, EIA and oil companies as well) predict continued increase in global consumption. The recent plunge in prices from over $100/barrel to below $50/barrel demonstrates that reserves of conventional and unconventional oil can be profitably brought to the market at prices of about $50/barrel as shown in Figure 10. Stagnation in demand and geopolitics can drive similar price volatility in the future.

Over the last decade, oil companies have developed and deployed the technology to exploit unconventional resources – deep sea, arctic, heavy oil, tar sands and tight or shale oil – and are beginning to realise their enormous potential. Even a very conservative estimate of conventional and unconventional resources suggests that up to 2050 and beyond, possible short-term shortages in oil supply would most likely be due to economic factors (e.g. uncertainty in demand leading to inadequate investment in exploration and recovery) and geopolitics, since most (80 percent) of the conventional reserves are controlled by national companies and are located in politically unstable regions. In the absence of major political instabilities, and without an increase in alternatives, the amount of oil extracted annually will depend on demand. Producing countries and companies will respond to this growing demand by bringing more resources online.

In a carbon-constrained world, unconventional oil may have a finite window of opportunity (also expressed in the ongoing discussion on “unburnable carbon”). At some point in time as the global population stabilises, shares of renewable generation and high mileage electric cars increase, the demand for crude oil, especially expensive unconventional oil, will start to decrease. Countries with large conventional reserves could then squeeze out

Figure 9: Change in the Share of Net Oil and Gas Imports/Exports in Selected Regions in IEA WEO 'New Policies Scenario' (2011-2035)



The percentages of exports and imports are respectively calculated from the following ratios:export/total produced and imports/total consumed.
Source: IEA WEO (2013), p. 77

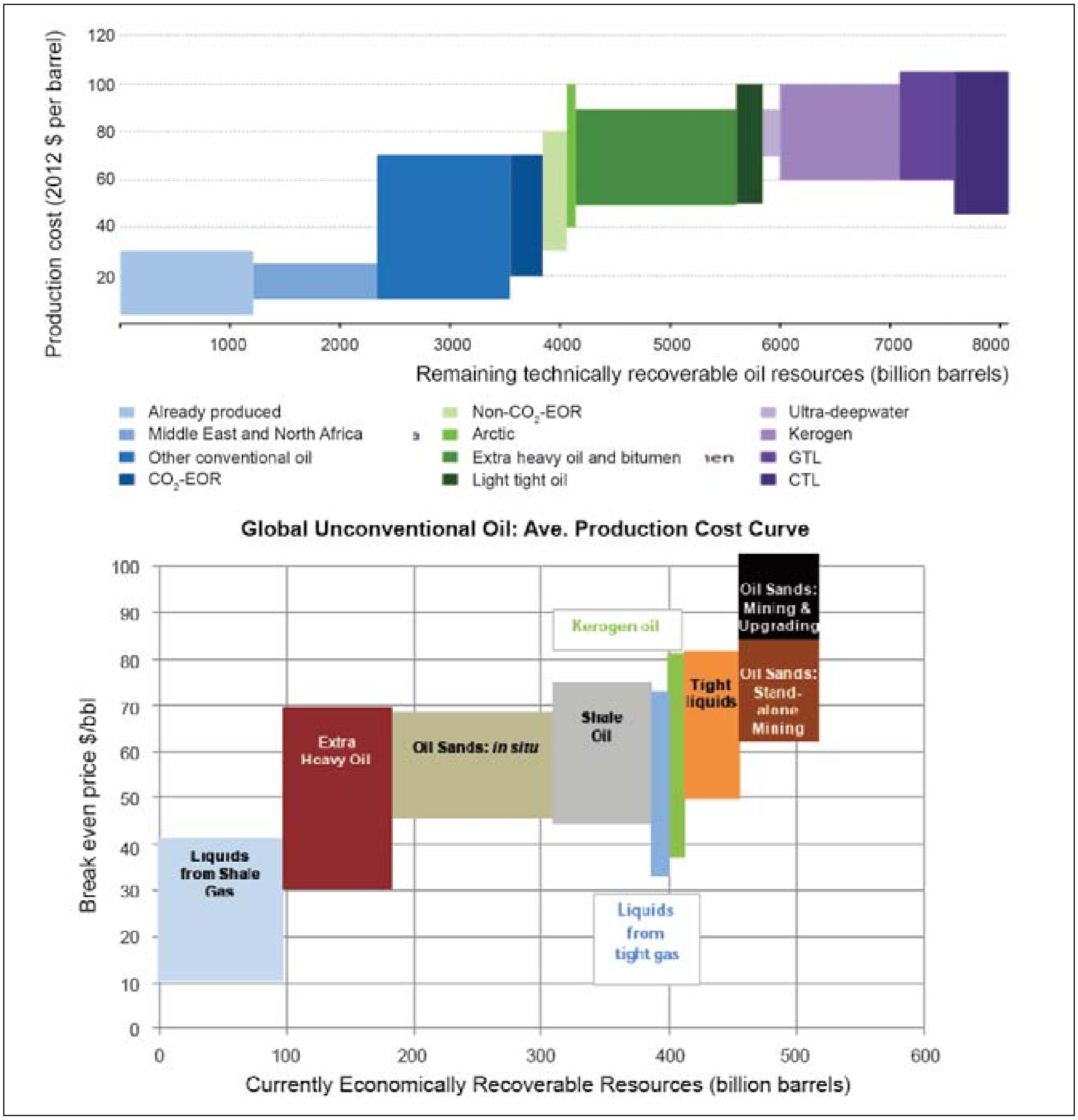
investment in exploration, production and export of unconventional oil and gas. For example, after the growth in production of pre-salt oil in Brazil over the next ten years, conventional production from OPEC countries is projected to rise and could squeeze out more expensive unconventional oil if growth in demand stalls. This could start happening as early as 2030. Unforeseen developments such as the dramatic fall in crude oil price in 2014 due to stagnation in demand, large strategic reserves, Saudi Arabia's strategic swing vote and the concomitant ineffectiveness of other OPEC countries are providing a preview of this effect.

Since the development of unconventional resources is relatively new, estimates of global reserves have large uncertainties; nevertheless, given the long lead-time (five to 10 years) needed to bring new resources online, one can assess, based on history, who will be the major suppliers and importers of oil over the next three decades. Europe, South Asia, China, the Asian Tigers and the US will remain the major importers; the Persian Gulf and Caspian Sea countries, Russia, West Africa (Nigeria and Angola), North Africa, Venezuela, Mexico and Canada will remain the main exporters. The most significant changes anticipated by the IEA, as illustrated in Figure 9, are the decreasing imports by the US due to its development of unconventional sources; continued increase of imports in China, India, Southeast Asia and exporting countries; and increase in exports of pre-salt oil from Brazil.[11]

Price and its stability are harder to predict. In a purely market-driven economy, the supposed driver of international price is the marginal cost of production, shown in Figure 10, that varies significantly between conventional and non-conventional sources. Unconventional oil is more expensive, partly because more expensive technology is required and also because continuous investment is required over the lifetime of a well to maintain production.

Countries with large conventional reserves can more easily increase production and influence the price to discourage investment in unconventional

Figure 10: Production Cost/Break-Even Prices and Size of Remaining Technically Recoverable Oil Resources (above) and of Economically Recoverable Unconventional Oil (below)



Rystad develops estimates based on bottom up analysis of global fields, licenses, and potentially recoverable resources given currently available technology and activity levels. All resource values depicted in the graph are cumulative expected production from 2012 until 2100, excluding already produced oil through 2011. Oil and field condensate only, not natural gas plant liquids. Note that for oil sands development costs CERI, Alberta ERCB, and NEB are used.
Source: IEA analysis of Rystad Energy data.

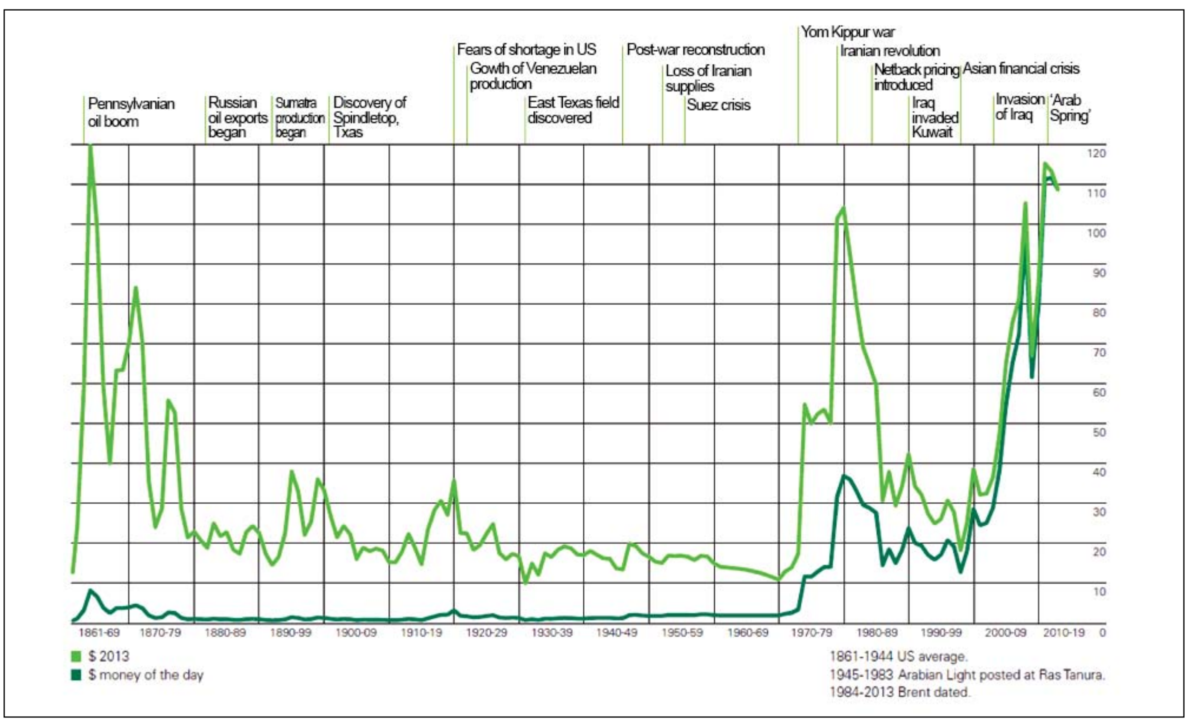
exploration – as the Saudis have shown in the course of 2014 in order to maintain their global market share, especially in competition with tight oil production in the US. In theory, it is in the interest of all exporters, however, to keep the oil price high to maximise profits and attract investment in exploration and production, but not too high to cause an economic recession and make investments in alternatives attractive – something OPEC is familiar with given that it wants to maintain a sustained demand for oil. In the near to mid-term, keeping unconventional oil in the supply mix to set the marginal cost of production helps keep the prices high.

Volatility in the oil market has historically been correlated with political instability and/or lower production due to under-investment in exploration and recovery (poor governance in producing countries) than due to any real shortages in reserves (Figure 11). For example, the recent declining production in Mexico and Venezuela is due to poor governance – inadequate investment and the fact that foreign companies with latest technology are being driven out.

One must also always keep in mind the existence of extensive additional resources globally, as shown in Figure 12, which might be exploited as prices rise. With growing demand and improvements in recovery technology, the only foreseeable impediment to their development (i.e., converting these resources to reserves) could be cost or public/political opposition in response to environmental impacts and climate change given rising greenhouse gas emissions.

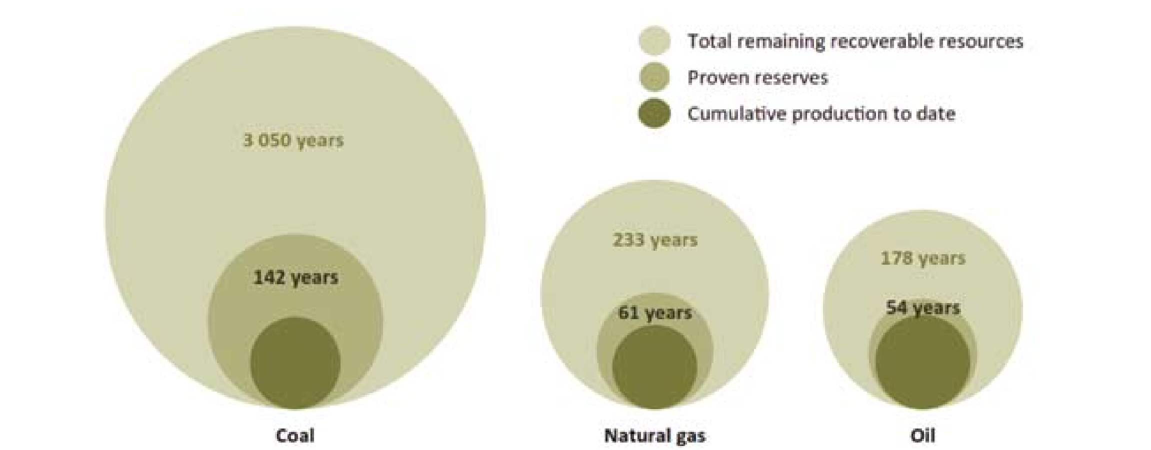
In short, on the supply side, there is little incentive for countries and companies that can produce and export oil/gas competitively in the international market to not continue to develop these resources since it is unlikely that the transportation sector will transition away from liquid fuels any time soon. The use of hybrid and higher mileage

Figure 11: Crude Oil Prices ($/barrel) and World Events that Influenced Major Changes (1988-2013)



Source: BP Statistical Review of World Energy 2014, p. 15

Figure 12: Estimates of Cumulative Production to Date, Reserves and Total Recoverable Conventional and Unconventional Resources for Coal, Natural Gas and Oil (2011/12)



Notes: All bubbles are expressed as a number of years of production based on estimated production in 2013. The size of the bubble for total remaining recoverable resources of coal is illustrative and is not proportional to the others. The figure specifies the status of reserves for coal as of end-2011, and gas and oil as of end-2012.

Source: IEA WEO (2013), p. 72

electricity vehicles will grow, as will those running on CNG or LNG; however, it is unlikely that these will grow fast enough to result in a decrease in demand for oil in the coming decades. Unfortunately, the investment in public transport systems is small compared to the growing demand for mobility driven by rapid urbanisation in the developing world. As long as the only other option is poor/unsafe public transport, people will continue to invest in individual transport.[12] With little or no threat to their bonanza in the near term, the important question for oil exporting countries is: Are they investing oil revenues in broad-based development so that their citizens become innovators, compete globally in other manufacturing and service industries, and help diversify the economy? Norway is a good example of a country investing its oil and gas revenues to facilitate long-term development.[13]

The Persian Gulf countries are the largest exporters of oil. It is therefore instructive to examine the case of one of them: The United Arab Emirates (UAE) has started to diversify its portfolio of energy sources and economy while still relying on revenues generated by exporting oil. The UAE holds the seventh largest reserves of conventional oil (97.8 billion barrels in 2012) and of natural gas (6 tcm).[14] Of the seven emirates comprising the UAE, Abu Dhabi holds about 94 percent of these reserves. Export of oil accounts for over 80 percent of UAE's revenue.

Most of the electricity in the UAE is generated in highly efficient power and water desalination plants using gas turbines. In spite of its large reserves of natural gas, it is a net importer of gas since a large fraction of the gas it produces is sour that is re-injected for enhanced oil recovery. To meet its growing gas demand, it invested in the Dolphin gas pipeline linking Qatar to UAE and Oman.[15] Furthermore, LNG regasification terminals have been set up.

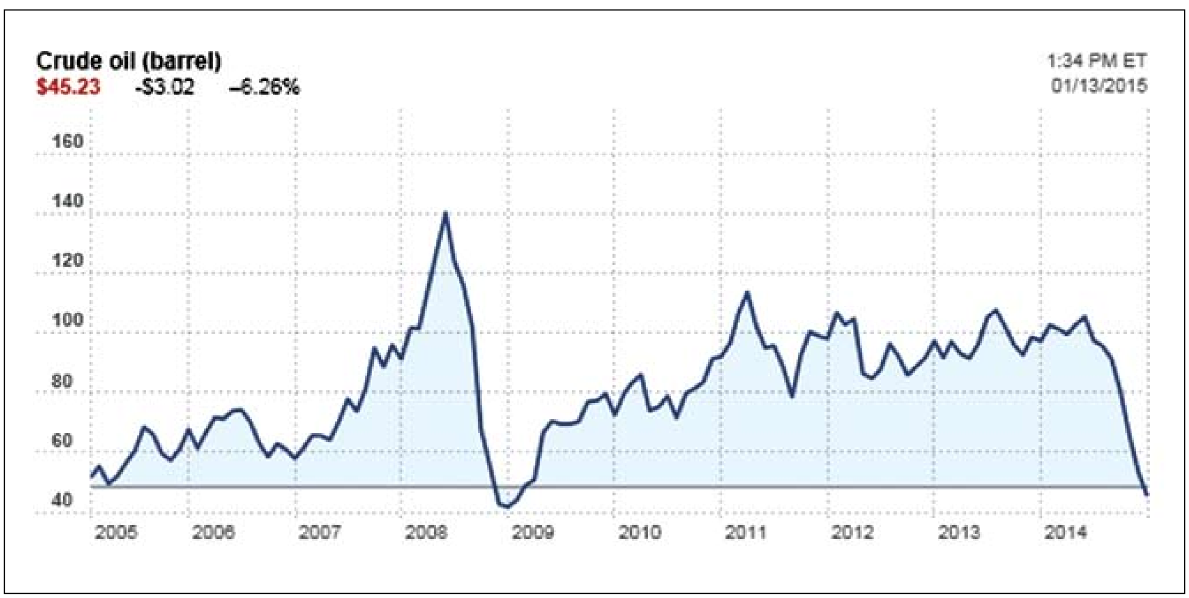
With a rapidly growing population and domestic consumption, the UAE can no longer rely on oil exports to maintain its high per capita GDP. It needs other sources of revenue. Its initiatives at diversification include: (i) Becoming an important financial and trading center in the Middle East; (ii) developing its gas fields and processing sour gas for export; (iii) commissioning, in 2012, the Habshan-to-Fujairah oil pipeline to bypass the strategic Straits of Hormuz, a potential choke point due to regional conflicts; (iv) integrating its electric grid and gas supply with the other members of the Gulf Cooperation Council (GCC); (v) the ongoing construction of the Barakah 5.6 GW nuclear power plant (four AP-1400 reactors) west of Al Ruwais in Abu Dhabi by Korea Electric Power Company; and (vi) investing in power-intensive heavy industry such as the EMAL Aluminum smelter.[16]

In addition to investments in infrastructure and industry, development of human resources is of equal importance for diversification of the economy. Progress in this area is much harder to quantify. Along-term challenge before all six members of the GCC is the reliance on foreign workers and an underutilised indigenous population. It is too early to assess how long it will take before the establishment of world-class universities by Qatar and Saudi Arabia creates an indigenous highly skilled workforce that will bear fruit. Meanwhile, they will need to partner with foreign companies and attract talent to grow and sustain a diverse economic portfolio. Oil and gas exports provide them with the revenue to pursue both strategies simultaneously – attracting foreign workers and developing their own.

The collapse of oil prices in 2014 underscores the need for diversification of the economy:

The global production of oil exceeded consumption through all four quarters of 2014 after four years of relatively tight markets. This was predominantly due to the increase in unconventional oil production in the US and Canada and less-than-expected growth in the global consumption led by weak demand from China. The result, once Saudi Arabia decided to break ranks with other members of the OPEC cartel and not reduce oil production, has been a dramatic decrease in the price of oil to below $50/barrel by the end of 2014 as shown in Figure 13.

Figure 13: History of American Benchmark WTI (West Texas Intermediate) Crude Oil Prices (2005-2014)

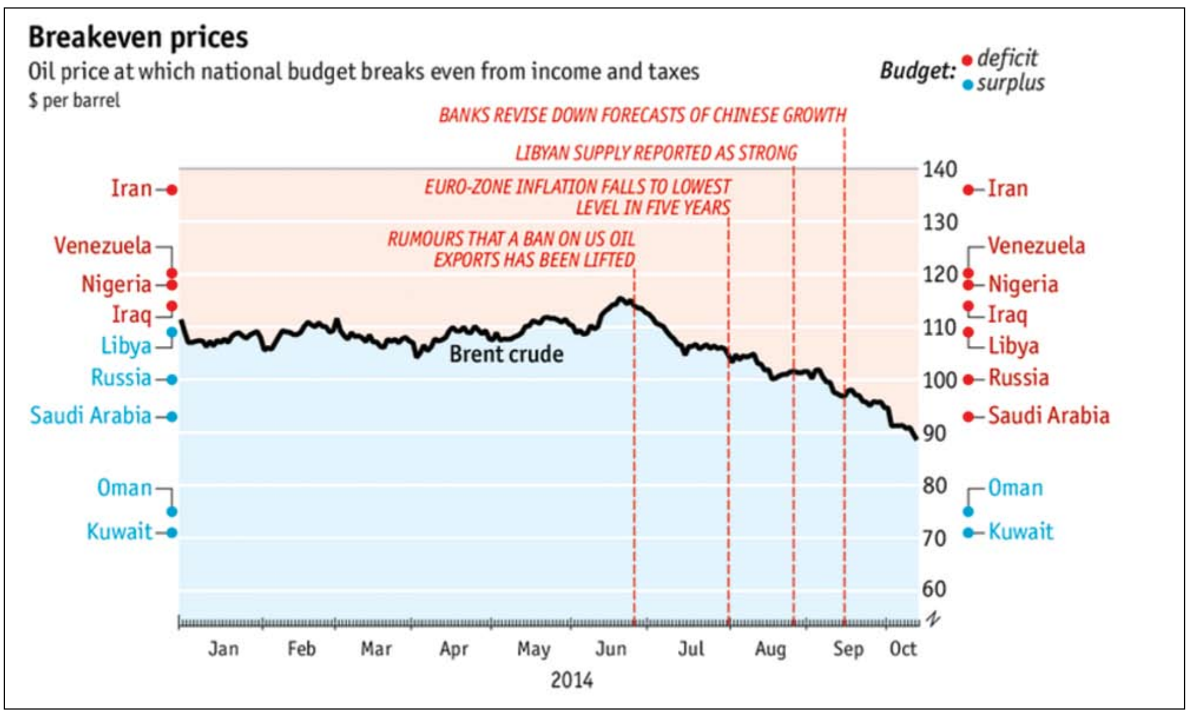


Source: http://www.nytimes.com/2015/01/13/business/energy-environment/oil-prices-fall-to-their-lowest-since-2009-recession.html

The trillion-dollar question is – will the prices stay low? The oil reserves of most oil exporting countries are nationally owned and oil revenues constitute the bulk of the government revenues. Over the years, these governments have built up large budgets and costly public appeasement policies by providing subsidies based on these revenues. As a result of these commitments, they start incurring budget deficits once the price of oil falls below a certain value independent of the marginal price of production. This break-even price for a number of exporting countries is shown in Figure 14. The current price of about $50/barrel is well below the break-even price for all major exporters, including Saudi Arabia (about $90/barrel), other than perhaps Canada, and has put a huge pressure on their economies. Past high oil prices allowed Saudi Arabia to build large reserves that are held in its central bank, the Saudi Arabian Monetary Agency; its high break-even price is because it also significantly increased its expenditures over the last five years.[17] While it may be willing to use its monetary reserves to keep the prices low for some time, the other exporters are already hurting. For example, by January 2015 Venezuela and Iran were canvassing OPEC to cut production and raise prices.

Sustained low prices will also drive out some high-cost non-conventional oil production and might set back investments in them for years. The bottom line is, even if global consumption picks up because of the current low price, it will not offset the loss of revenues incurred by the exporters who have gotten used to prices over $100/barrel. It is therefore anyone's guess as to when any given exporter will reach its breaking point, what austerity measures these nations can adopt, what social disruptions will result and what will be the consequences to the global economy of their

Figure 14: Price of Brent Crude Oil Prices in 2014 vs. Price at which Select Large Exporting Countries Start Incurring Budget Deficits since 2009



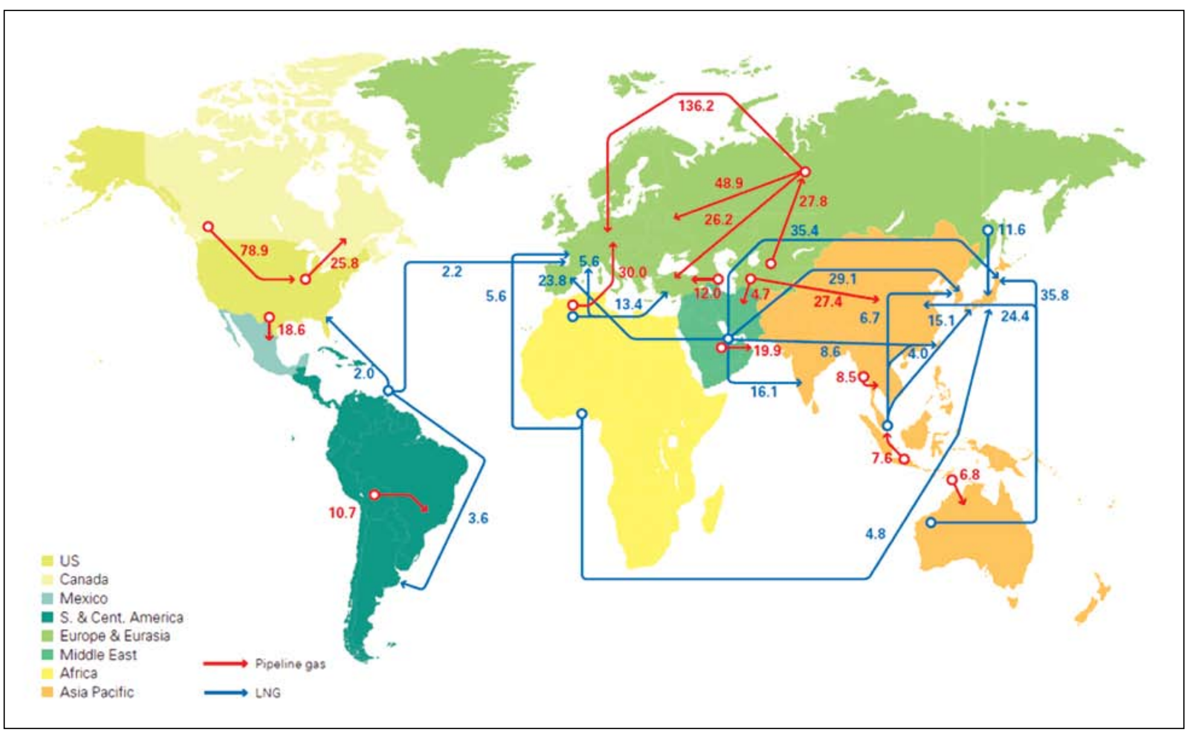
Note that in January 2015, the prices had fallen even further to $50/bbl.
Source: The Economist, http://www.economist.com/blogs/graphicdetail/2014/10/daily-chart-7

misery. The swing vote and the future of oil prices, for the time being, remains largely in the hands of Saudi Arabia.

Natural Gas

Natural gas is widely hailed as the bridge fuel between the fossil-fuel dominated economy of the 20th century (mostly by coal and oil) and the future zero-carbon economy based on renewable sources. Even though it is a relative newcomer vis-à-vis coal and oil, it is the cleanest burning and most multipurpose fuel of the three. It is used widely for home, commercial and industrial use. It is an energy-efficient transportation fuel in the form of CNG or LNG, and is used extensively for generating power using combustion turbines. It is also a key feedstock in the fertiliser and petrochemical industry. After processing, natural gas burns with relatively little pollution, but it is nevertheless a fossil fuel that produces CO_2 when burned. Methane is a powerful greenhouse gas and any leakages during production, processing and/or transport contribute to global warming. From an economic and logistics perspective it has two major drawbacks because it is a gas – transport and storage. The cost of transport when a pipeline is not an option, for example exporting gas from the US to China, is large, about \$4-8/MMBtu,[18] and storage of natural gas as LNG is expensive and limited in scope. The questions that need to be addressed with respect to realising the full potential of natural gas as a multipurpose fuel are: (i) Is there sufficient economically recoverable reserve of natural gas, and its geographic distribution, that the industry will invest in enlarging not just production but the natural gas-based economy as a whole, for example CNG-fueled cars?; (ii) Where will the price stabilise with respect to coal and oil?; and (iii) Can

Figure 15: Global Flows of International Natural Gas Trade in 2013 (bcm)



Source: BP Statistical review of World Energy 2014, p. 29 the production, especially of shale gas, be made more environmentally benign to overcome the environmental impacts and objections regarding the current practice of hydraulic fracturing?

Most of the natural gas production in 2013 was from the exploitation of conventional reserves; the geographic trade in 2013 is illustrated in Figure 15. Four countries – Russia, Turkmenistan, Iran and Qatar account for about 60 percent of current conventional reserves. The next largest reserves, about four percent each, are in the US and Saudi Arabia. After these there are 11 countries, each with a share of one to three percent of the world's total, and these include many of the current exporters: Trinidad and Tobago, Norway, Algeria, Australia, Indonesia and Malaysia. Historically, European countries and the Asian Tigers (Japan, Taiwan, South Korea and Singapore) have dominated imports of natural gas. Recent growth in demand has been mostly in producing countries and Asia-Pacific, and has been driven by the power generation sector. Outside of North America, export of natural gas is dominated by the Netherlands, Norway, Russia, Turkmenistan (mostly by pipelines); Trinidad and Tobago, Nigeria, Qatar, Indonesia, Malaysia and Australia (mostly as LNG); and by Algeria through pipelines and as LNG. The development of new pipelines and LNG terminals takes five to 10 years and requires very significant investment. So, growth in supply is incremental and most of the LNG liquefaction terminals under construction are in Australia, East-Africa and Asia-Pacific, the new centers of export and of demand respectively.[19]

Most developed countries have over built capacity in both gas and coal-fired power plants to balance their energy portfolio by increasing coal-fired generation when the price of natural gas is high and vice-versa. This is evident in Europe since 2010, where demand of gas has not taken offdue to high relative price, and many countries, for example Germany as discussed later in this paper, have expanded their coal-fired power generation instead for the time being. Because of this elasticity in demand for natural gas, producing countries are developing their export capacity incrementally and in sync with long-term sale agreements and construction of new pipelines and/or LNG facilities. Even then, as price fluctuates and demand varies, these facilities go through periods of underutilisation, for example LNG regasification terminals in Europe since 2011.[20] A second strategy that countries importing natural gas, especially as LNG, follow to ward against disruptions in supply is to maintain a diverse portfolio of sources. Large importers, for example Japan, South Korea and Spain, have spread their purchases over many suppliers.

Post Fukushima, the landed price of LNG in Japan reached about \$20 per MMBtu as a result of the shutting down of all nuclear reactors and the consequent sudden increase in gas demand. In terms of stored chemical energy, this price was equivalent to that for oil (1 toe = 40 MMBtu and \$800/tonne for the price of oil) and about seven to eight times that of coal (using 1 tce = 30 MMBtu and \$80/ton for the price of coal). At these prices, coal-fired generation becomes much more attractive in the absence of a carbon tax or trading scheme as well as in spite of its environmental impacts. Three changes can tip the scale back in favor of natural gas: (i) A significant carbon tax that makes coal more expensive; (ii) global development of shale gas resources leading to lower prices; and (iii) a global rejection of nuclear power.

The first and third are mostly policy issues, albeit driven by economics and energy security. In this paper the second issue is reviewed – development of shale gas resources in Europe, which currently imports most of the natural gas it consumes. Since European countries are also leading the world in experimenting with a carbon pricing and in rejecting nuclear power, the question is whether Europe is on a fast track to repeat the success of shale gas production in the US or whether it will remain dependent on gas imports.

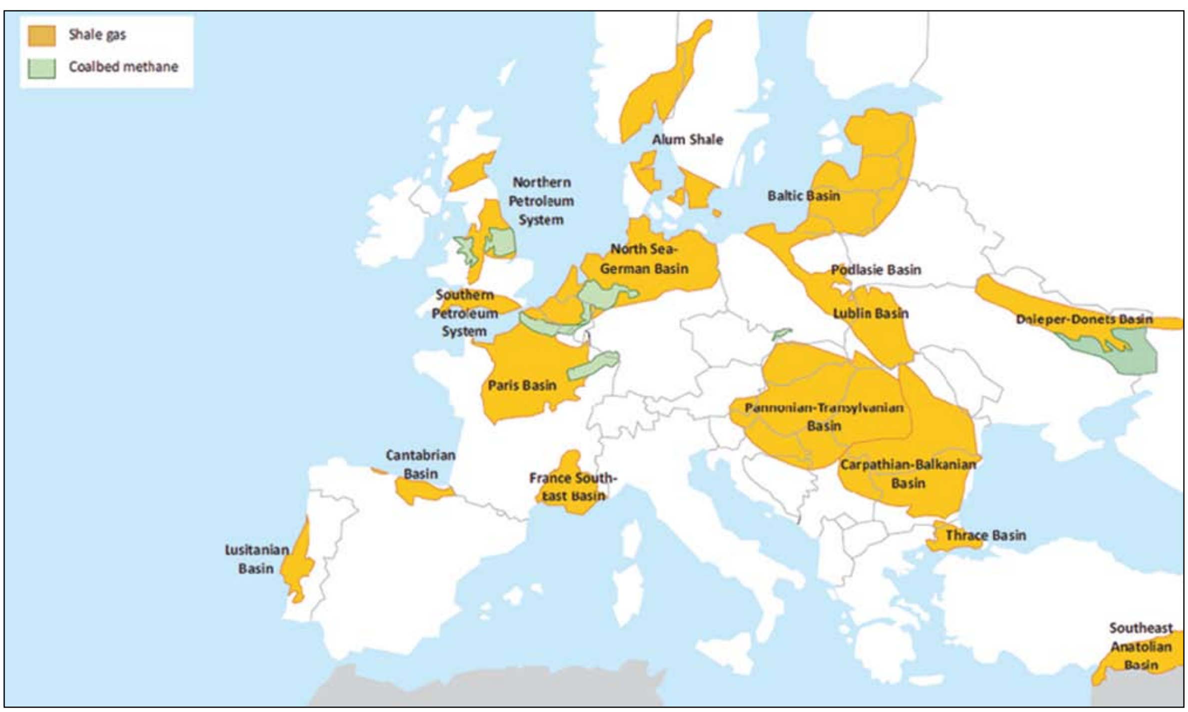
Prospects for shale gas production in Europe:

According the recent study by ARI, Europe holds about 25 tcm of technically recoverable shale gas.[21] This is about a third of conventional reserves in Europe and Eurasia that are essentially all concentrated in Russia and Turkmenistan. The region's shale gas resources are located in three major areas that contain multiple basins, sub-basins and different plays as shown in Figure 16. One area of prospective gas runs from eastern Denmark and southern Sweden (Alum shales) across northern and eastern Poland (Silurian shales) into Ukraine; the second stretches from northwest UK through the Netherlands and northwest Germany to southwest Poland; and the third from southern UK through France (Paris basin), the Netherlands, northern Germany and Switzerland. According to these assessments, southern Europe does not have large basins. It should be noted, however, that with limited validated drilling results, overview maps such as the one shown in Figure 16 are largely based upon geological evidence and do not provide a statement on commercial viability of gas extraction.

In addition to the lack of adequate data from drilled wells, there are many geological, social and economic reasons why Europe is likely to be less prospective than North America. These reasons include:

- A more fragmented geology (volume and area), and less mature and more geologically active basins resulting in smaller sweet spot areas than in the US.
- Significantly deeper shale formations (2,500 to 3,700 meters below the surface) than the formations in North America, and many promising ones offshore in the North Sea.
- Higher population density, which limits both access to promising drilling sites and constrains

Figure 16: Map of Shale Gas and Coal-Bed Methane Basin in Europe



Source: IEA (2012), Golden Rules for a Golden Age of Gas, p. 121 large-scale, closely-spaced drilling sites.

- Stricter environmental regulations, higher public awareness and active opposition. The public is sensitised to the disruptive impacts of the truck traffic associated with the wells for transporting water and equipment.
- State ownership of oil and gas rights versus landowner's rights in the US, which might limit the incentives for private landowners and communities to accept and benefit from local shale gas development.
- Highly fragmented and nationalised legislation and regulations regarding upstream unconventional gas production within Europe, even though the European Commission has adopted non-binding recommendations in January 2014.
- Significantly higher shale production costs in Europe compared to the US due to geological and technical reasons as well as higher regulatory and environmental expenses.
- A lack of dynamic investment and production stimulating factor of continuous drilling obligations in Europe.
- The need for shale gas in Europe to be competitive with imports of conventional gas from Russia, the Caspian Sea basin and North Africa, regions to which it is connected via an extensive network of pipelines.

Keeping these challenges in mind, the state of affairs in selected European nations is as follows:

- *France,* with estimated reserves of about four tcm (compared to annual consumption of 0.04 tcm and negligible indigenous production of conventional gas), was expected to be one of the first countries to develop its shale gas resources. However, in 2011 the government banned shale gas production using hydraulic fracturing (fracking) because of public and political concerns over the environmental impacts and furthermore cancelled the exploration permits issued in 2010 to Schuepbach Energy and Total. President Hollande confirmed the ban and France's constitutional court upheld it on 11 October 2013.[22]
- In the *UK* (0.75 tcm), shale gas activities are strongly backed by the current government, but it is unlikely to be a game changer soon as the estimated reserves are less than one tcm and public discussion on its need is ongoing. Although the moratorium due to environmental and seismic concerns has been lifted, progress is still slow.
- *Germany,* with about 0.5 tcm listed, is in a similar boat as the UK and faces strong public awareness and opposition. The new draft legislation has taken a cautious approach that may allow fracking based on strict environmental regulations and audits.
- *Scandinavia* (1.2 tcm) sits on top of the large and promising Alum Basin. However, after some test wells in Sweden, Shell stopped activities there. The 2013 updated assessments from ARI has eliminated speculative area for Alum Shale in Norway and put reserves down to zero from a promising 2.3 tcm in the former version.
- *Poland,* with its promising Baltic Basin, was the designated European champion and the Polish government has been actively boosting the shale gas industry to reduce its unwelcomed dependence on Russian gas and to diversify away from coal. Several setbacks and problems have dampened Poland's hopes. A series of first test drills did not prove viable for commercial shale gas production, leading to the exit of some multinational players (ExxonMobil, Talisman and Marathon). Recent reassessments by the Polish Geological Institute and the EIA have scaled down expectations. Furthermore, a number of hurdles exist regarding geology, gas transmission and distribution infrastructure, legislation and bureaucracy and, last but not least, the questionable profitability of shale gas production. In order to trigger shale gas exploration, the Polish government has established tax breaks and streamlined regulations and procedures. Nevertheless, the current assessment is that even with strong political support, large-scale production is not

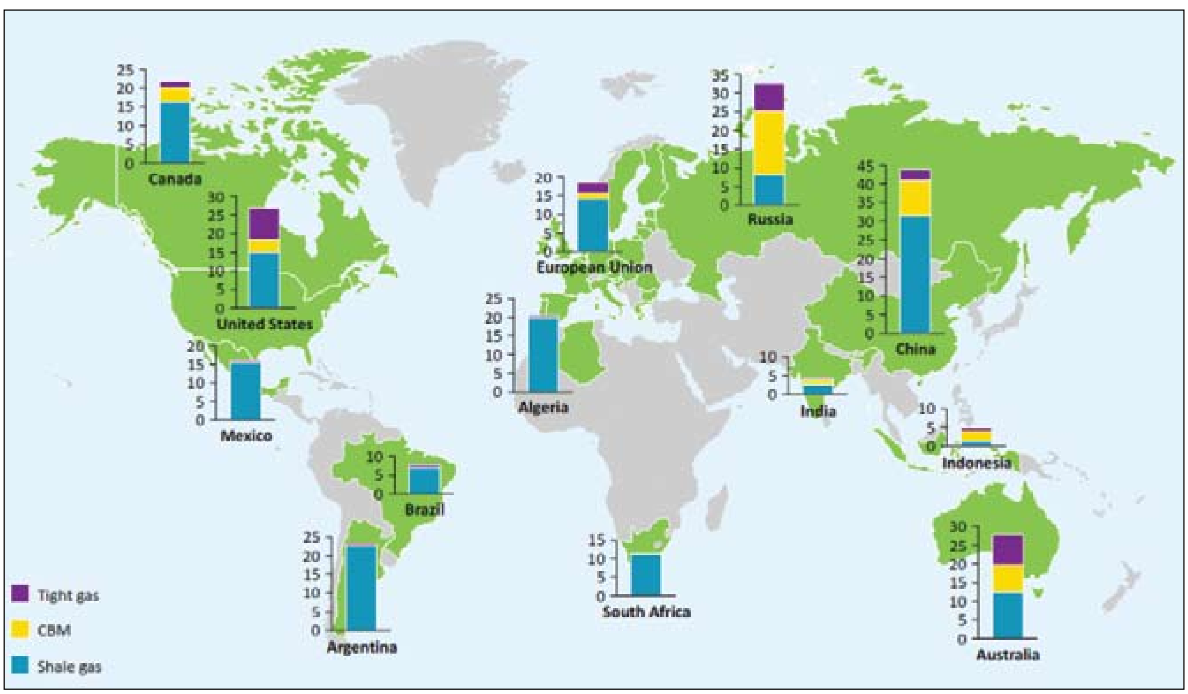
expected before 2020.

- *Ukraine,* with estimated 3.5 tcm, is also keen to exploit its shale gas resources to reduce dependence on Russia. In 2013 it signed a contract with Royal Dutch Shell allowing it to explore the Yuviska block, and ENI, Chevron and other majors are said to be ready to join in. While encouraging, it is too early to assess how shale gas recovery will evolve in Ukraine, especially in light of the current political instability.

The upshot is that shale gas is unlikely to be a game changer in Europe in the near term. One would have thought that Russia would view the development of shale gas as not being in its best interest and improve trade relations to maintain its strong position vis-à-vis gas and oil exports to Europe. Its annexation of Crimea and intervention in Ukraine in 2014 has instead led to economic sanctions and isolation. Moreover, against the backdrop of the ongoing Ukraine crisis with Russia, the EU has published a European energy security strategy and cautiously addressed the option of shale gas development to compensate for falling conventional gas production.

Figure 17 gives the IEA assessment of the global geographic distribution of remaining unconventional gas resources in tcm at the end of 2012. According to such assessments, Argentina and China have amongst the largest predicted resources of shale gas and they have the motivation to exploit them because of a large growing demand for gas. Again, both countries face serious social, infrastructure and technological challenges, and regulatory impediments to attracting investment and international participation. Argentina will have to address issues of populist government policies, price controls and an unattractive business climate for foreign companies.[23] The Chinese government

Figure 17: Remaining Unconventional Resources of Gas (tcm) in Selected Regions in IEA WEO 'New Policies Scenario' (end of 2012)



Source: IEA WEO (2013), p. 116

is committed to rapid development of its shale gas resources, but their reserves are again deeper than in the US and in less accessible and more water-stressed areas (mountainous, arid west and southwest or overlapping with conventional oil or gas fields) that will need larger investment in exploration and infrastructure.

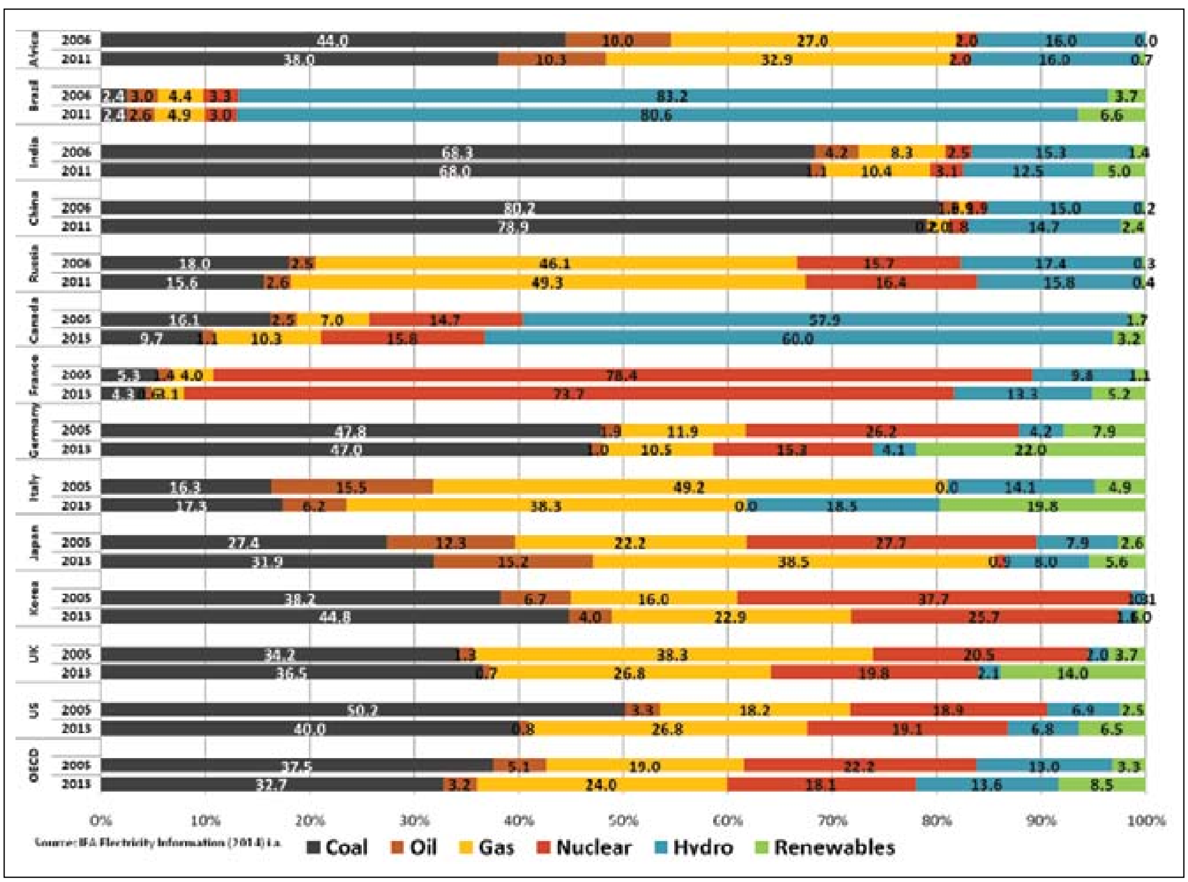
The regulatory and business climate for foreign companies also needs to be improved.[24] As a result, the growth in exploration and production is much slower than expected. The bottom line is that it remains to be seen how soon any country outside North America can join in the shale gas revolution.

Diversification in Power Generation

In the last section opportunities and hurdles in the future supply of fossil fuels were discussed, with the conclusion that historic models based on demand and supply, and moderated by geopolitics, persist for investment in the exploration and production of coal, oil and gas. The focus now is on electric power generation; the impact of integration of utility scale solar and wind plants; and the long-term promise of creating combinations that evolve towards zero-emission systems.

Figure 18 compares the composition by fuel source of electric energy generated in 2011/2013 versus

Figure 18: The Fraction of Electric Energy Generated as a Function of the Fuel Source in Thirteen Large Consumer Countries/Regions and the Average for OECD Countries



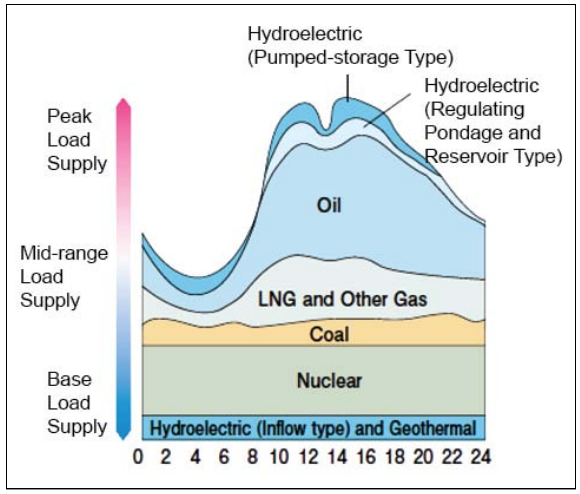
Data are compared for years 2005 and 2011/2013.
Source:IEA Electricity Information. Compiled by authors.

2005 in thirteen major countries or regions. It reflects a historical picture driven by economics, indigenous reserves of fossil fuels, hydro and nuclear capability and shows that renewables are beginning to become significant. Even though the distribution varies by country, some trends stand out: (i) Oil has ceased to be a major fuel for power generation due to cost and has been replaced by natural gas and coal; (ii) almost eighty percent of the supply of electricity in the OECD countries comes from coal, natural gas and nuclear, with coal still maintaining the largest, though decreasing, fraction; and (iii) the contributions of renewables (colored green in Figure 18 and includes biomass, geothermal, solar and wind) are small but have grown significantly in the last decade. What is also clear is that most major economies already have a diverse portfolio, i.e., they have significant installed capacity, expertise and experience in systems utilising the six major energy sources – coal, natural gas, nuclear, hydro, solar and wind. They have the technological expertise and resources to grow any one or all of them as need and opportunities arise or in response to climate change regulations and/or economic crises. Experience with control systems to integrate solar and wind into the grid is also accumulating rapidly, allowing these systems to become an integral part of a diverse portfolio.

Mitigation of climate change requires that these fractions transition from the current domination by fossil fuels to one with renewable generation. Before examining how these fractions could evolve in the future, it is instructive to examine the potential for such changes by reviewing recent significant changes in Japan, Germany and the US.

Figure 19 shows a schematic of how power demand in a typical 24-hour period in Japan was met before 2011. The schematic shows that run-of-the-river hydro, geothermal, nuclear and coal provided baseload generation. LNG and oil-fired plants and reservoir-based hydro were used to meet peak demand. Solar and wind were too small to impact the picture.

Figure 19: 24-Hour Electricity Generation Profile in Japan by Fuel Source (before 2011)

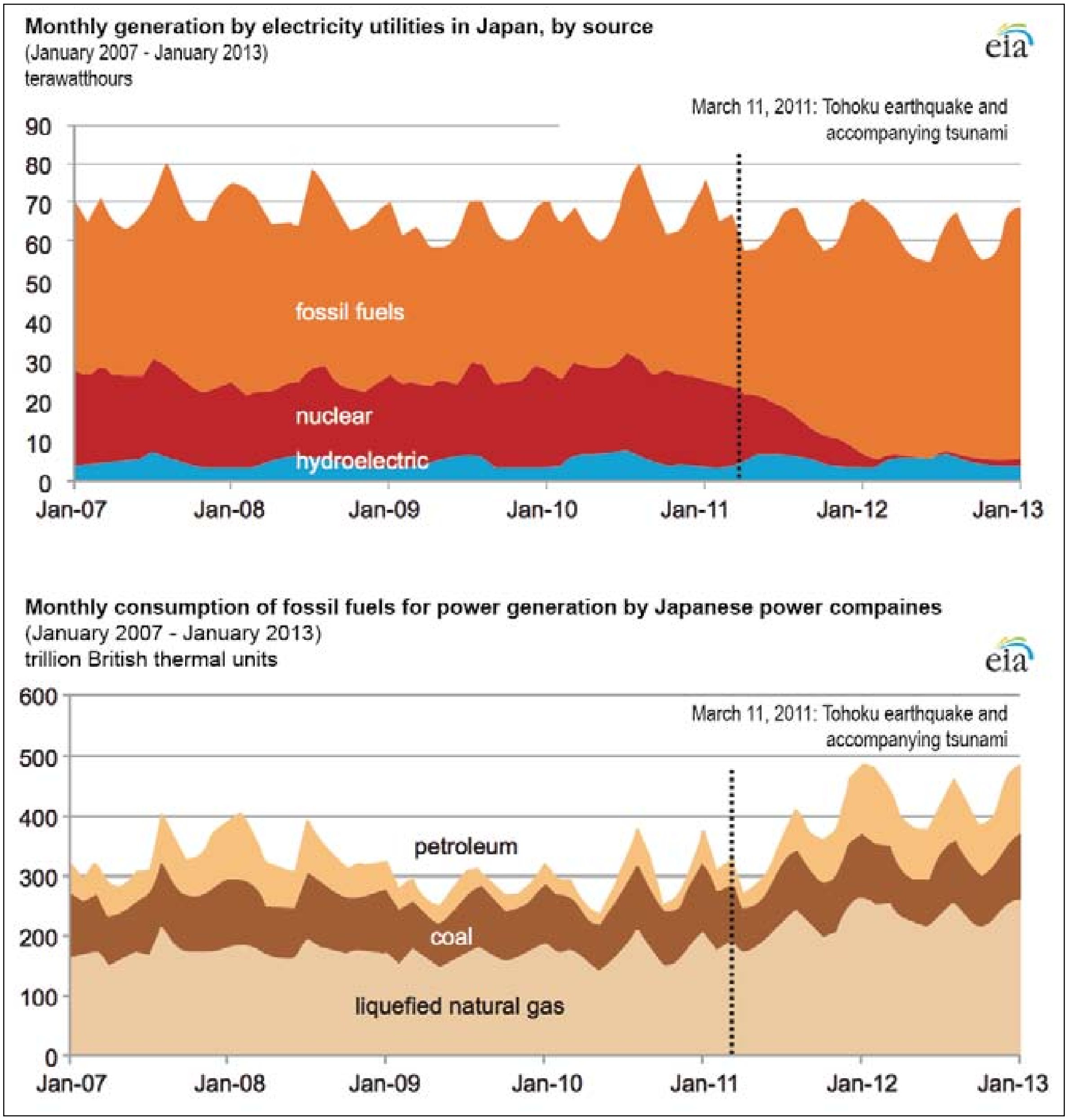


Source: The Federation of Electric Power Companies of Japan (FEPC)[25]

The social and political support for nuclear power eroded in Japan after the accident at the Fukushima Daichi nuclear power plant caused by a tsunami on 11 March 2011. All nuclear reactors were shut down and Japan lost about 27 percent of its generation overnight. Since then, over the last years, Japan has compensated for this loss by ramping up production in its existing underutilised coal, gas and oil-fired units as shown in Figure 20. The cost, however, has been high and the additional oil and natural gas imports are very significant contributors to the growing trade deficit (see Figure 5). Most other developed countries have similar overbuilt capacity, over and above that required to cover scheduled and unscheduled maintenance and smooth operations.[26] Having such overcapacity makes them less vulnerable to large shocks and forced transitions but they will face similar financial hardship if they have to import additional oil or gas to meet their power demand.

Germany, post Fukushima, reassessed its nuclear policy in 2011 and decided to shut down all nuclear power plants by 2022. Belgium as well as Switzerland, which both have aging reactors, are likely to follow. Again, Germany had options since

Figure 20: Monthly Electricity Generation by Source and Consumption of Fossil Fuels before and after the Fukushima Disaster (2007-2013)



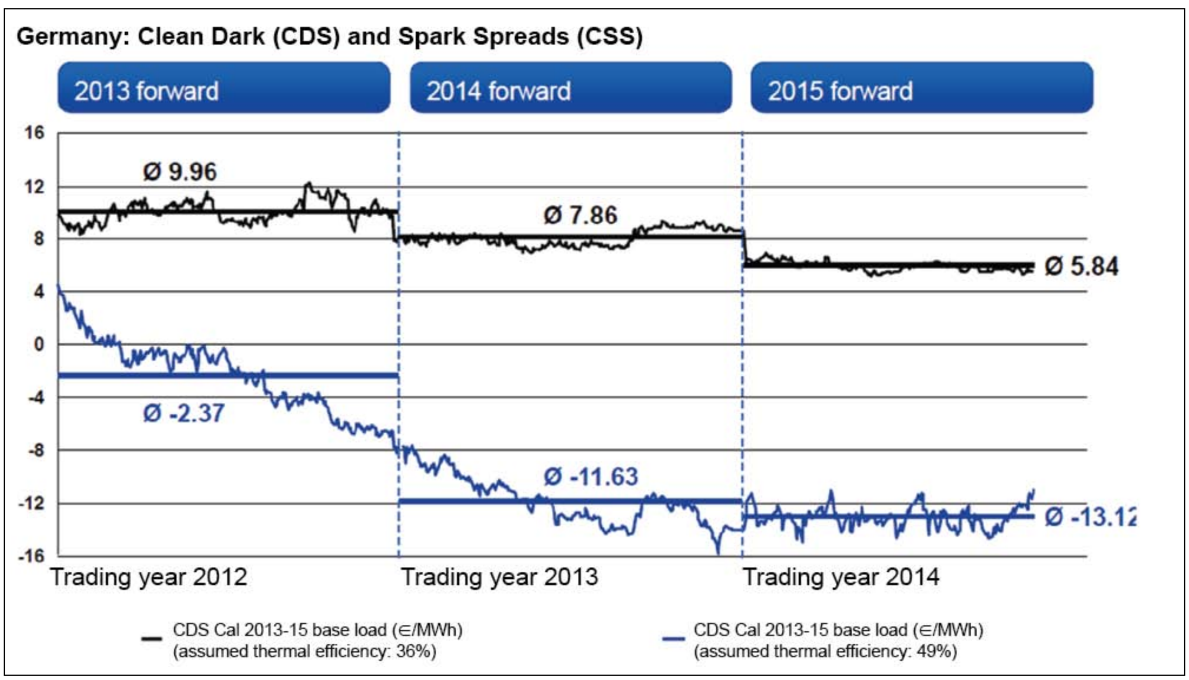
The loss of nuclear capacity was compensated by increased imports and use of LNG and oil. Post Fukushima, fossil fuels contributed about 90% of the electricity generation.
Source: EIA Today in Energy, http://www.eia.gov/todayinenergy/detail.cfm?id=10391

it had excess capacity in both coal and gas-fired units and was making very significant investment in solar and wind systems driven by policy and incentives. The guaranteed tariffs to solar and wind operators (part of the "Energiewende" policy that set the goal of 80 percent share of renewable energy in electricity generation by 2050) meant that power companies were obliged to first absorb generation from these and run-of-the-river hydroelectric power plants.[27] For the remaining generation, the way the German system evolved, included surprises. In the short term, due to the collapse of the EU Emission Trading Scheme, the higher costs of power from natural gas versus coal (Figure 21) favored higher utilisation of coal-fired units, many of which are the recently built high-efficiency supercritical units (those burning domestic lignite are called BoA, short for Braunkohlenkraftwerk mit optimierter Anlagentechnik). The result is that natural gas units (albeit cleaner and more energy-efficient) have been squeezed out of the market. Even the recently commissioned high-efficiency CCGT units, such as the latest SGT5-8000H turbines by Siemens at Irsching, are highly underutilised as a result.[28]

In Figure 22, electricity demand over a typical week in Germany and the composition of the supply is shown. To accommodate the large generation from wind turbines during that weekend, energy companies scaled back generation from black coal and natural gas since these fuels are imported and more costly. To optimally reduce overall costs, power plants using them are the first to be scaled back independent of conversion efficiency. Also, grid connections to neighboring countries allow Germany to export excess generation (shown in green in Figure 22), which was substantial and comparable to the sum of wind and solar generation throughout the week. Integration at the system level allows Germany to maintain energy security and export excess generation.

Germany has taken a bold step towards zero-carbon generation by promoting renewables and renouncing the option of nuclear power. The initial transformation towards renewables has

Figure 21: Development of Clean Dark and Spark Spreads in Germany (2013-2015)

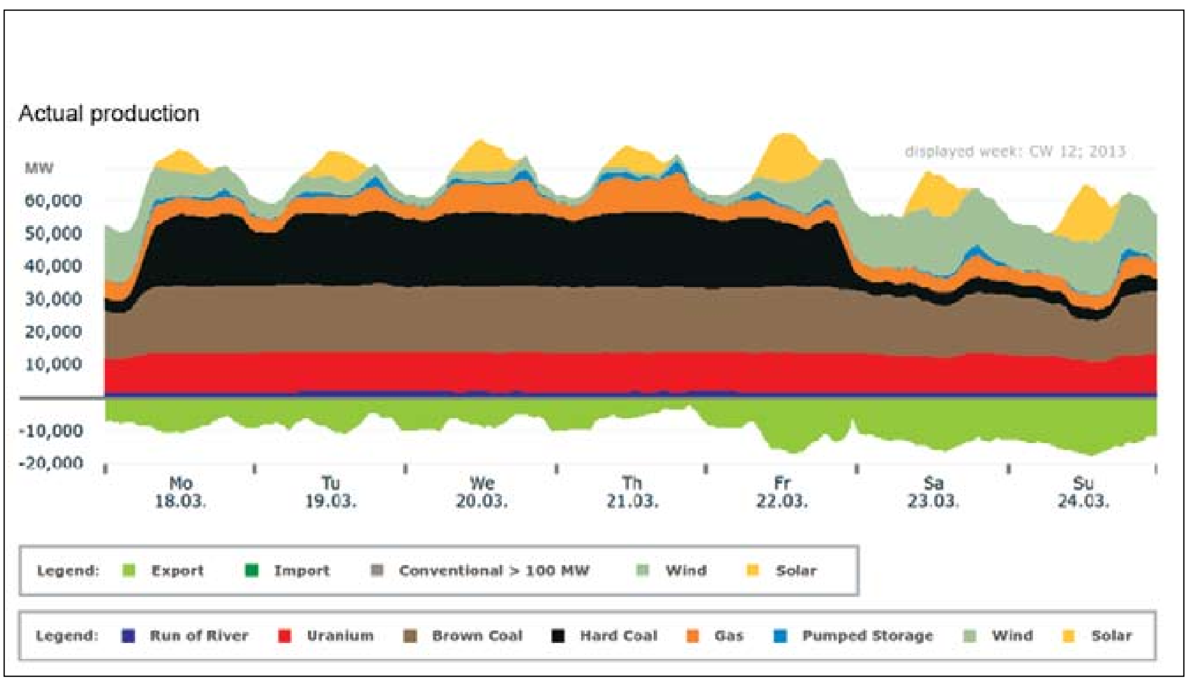


The curves show the evolution of the clean dark spread (black) and clean spark spread (blue) in EUR/MWh. The spreads are the difference between the price received for electricity produced and the cost of the natural gas (coal) needed to produce that electricity, including CO_2 emissions (allowance) cost. If the spread turns negative (blue curve for gas) the power station loses money by operating. There is a growing divergence between clean dark and spark spread, making investments in coal power plants (relatively) increasingly attractivein recent years. Source: RWE[29] been achieved with a price tag in the form of the EEG surcharge. Germany, with its high-technology industry, ground-up activism by the municipal corporations and citizens, and willingness of the citizens to pay higher price for green energy, faces the near- and medium-term questions of whether the renewable subsidies can be phased away and whether the economy will be able to withstand the impacts of higher cost of electricity.[30] Already, protests against high household energy costs have led to sweeping reforms of renewable energy laws to keep power prices from spiralling out of control.[31] Not surprisingly, the reform of Germany Renewable Energy Act that entered into effect in August 2014 is going to address not only the problem of escalating costs by focusing on the most cost-effective technologies, but also improve the cost distribution among industrial and private consumers.

The *US* has historically obtained about 50 percent of its electric power from coal-fired units. The boom in shale gas production has made natural gas-fired generation highly competitive since 2008. Serendipitously, the US had overbuilt CCGT capacity during 1995-2004 when gas was cheap, so in 2008 it was in a position to rapidly transition from coal to gas-fired units and reduce its coal-fired generation fraction to about 37 percent by 2012.[33] (Also note that a GW capacity CCGT power plant can now be brought online in about 18-24 months and the regulatory requirements are fewer). As a result, the two goals – profit and reducing the carbon and environmental footprint – became aligned.

The examples of these three countries highlight the advantages of a diversified portfolio of generation, integrated systems and of maintaining excess capacity. Countries with large fuel reserves and/or overbuilt capacity have options and can exploit them quickly: the natural gas-rich US could make the transition from coal to gas overnight, whereas Germany could renounce nuclear power

Figure 22: Actual Electricity Generation in Germany by Fuel Source and Exports (during a Week in March 2013)



Source: Fraunhofer Institute for Solar Energy Systems (ISE)[32] in response to public pressure and go back to a higher fraction of coal-fired generation. Germany could equally well have increased gas-fired generation but due to prevalent market conditions expanded coal because it is the much cheaper option. Similarly,overbuilt capacity allowed Japan to substitute nuclear by fossil fuel systems in a short time in response to a crisis.

However, in a carbon-constrained world, the question is how countries starting with distributions similar to those shown in Figure 18 can accelerate the transition to carbon-neutral systems. Installations of wind and solar systems are growing and wind is now price competitive with natural gas on total energy generated ($/kWh) basis (see, for example, the analysis of levelised cost of generation by EIA[34]). Nevertheless, the challenge of integrating intermittent and fluctuating generation from solar and wind, real-time management of economics of different systems and the long experience with and investment in existing fossil fuel-based systems makes the transition difficult. Countries therefore maintain the full diversity of generating options to ensure energy security under rare, disruptive events and integrate renewable generation in small increments to ensure reliability of supply at each step. Below are examples of three countries – Brazil, Canada and Denmark – which have the resources to follow credible roadmaps towards zero-carbon systems while preserving energy security and yet have not stopped installing and using fossil fuel-based units.

Brazil generates about 80 percent of its electricity from hydro, and a large fraction of these projects are reservoir based.[35] It can therefore integrate very substantial amounts of solar and wind energy into the grid, with hydro providing backup and stability. So it should come as no surprise that the availability of inexpensive backup power from hydro allowed a large number of wind farms to win bids at the annual energy auctions at rates that made bids from coal- and gas-based plants less competitive. The government, however, wants to maintain a diverse portfolio for times when the wind does not blow, there is a year with low rainfall, or in the event of any other emergency. It thus revised its rules for energy auction starting in 2013 by creating different categories of plants so that hydro and fossil fuel-fired plants do not compete against wind to ensure development of all three.[36] New installations of CCGT plants that provide additional generation capacity for meeting peak demand and as backup to renewables have also been facilitated by the linking of the natural gas pipelines in the northeast and southeast by the Southeast Northeast Integration Gas Pipeline (GASENE) in March 2010.[37] (The GASENE pipeline will also reduce the amount of natural gas that Brazil imports by transporting gas from new fields in the Campos Basin to Rio de Janeiro). Adding to this mix, Brazil plans to enlarge its nuclear power fleet, starting with the 1,350 MW Angra-3 reactor that is expected to come online in 2016, as an important part of its diverse portfolio to ensure long-term energy security and to meet its growing demand for electricity.

Brazil could provide an example of an emerging economy that is rich in fossil fuels and yet chooses to meet its electric demand through a combination of hydro, nuclear, solar and wind systems. Achieving this would require significant investment in the transmission grid. Or it can continue with the current policy of opportunistically installing CCGT (and even coal) plants near demand centres along with hydro, wind and solar. The question for the future, assuming a continued demand growth of about seven percent per year as seen over the last decade, is if the public will advocate for a mix including significant fossil fuel-based generation that results in a lower tariff or whether the public will be willing to pay higher rates and require utility companies to work towards a zero-carbon system and, at the same time, maintain underutilised fossil fuel-based capacity to be used only for backup to guarantee high-quality reliable power. Brazil has the resources and the revenue from growing oil exports to try the bolder approach, similar to what Germany is trying under a different economic, social and resource environment.

Canada presents a different case study. It obtains about 60 percent of electricity from hydro and has vast untapped hydroelectric potential concentrated in British Columbia, Ontario and Quebec, whereas Alberta has large deposits of coal, gas and tar sands. The electric power grid in each state is mostly oriented north-south, so it is much easier to export power to the US than to even a neighbouring state. As a result, for example, Quebec cannot easily export power to its neighbours or further develop its hydro potential in response to demand growth in other states without significant investment in an east-west transmission grid. Ontario, with a diverse portfolio, had previously decided to eliminate coal-fired generation by 2014 (in which it has been successful) and is investing in CCGT, hydroelectric and wind projects. It has also recommissioned mothballed nuclear reactors. Alberta is modernising its coal-fired units. Overall, Canada is therefore consuming less coal but the fall in coal production is much less. The savings in coal that used to be consumed in Alberta and the coal that used to be transported from Alberta to Ontario is now being exported to Asian markets. Thus, while Canada is making serious efforts to reduce its carbon footprint in the power generation sector, it is at the same time capitalising on the opportunity to export the "saved" coal to be burned elsewhere. Will this story be repeated by other countries with multiple fuel options as they transition away from coal-fired generation? The answer most likely is yes, as long as China and India continue to rely on imported coal.

Lastly, the well-publicised success story of wind-power in *Denmark* is considered, which in 2013 obtained almost 30 percent of its electricity from wind, a percentage that has only been growing.[38] This growth is, however, not occurring in isolation, as many favourable conditions exist. Denmark is, in fact, a good example of what needs to happen for renewable generation to become a significant fraction of the total. First, Denmark has plenty of onshore and offshore wind resources with a country average turbine load factor of more than 25 percent. Second, it has two pioneering state-of-the-art turbine manufacturing companies, Vestas and Siemens Wind Power, that are creating new opportunities with the development of high-capacity onshore and offshore systems. Third, the integration of wind is facilitated by the Danish grid being part of the Scandinavian grid, which allows fluctuations in wind energy to be balanced by hydro generation in Norway and Sweden and nuclear power from Finland and Sweden. Fourth, there is active electricity trade with Germany, Sweden and Norway, providing an outlet for excess generation from wind. Wind power has been effectively integrated into a larger, well-integrated system. Fifth, Denmark takes climate change very seriously and has formulated a very aggressive Energy Strategy 2050,[39] with the target of full phase-out of fossil fuels for electricity and transport purposes by 2050. It strongly supports aggressive reductions of greenhouse gas emissions in international meetings and is developing a detailed implementation plan to meet its zero-carbon goal. Lastly, the public is very supportive of wind farms in their backyards and is willing to pay a higher price for electricity to promote them. Looking ahead, it will be instructive to see how, given all the favourable conditions, it replaces the current share of generation by fossil fuels (about 45 percent of the electricity comes from coal and another 20 percent from natural gas) by low-carbon options.

The Future of Nuclear Power

No discussion on power generation and a zero-emission economy is complete without a peek into the crystal ball of nuclear energy. The legacy of the Three Mile Island and Chernobyl accidents, and the recent meltdown at the Fukushima Daiichi plant, have created very significant setbacks to the growth of nuclear power. The challenges are largely economic, relatively high-cost of new builds in the absence of a carbon tax, and public perceptions. Even if one makes a convincing case that modern generation III and III+ reactors are overdesigned and safe, the public is not convinced that the cadre of operators are well trained in safety and security procedures and the utility companies sufficiently well-motivated (regulated) to not cut corners vis-à-vis operations and maintenance during the lifetime of the plant. Such a visceral lack of trust by the public played a very significant role in forcing the German government to decide to shut down all nuclear reactors by 2022.

Further, the global public is wondering who can be trusted if even the Japanese and Germans operators and utility companies cannot be trusted to follow safety and security procedures. They question the basic premise that a workforce that is adequately steeped in a culture of safety and security can be trained and maintained globally. Lastly, there is the additional issue of waste disposal, for which technical options exist but the public is not convinced of their long-term viability and safety. In short, they do not want reactors or waste-disposal sites "in their backyard."

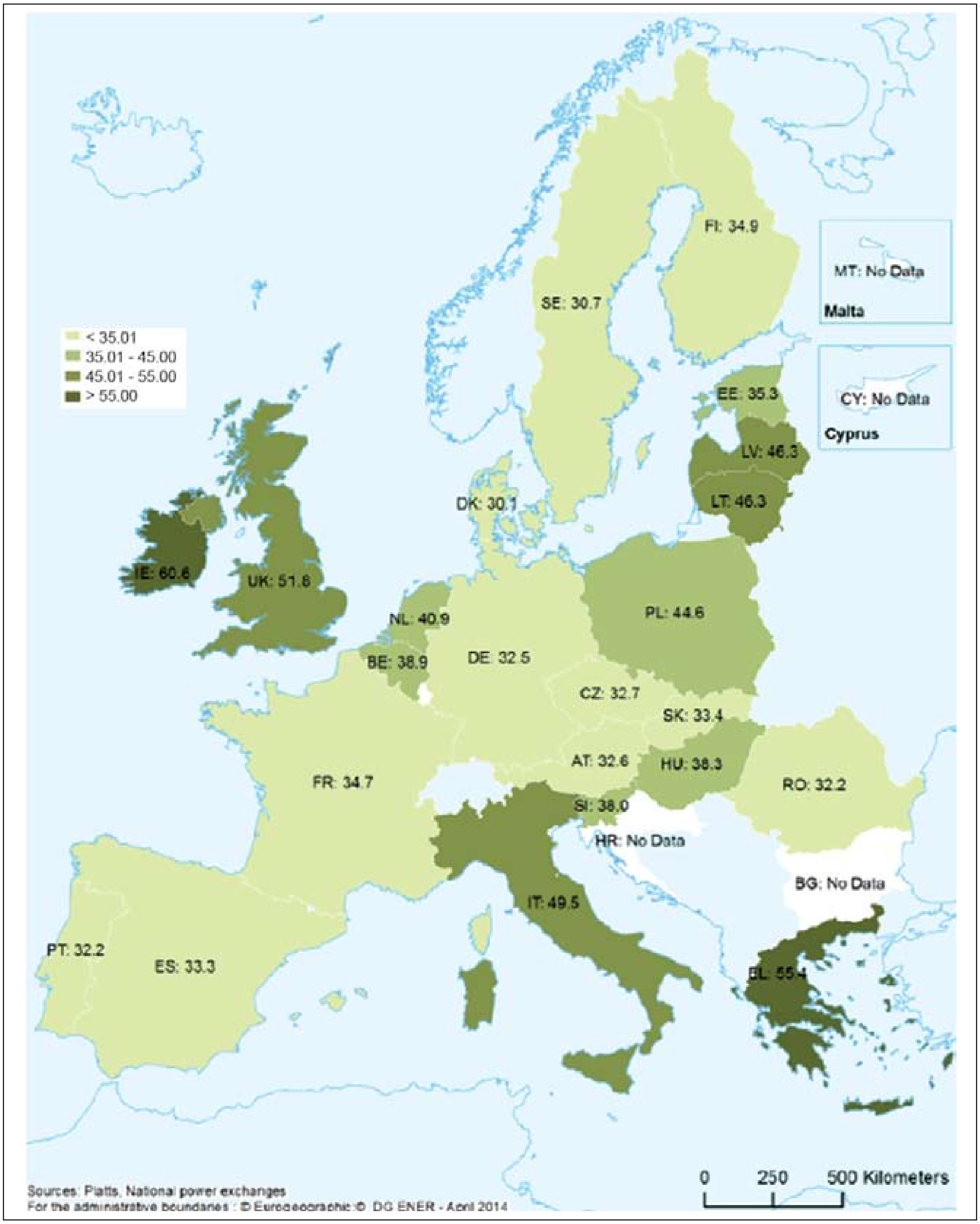
Addressing all the safety, security and liability concerns has contributed very significantly to price escalation and delays in construction.[40] As a result, nuclear power and nuclear industry in 2013 has mostly grown in four countries in which government-controlled companies play a major role – Russia, China, India and South Korea. A number of countries such as the UAE, Turkey, Vietnam, Egypt and Saudi Arabia are planning or constructing their first reactors; nevertheless, large-scale growth of nuclear power worldwide remains uncertain. Without significant growth of nuclear power, the remaining near-term options to transition to a zero-carbon economy are increases in efficiency, terawatt-scale installations of hydro (with a total potential of about two TW of which about one has been realised), solar and wind, and fossil fuel-fired plants with carbon capture and storage.

Cost of Electricity

One must, in addition to an analysis of the fraction of energy generated by the various fuel sources as shown in Figure 18, discuss the cost of electricity to the public. Household electricity prices (in Euro cents/kWh and including all taxes) in European countries are shown in Figure 23 for the second semester of 2013.[41] A comparison of the 2013 prices in US cents/kWh for major economies is shown in Figure 24. It is evident from these figures that the public in countries that take climate change seriously are willing to live with (or at least experiment with for the time being) higher cost of electricity. Three countries that strongly support measures to reduce emissions of greenhouse gases – Denmark, Germany and Spain – have the highest prices. Their experience suggests that the sustainable cost of electricity with about 30 percent renewable generation is between \$0.3-0.4/kWh. Environmentalists contend that this is indeed the true sustainable cost of electricity, and if fossil fuel-based generation is cheaper, it is because it is subsidised and because externalities (such as climate change, environmental and health impacts) have not been accounted for.

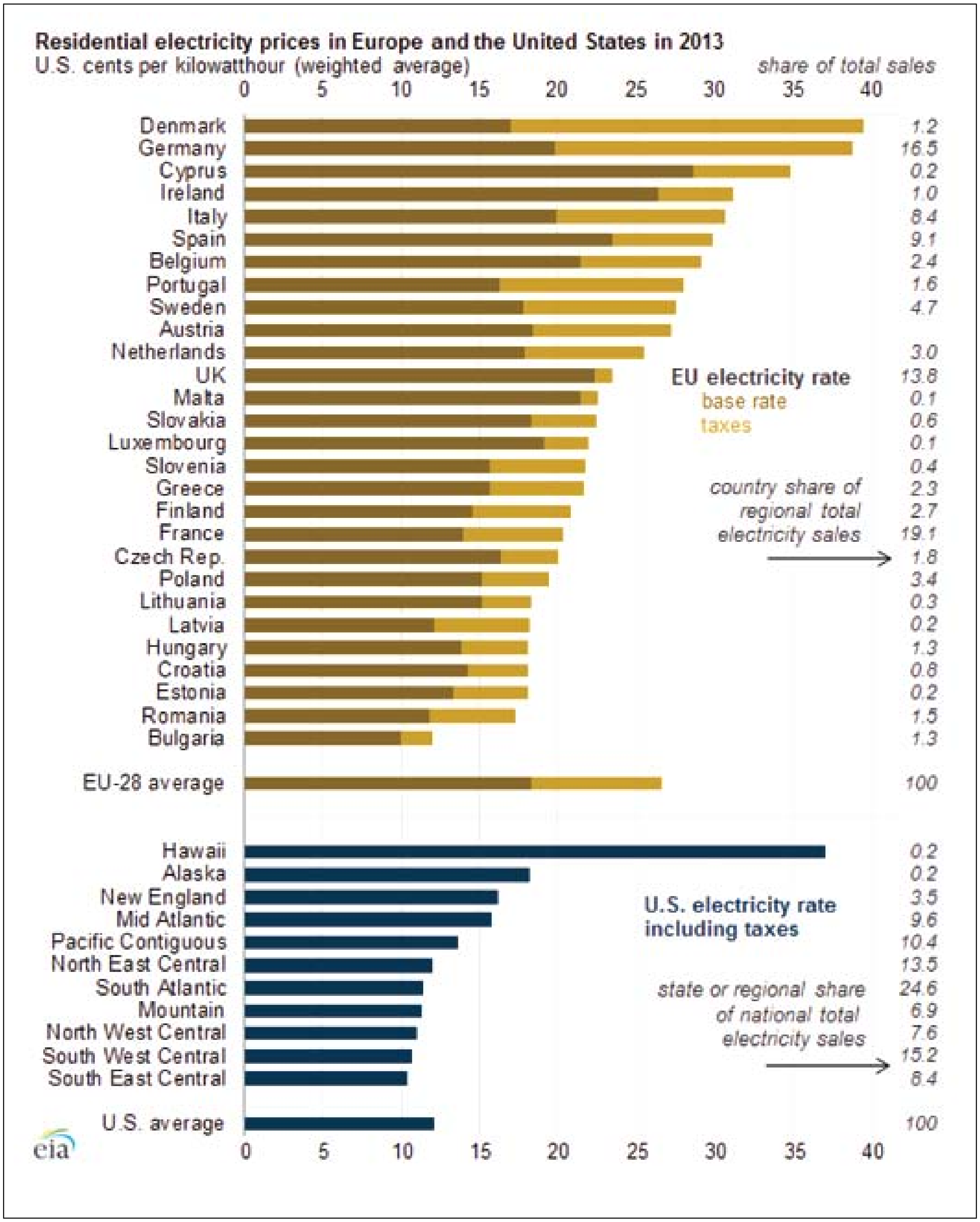
Can all countries afford a higher price of electricity in a range of \$0.3-0.4/kWh? As discussed earlier, developing countries without large reserves of fossil fuels are already facing a dilemma: Should they follow the fastest road to development using imported fossilfuels and ignore impacts of emissions, or should they pursue slow growth that is based on more costly renewable generation but one that is sustainable in the long run? Initially and in the near term, they are more likely to continue to rely on fossil fuels and may be unwilling or unable to afford the additional costs of solar and wind systems, or they may not have an adequate transmission grid or control systems to integrate renewables. They may also be willing to accept the environmental consequences of using fossil fuels. For instance, very few coal-fired plants in India have scrubbers to limit emissions of even SOx and NOx. Internally, they can get

Figure 23: Cost of Electricity for Households (Inclusive of Taxes) in Various European Countries (Euro cents/ kWh) for the Second Semester of 2013



Source: European Commission, DG Energy

Figure 24: Comparison of the Average Price of Electricity (Including All Taxes) in Europe and Select States in the US (US cents/kWh) (2013)



Source: EIA, http://www.eia.gov/todayinenergy/detail.cfm?id=18851 away with this option because most of these countries have growing and restive populations demanding fast growth as their highest priority. In the medium to long term they may be forced to close down coal-fired plants before the investment has been fully recovered (coal plants have a 30-50 year life) in a carbon-constrained world if the public rebels against environmental pollution or the government is unable to afford adequate supplies of imported fossil-fuels as indigenous/conventional reserves are exhausted and international prices continue to rise. These challenges pose a constant threat to energy security and achieving a balance between the two strategies in a fiscally strapped environment is not easy. In less than ideal conditions, either strategy could easily fail and undermine their investments and development. Independent of the strategy they choose, developing countries also need to plan for impacts of climate change that are expected to be large, especially for those countries lying within the tropics. In short, lack of energy and climate security could accelerate the many other serious challenges they face to create the "perfect storm."

Serious Challenges to Integration of Solar and Wind Systems

Here are two examples to illustrate why integration of wind and solar systems into the grid above a certain percentage poses an economic challenge and requires special enabling circumstances. These examples also highlight the observation that if significant reservoir-based hydro or nuclear capacity does not exist and fossil fuel-fired plants are used for backup, reductions in greenhouse emissions will continue to be limited.

Consider a grid-connected community in which every household has installed solar photovoltaic (PV) systems that under net-metering makes their electricity bill zero. The utility company then has no revenue generation from this community. Its function is to absorb all the extra production from solar during the day and supply backup power (largely from fossil fuel-based generation) during the times when there is no sunlight, and to do this without any compensation. To survive economically, the utility company needs to export the extra power to other communities during the day and/or charge all customers a connection fee for providing backup power. Assuming that on average there are six hours of sunshine in a day, to absorb the extra power generated by the enlightened community would require the utility company provides this power to another two or three similar communities that do not have any solar installations. Furthermore, the company would also need to maintain the original fossil fuel-fired generation capacity as "backup" to cover all the non-daylight hours and cloudy days without sufficient PV generation. Charging for these backup services, either on a per kWh basis (which amounts to negating the net-metering agreement) or as a fixed monthly connection charge would increase the cost to the consumer. In this ideal scenario, even with only about a third of the people installing solar PV systems, net-metering would not be sustainable and utility companies would need to charge a higher tariff to survive.

Off-grid solar and wind systems are an invaluable resource for communities that today have no electricity. However, as their expectations grow beyond low-power applications (solar lanterns, LEDs, fans, battery chargers) to fully switched systems, solar power or small wind turbines with battery storage become too expensive. As mentioned earlier, even when solar PV and wind systems become cost competitive, storage/backup remains the key hurdle to large-scale deployment.

Many of these issues are already affecting the market. The rising shares of renewable generation and characteristics of conventional generators are already challenging the usual business models of power companies at various levels. For instance, Europe is discussing establishing a capacity market for power generators that are severely impacted by current market conditions. The idea is to compensate power plants with (too) low load factors for providing capacity, therefore making them financially viable for the long term. The markets would be setup via auctions; the first such auction by the UK power market was held in December 2014.[42]

The second example is Denmark, already discussed above. It, as well as Norway, Sweden and Finland, can continue to install more wind capacity because they are part of the larger Scandinavian grid. Hydro generation from Norway and Sweden, and nuclear from Sweden and Finland, can provide low-emissions backup. Also, Denmark can trade electricity with Germany. Other possible region where conditions for such integration exist are in countries of former Yugoslavia (Slovenia, Croatia, Serbia, Bosnia and Herzegovina, Kosovo and Montenegro) and the region around Austria and Switzerland, since they have large hydropower capacity and an interconnected transmission grid. The tough question, however, is can such prototypes of low-carbon systems be reproduced globally? The answer is yes for regions with large hydroelectric (or CCGT) capacity and for regions in which countries (provinces) are willing to cooperate, build an interconnected grid and agree on a common, reasonable tariff structure. In the absence of cooperation, countries with large baseload generation capacities can blackmail those with mainly solar and wind systems. Unfortunately, such favourable conditions of trade and cooperation do not exist in the most populous continent with the highest growing demand for energy – Asia. Even in the case of Denmark, it will be interesting to see how, having demonstrated 30 percent integration of wind, it replaces its coal and gas-fired generation, which today provides about 65 percent of the electricity, without further large increases in the tariff. Will Denmark retire its fossil fuel-based capacity if Norway develops its wind resources and offers to export more power to Denmark? More generally, will countries even within the European market be willing to accept long-term reliance on other countries for the majority of their electricity?

Potential Game Changing Technologies

What novel technologies can help overcome current limitations of energy systems and address climate change? Below are brief mentions of five amongst many (see Table 1.6 and section 7 in WEO 2013), which are likely to be low probability possibilities in the nearterm, but may provide large-scale options in the medium to long term.

Batteries for electric Vehicles: The point at which electric cars are expected to become economical and start gaining a market share is when the price of lithium-ion (or equivalent high-performance rechargeable) batteries comes down from the current \$500/kWh to about \$100/kWh. The payoffs of an affordable battery are so large that venture capital is supporting many start-ups with a wide range of technologies. But the technological challenges remain equally large.[43] Large-scale transition to electric vehicles will shift the burden of zero-carbon economy to the electricity generation sector.

A hydrogen economy: If hydrogen can be produced cost-effectively from non-fossil sources (bio-inspired or by electrolysis using inexpensive electrodes and electricity generated by wind and solar systems), then it can be used for both power generation and transport and also for producing hydrocarbons. Achieving such industrial-scale production, however, needs major technological breakthroughs that are unlikely in the near or mediumterm.

Carbon capture and storage (CCS) on gigatonne scale from large point sources such as fossil fuel-fired power plants would allow them to become part of the low-emissions generation mix. For CCS to become the norm, breakthroughs are needed for cost-effective technologies for separation of CO_2 from flue gases emitted by conventional coal and gas-fired power plants and from syngas in case of integrated gasification combined cycle (IGCC) plants. In addition, extensive risk analysis and characterisation of each storage site needs to be done. Even when these hurdles are overcome there will be an economic and environmental cost: The additional cost of CCS is expected to double the cost of electricity even in regions with nearby storage sites and an extensive network of pipelines will need to be built to transport the CO_2.

The fourth, and most likely long-term, innovation is in situ gasification for the utilisation of coal.[44] Breakthroughs in technologies for controlling the underground burn and mitigation of environmental impacts would open up new large resources that would otherwise not be cost-effective. Produced syngas would fuel IGCC power plants, which have lower carbon intensity, and the separation of greenhouse gases from syngas and exhaust gases is easier. The overall environmental impacts of in situ gasification could potentially be less, since production would not involve strip mining or processing of coal, and much less water will be needed. One has to, however, ensure that the many toxic substances such as phenol and heavy metals left behind underground after the burn do not migrate and pollute aquifers. While many countries with large coal reserves/resources such as China, India, South Africa, New Zealand and Australia are pushing such unconventional technologies, especially after the success of deep horizontal drilling and hydraulic fracturing techniques leading to cost-effective production of shale gas and oil, the prospects of their large-scale implementation remain uncertain.

The last technology to highlight is the transmission grid that needs to be modernised and evolved towards a smart grid. The ultimate goal of a smart grid is incorporation of four novel characteristics: Sensors monitoring, in real time, the performance of the grid and energy utilisation along the entire network and at the load; information flow in both directions from control centres to end-users and back; accessible controls at the load to manage demand; and the ability to seamlessly integrate distributed, intermittent and fluctuating generation (solar and wind). Development of smart grids poses technological, financial and social challenges. Low-cost and robust monitors need to be developed for mass deployment at all levels of the grid, of which smart meters are the first step. Control (SCADA) systems to collect, transmit and integrate data securely and process it in real time need to be developed as well as the human resources to manage and operate them. Lastly, the end-users have to allow dispatch centres and utility companies cyber access to their home systems to control load (raising serious legal and emotional issues of privacy, control, accidents and abuse) and to manage demand in exchange for lower rates, which realistically could be much higher than current rates due to the additional instrumentation needed and its management, maintenance and operation. Research and prototype development of these technologies has begun, but large-scale implementation is not expected in the nearterm.

Conclusions

A diverse portfolio of energy sources, supplies and technologies are being pursued by all countries to address their energy security needs and to counter price volatility and possible disruptions in supply. In addition to a discussion of evolving supply and demand, some features common to countries that have large renewable generation and stringent climate change mitigation policies have been abstracted. The key features examined and highlighted in this study include:

Fossil fuels will remain the backbone of energy systems for at least the next 20-30 years. In addition to large conventional reserves of coal, oil and natural gas, there exist extensive unconventional resources. The technologies to exploit them are being steadily developed.

Exports of coal and natural gas are dominated by very few countries. Importing countries seek to establish a diverse portfolio of suppliers, but many have established long-term contracts with one or two suppliers due to geographic or economic benefits. Stable spot market prices and the development of coal ports and LNG terminals allow countries to maintain a larger portfolio of suppliers.

It is unlikely that there will be a significant competitor to oil for transportation in the near or medium term. Gains in efficiency (high mileage cars and hybrids) and an increase in the number of vehicles powered by natural gas will be countered by the increase in the number of vehicles on the roads and total miles driven. Significant penetration by electric cars is unlikely in this same time period. Thus, oil producing companies and exporting countries do not see a threat to their market in the near or mediumterm.

Countries that earn a significant fraction of their revenues from the export of oil and gas have not been able to diversify their economies.

The success of shale gas and oil in the US and Canada is unlikely to be duplicated in other countries in the short term. China is the most likely country to make the investments in the short run. It, however, needs to develop the required infrastructure and partner with international companies to repeat the North American success story. In the near term, new producers (LNG from conventional reserves in Australia, Tanzania and Mozambique and pre-salt oil from Brazil) are best poised to help meet the growing demand.

The future of nuclear power remains very uncertain. Most of the growth is projected to be in four countries – China, India, Russia and South Korea – with state owned or supported nuclear power companies. Many more countries, such as the UAE, Turkey, Vietnam and Egypt, are on their way to joining the nuclear club, raising additional concerns of safety and security.

There continue to be steady incremental improvements in energy efficiency, both in energy generation and in use. As a result, developed nations with stabilised populations and peaked primary energy demand are reducing their energy usage, energy intensity and carbon footprint.

The installation and integration of wind and solar systems without government subsidies is a very significant addition to the cost of electricity due to the capital costs, needed enhancements to the grid and the cost of backup. With backup provided by existing hydroelectric and gas turbines, countries can generate up to about 30 percent of the electricity from wind and solar but at a higher average cost of about $0.35/kWh. Lifecycle cost analyses of fossil fuel-based generation show that this is the true cost of electricity and that current rates are cheaper only because external costs (pollution, climate change and environmental impacts) have not been adequately accounted for.

Countries with very favourable incentives for the development of wind and solar power, for example Denmark and Germany, have attained significant capacity. For these to be sustainable without subsidies, the public has to be willing to pay a higher tariff for electricity, which it seems to be.

Countries which generate a large fraction of their electricity from wind and solar (for example, Denmark and Germany) are part of a larger grid and have active trade in electricity with their neighbours that significantly helps balance supply and demand. A well-connected grid, large reservoir-based hydroelectric generation and gas turbine-based generation capacity facilitates the integration of utility-scale solar and wind plants. Such integrated systems provide a credible path for evolution to zero-carbon systems.

Industrialised countries have overbuilt capacity of power generation spread over multiple fuel sources. This excess capacity provides resilience against volatility in price of fossil fuels and against disruptive consequences of disasters such as Fukushima in 2011. Developing countries do not have this flexibility, as demand exceeds supply by a large amount. Developing new capacity is already limited by the cost of the plant and the investment required to build and maintain the enabling infrastructure and the human resources. Developing the human resources to operate and maintain increasingly complex integrated systems is essential and takes significant time. They need technical and financial assistance to attain energy security and develop low-carbon systems.

The world is faced with an enormous challenge – to provide the anticipated nine billion people with 21st century opportunities in an environmentally responsible and sustainable manner. While technological innovations are the default hope, social responsibility and lifestyle changes leading to efficient use of resources have an equally large role to play. Nature is being pushed to, and in many cases beyond, limits of sustainability. The impacts are long term, and in many cases, such as loss of species and desertification, are irreversible. The decisions made in this century will impact life on earth for centuries to come.

Endnotes

1. *Jan Steckel et.al. "Development without energy? Assessing future scenarios of energy consumption in developing countries", Potsdam Institute of Climate Impact Research, http://www.pik-potsdam.de/members/steckel/publications/development_energy_new.*
   IIASA [International Institute for Applied System Analysis, "Global Energy Assessment", Chapter 2 presentation slides, http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter2.pdf.
2. *United Nations, "The Kyoto Protocol", http://unfccc.int/kyoto_protocol/items/2830.php.*
3. *IEA [International Energy Agency], "World Energy Outlook 2013 Factsheet", 2013, http://www.iea.org/media/files/WEO2013_factsheets.pdf.*
4. *REN21 Renewable Energy Policy Network for the 21st Century, "Renewables Global Status Report 2013", 2013, http://www.ren21.net/portals/0/documents/resources/gsr/2013/gsr2013_lowres.pdf .*
5. *IEA [International Energy Agency], "World Energy Outlook 2014", 2014, p. 351.*
6. *Statoil, "Energy Perspectives: Long-term macro and market outlook", June 2013, http://www.statoil.com/no/NewsAndMedia/News/EnergyPerspectives/Downloads/Energy%20Perspectives%202013.pdf.*
7. *BP, "Statistical Review of World Energy 2013", \http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf.*
8. *EIA [U.S. Energy Information Administration], "Quarterly Coal Report", Release Date: Oct. 08, 2014, http://www.eia.gov/coal/production/quarterly/.*
9. *Randy Schnepf and Brent D. Yacobucci, "Renewable Fuel Standards (RFS): Overview and Issues", Congressional Research Service, 2013, http://www.fas.org/sgp/crs/misc/R40155.pdf.*
10. *Worldometers, http://www.worldometers.info/cars/.*
11. *EIA [U.S. Energy Information Administration], "Recent production growth from presalt resources increases Brazil's total crude output", Today in Energy, Nov. 13, 2013, http://www.eia.gov/todayinenergy/detail.cfm?id=13771.*
12. *UITP, http://www.uitp.org/; UNEP, http://www.unep.org/transport/.*
13. *Government of Norway, "The Government Pension Fund", http://www.regjeringen.no/en/dep/fin/selected-topics/the-government-pension-fund.html?id=1441.*
14. *EIA [U.S. Energy Information Administration], "UAE country report", http://www.eia.gov/countries/cab.cfm?fips=TC.*
15. *Dolphin Energy, "The Dolphin natural gas pipeline, Qatar Operations", http://www.dolphinenergy.com/en/13/operations/qatar-operations.*
16. *Angela Neville, "Top Plant: Emirates Aluminium Smelter Complex (EMAL), Al-Taweelah, Abu Dhabi, United Arab Emirates", Powermag, Jan. 9, 2011, http://www.powermag.com/top-plantemirates-aluminum-smelter-complex-emal-al-taweelah-abu-dhabi-united-arab-emirates/?pagenum=1.*
17. *Reuters, "Saudi could see budget deficit next year, risks draining reserves –IMF", Sep. 14, 2014, http://www.reuters.com/article/2014/09/24/imf-saudi-budget-idUSL6N0RP47K20140924.*
18. *D.K. Das, "Issues facing US Shale Gas exports to Japan", Pipeline and Gas Journal (Dec. 2011), http://pipelineandgasjournal.com/issues-facing-us-shale-gas-exports-japan.*
19. *GIIGNL, http://www.giignl.org/publications.*
20. *Reuters, "Many European LNG Terminals face idling, seek new activities", Sep. 20, 2013, http://www.reuters.com/article/2013/09/20/energy-lng-europe-idUSL5N0HF3KD20130920.*
21. *ARI [Advanced Resources International], EIA/ARI World Shale Gas and Shale Oil Resource Assessment, 2013, http://www.adv-res.com/pdf/A_EIA_ARI_2013%20World%20Shale%20Gas%20and%20Shale%20Oil%20Resource%20Assessment.pdf]*
22. *David Jolly, "France upholds ban on hydraulic fracturing", The New York Times, Oct. 11, 2013, http://www.nytimes.com/2013/10/12/business/international/france-upholds-fracking-ban.html.*
23. *PlattsMcgraw Hill Financial, "Argentina's Shale Gas holds promise, but better policies needed", Experts", September 25, 2013, accessed January 11, 2014,http://www.platts.com/latest-news/natural-gas/washington/argentinas-shale-gas-holds-promise-but-better-21607352.*
24. *Jennifer Tomsen and Marc Davies, "Shale Gas in Asia: Significant Reserves, Substantial Challenges", Bloomberg Law, November 1, 2014, accessed January 11, 2015, http://about.bloomberglaw.com/practitioner-contributions/shale-gas-in-asia-significant-reserves-substantial-challenges/.*
25. *The Federation of Electric Power Companies of Japan, "Graphical Flipchart of Nuclear & Energy Related Topics", 2013, http://www.fepc.or.jp/english/library/graphical_flip-chart/__icsFiles/afieldfile/2013/06/13/all_english_2013_r1.pdf.*

26. *This overbuilt capacity is much larger than required for scheduled and unscheduled outages and maintenance.The exact amount as a function of the share of renewable generation remains to be determined.*
27. *BMU [The Federal Environment Ministry, Germany], "Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global", Schlussbericht BMU - FKZ 03MAP146, DLR, IWES and IFNE, 29. März 2012, http://www.fvee.de/publikationen/publikation/?sb_damorder%5Buid%5D=4636&cHash=06b2c3f1ab6b2757a44b77db72802b87 .*
28. *Reuters, "E.ON's Irsching plant in Bavaria to stay open – sources", April 25, 2013, http://www.reuters.com/article/2013/04/25/germany-eon-irsching-idUSL6N0DC47N20130425.*
29. *RWE, "Forward Looking Statement(as of November 2014"), http://www.rwe.com/web/cms/mediablob/en/2620794/data/2620914/4/rwe/investor-relations/results-for-the-first-three-quarters-2014/RWE-Presentation-Q1-Q3-2014.pdf , Timera Energy, "A tough spread environment", http://www.timera-energy.com/commodity-prices/a-tough-spread-environment/.*
30. *Bloomberg, "German Power-Price Swings Threaten Growth Engine: Energy Markets", R. Morison and J. Mengewein, Oct. 16, 2013, http://www.bloomberg.com/news/2013-10-16/german-power-price-swings-threaten-growth-engine-energy-markets.html.*
31. *Reuters, "German cabinet set to approve flagship renewable energy reform", M. Wacket, April 7, 2014, http://in.reuters.com/article/2014/04/07/germany-energy-idINL6N0MZ3EL20140407.*
32. *ISE [Fraunhofer Institute for Solar Energy Systems], Electricity production from solar and wind in Germany in 2013, Bruno Burger, (as of January 2014).*
33. *EIA [U.S. Energy Information Administration] ,http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3.*
34. *EIA [U.S. Energy Information Administration], "Annual Energy Outlook 2013"; http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf*
    OpenEI [Open Energy Information], "Transparent Cost Database", http://en.openei.org/apps/TCDB/.
35. *EIA [U.S. Energy Information Administration], "Brazil country report", http://www.eia.gov/countries/cab.cfm?fips=BR.*
36. *Bloomberg, "Brazil Seeks Higher Power-Auction Rate to Spur Use of Coal, Gas", St. Nielsen, April 13, 2013, http://www.bloomberg.com/news/2013-04-12/brazil-seeks-higher-power-auction-rate-to-spur-use-of-coal-gas.html.*
37. *Hydrocarbons-technology.com, "The Southeast Northeast Natural Gas Pipeline, Brazil", http://www.hydrocarbons-technology.com/projects/southeastnortheastga/.*
38. *Denmark.dk [The Official Website of Denmark], "Wind energy", http://denmark.dk/en/green-living/wind-energy/.*
39. *IEA [International Energy Agency], "Energy Policies of IEA Countries, Denmark", 2011 Review, http://www.iea.org/publications/freepublications/publication/Denmark2011_unsecured.pdf.*
40. *For example, the delays in the construction of the EPR reactors Olkiluoto-III (Finland) and Flamanville-III (France) by Areva.*
41. *European Commission, DG Energy, "Quarterly Report on European Electricity Markets", Volume 6 (July 2014).*
42. *Timera Energy, "Commercial Implications of the UK Capacity market", http://www.timera-energy.com/uk-power/commercial-implications-of-the-uk-capacity-market/.*
43. *See some examples of challenges to development of batteries for electric cars here: JCSER [Joint Center For Energy Storage Research], "Scientific and Technical Need", http://www.jcesr.org/research/technical-summary/.*
    DoE [U.S. Department of Energy], "Batteries for Advanced Transportation Technologies (BATT) Program", http://batt.lbl.gov/home/.
    Kevin Bullis, "For Tesla Motors, Success Is All About the Batteries", in: MIT Technology Review, Nov. 6, 2013, http://www.technologyreview.com/view/521201/for-tesla-motors-success-is-all-about-the-batteries/.
44. *E. Burton, J. Friedman and R. Upadhye, "Best practices in underground coal gasification", draft, Lawrence Livermore National Laboratory, https://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/BestPracticesinUCG-draft.pdf*