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Traversing the mountaintop: world fossil fuel production to 2050

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During the past century, fossil fuels—petroleum liquids, natural gas and coal—were the dominant source of world energy production. From 1950 to 2005, fossil fuels provided 85–93% of all energy production. All fossil fuels grew substantially during this period, their combined growth exceeding the increase in world population. This growth, however, was irregular, providing for rapidly growing *per capita* production from 1950 to 1980, stable *per capita* production from 1980 to 2000 and rising *per capita* production again after 2000. During the past half century, growth in fossil fuel production was essentially limited by energy demand. During the next half century, fossil fuel production will be limited primarily by the amount and characteristics of remaining fossil fuel resources. Three possible scenarios—low, medium and high—are developed for the production of each of the fossil fuels to 2050. These scenarios differ primarily by the amount of ultimate resources estimated for each fossil fuel. Total fossil fuel production will continue to grow, but only slowly for the next 15–30 years. The subsequent peak plateau will last for 10–15 years. These production peaks are robust; none of the fossil fuels, even with highly optimistic resource estimates, is projected to keep growing beyond 2050. World fossil fuel production *per capita* will thus begin an irreversible decline between 2020 and 2030.

Keywords: coal; fossil fuels; natural gas; peak fuel production; petroleum liquids; production scenarios

1. INTRODUCTION

As we near the end of a decade dominated politically by talk about renewable energy, emphasizing the role of fossil fuels in world energy production might seem totally perverse. However, the reality is that fossil fuels—petroleum liquids, coal and natural gas—have been the overwhelmingly dominant source of energy production for the world economy in the past century (table 1). Since 1950, the share of world energy production provided by fossil fuels has varied only slightly between 85 and 93 per cent. Moreover, from 2000 to 2005—the 5-year period with the largest *absolute* increase ever in world energy production—fossil fuels accounted for nearly 92 per cent of that increase. Fossil fuels are clearly not *passé*; they still provide nearly all of world energy production and increases to that production.

Growth in total energy production has been propelled by growth in fossil fuel production. From 1950 to 2005, energy production worldwide grew 571 per cent from 68.6 to 460.1 quadrillion Btu (quads). Fossil fuel production grew almost as rapidly, rising 521 per cent from 63.9 to 396.8 quads. Among the fossil fuels, growth varied widely during this period. Natural gas production was the star, increasing 1383 per cent from only 7.1 to 105.3 quads. Petroleum liquids production also grew faster than overall energy production, growing 633 per cent from 23.1 to 169.3 quads. Coal was the only laggard during the past half century, rising only 263 per cent from 33.7 to 122.2 quads. But even coal has shown new life recently; from 2000 to 2005, it provided half of the increase in world energy production.

During the past 55 years, these different growth rates by fuel source have changed the composition of world energy production considerably. Most of those changes have occurred among the fossil fuels. At the middle of the twentieth century, coal was clearly king, providing nearly 50 per cent of world energy production. In 1961, coal lost its leading role to petroleum liquids. By 2000, coal's share of total energy production had plummeted to 22.8 per cent. However, with the recent resurgence in coal production, its share has rebounded to 26.6 per cent in 2005. The share of petroleum liquids in world energy production grew rapidly during the 1950s and 1960s, reaching half of all energy production in 1973. But when production of petroleum liquids languished during the 1980s, their share dropped back just below 40 per cent, a level that remained largely unchanged until the present decade. From 1950 to 1985, the share of natural gas in world energy production doubled, rising from just over 10 per cent to just over 20 per cent. Since 1985, its share has remained in the 21–23% range. The share of other energy sources, principally hydroelectric power and nuclear electric power, has also doubled, growing from 6.9 per cent in 1950 to 13.8 per cent in 2005. The share of world energy production provided by biomass, geothermal, solar and wind did not exceed 1.5 per cent of world energy production until 2006, even after rapid growth in the past two decades.

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Table 1. World primary energy production by source, 1950–2005 (quads). Adapted from Energy Information Administration (2008), Mitchell (2000*a*,*b*,*c*) and Salvador (2005).

year	petroleum liquids	natural gas	coal	other[a]	total
1950	23.1	7.1	33.7	4.7	68.6
1960	46.7	17.2	48.0	8.7	120.6
1970	100.3	38.3	54.4	15.2	208.2
1980	133.1	54.7	71.3	28.5	287.6
1985	121.2	64.2	82.3	39.6	307.3
1990	136.2	75.9	91.0	46.7	349.8
1995	141.8	80.3	88.5	53.3	363.9
2000	156.5	91.3	90.4	58.1	396.3
2005	169.3	105.3	122.2	63.3	460.1

[a]Other is predominantly (approx. 90%) hydroelectric power and nuclear electric power.

Table 2. World primary energy production *per capita*, 1950–2005. Adapted from energy production—table 1 of this paper. Population—Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (http://esa.un.org/unpp/p2k0data.asp).

	energy production			*per capita* production	
year	fossil fuels (quads)	all sources (quads)	world population (billions)	fossil fuels (million Btu)	all sources (million Btu)
1950	63.9	67.6	2.54	25.2	26.6
1960	111.9	119.1	3.03	36.9	39.3
1970	193.0	206.2	3.70	52.2	55.7
1980	259.1	287.6	4.45	58.2	64.6
1985	267.7	307.3	4.86	55.1	63.2
1990	303.1	349.8	5.29	57.3	66.1
1995	310.6	363.9	5.72	54.3	63.6
2000	338.2	396.3	6.12	55.3	64.8
2005	396.8	460.1	6.51	61.0	70.7

From 1950–1980, the growth in fossil fuel production and all energy production exceeded world population growth (table 2). Consequently, energy production *per capita* grew 143 per cent from 26.6 to 64.6 million Btu per person (approx. 4.5 to 11.0 barrels of oil equivalent *per capita*). Although energy production continued to grow from 1980 to 2000, it only kept abreast of growth in world population during these two decades. Fossil fuel production *per capita* actually declined 5 per cent during this period. Total energy production *per capita* resumed increasing after 2000 only because of rapidly growing fossil fuel production (which accounted for 98 per cent of the *per capita* increase for 2000–2005).

World population is projected to increase from 6.51 billion in 2005 to 7.79–10.76 billion in 2050. This paper examines whether fossil fuel production can continue to grow to meet the energy demand of this increasing population, even to the extent of increasing production *per capita*, or whether fossil fuel production *per capita* will enter a period of continuous decline, necessitating a major transformation in the world energy economy. It addresses these questions by evaluating the outlook for future production of each of the three fossil fuels—coal, natural gas and petroleum liquids. Because forecasting fossil fuel production in the twenty-first century has several methodological problems, the paper begins with a discussion of these methodological issues prior to the discussion of the outlook for each fossil fuel.

2. FORECASTING FUTURE FOSSIL FUEL PRODUCTION: METHODOLOGICAL CONSIDERATIONS

Forecasting future fossil fuel production may seem like a straightforward task. Because comprehensive energy production forecasting has been occurring for over 30 years, it is commonly assumed that the problems of such forecasting are well understood, that a strong consensus exists regarding the basic assumptions all forecasters should use and that forecasting methods are well established and considered to be highly reliable. The primary problem for forecasting fossil fuel production over the first half of the twenty-first century is that none of these commonplace assumptions still apply.

Energy forecasting is currently in a state of flux because the energy system it forecasts is in a state of flux. During the early decades of the twenty-first century, the world will be transitioning from an energy system driven by changes in demand to one driven by changes in supply, particularly fossil fuel supplies. Since the beginning of large-scale energy system modelling in the 1970s, energy forecasting models have been demand driven. This choice of model drivers accurately reflected the basic fact of the time that fossil fuel production capacity exceeded fossil fuel demand. Thus, if production was to grow, demand had to grow first. Growth in energy demand was furthermore seen as a function of growth in economic activity.

Excess capacity, particularly for petroleum liquids—the largest source of world energy supplies—has now largely disappeared. The primary forecasting problems are thus how much, at what rate and even whether fossil fuel production will continue to increase.

In this increasingly supply-constrained world, energy demand still persists as a crucial driver. But it does so with a major change in emphasis. Previously, the emphasis has been on changes in energy demand as determined by changes in overall economic activity. In the future, the emphasis will be on changes in energy demand as determined by changes in energy prices.

This change in emphasis is a logical concomitant of the shift to a supply-constrained energy system. Supply only becomes a constraint when the real costs of adding new energy production capacity are steadily increasing. If these resources are to be developed, energy prices must increase.

The primary problem for forecasting here is the high degree of uncertainty regarding the long-term price elasticity of energy demand. Past energy demand grew and the world's energy-using technologies were developed over nearly a century of relatively low energy prices. We do not know how these energy-using technologies will be transformed over the next 40 years, how rapidly these transformative changes will occur and be disseminated, and how patterns of energy-using behaviour will change in response to considerably higher prices. Price-driven changes in energy demand could conceivably, even temporarily, make demand, not supply, the major constraint in many sectors of the energy economy.

The transition to a supply-constrained energy system makes understanding fossil fuel *resources* the essential foundation of a sound forecasting approach. The ultimate level of recoverable resources is the ultimate constraint on supply.

Understanding fossil fuel resources first requires understanding the basic terminology and definitions of in-place resources, ultimate recoverable resources and the various varieties of reserves, and how these definitions are applied (or misapplied) in published energy statistics. It requires an understanding of the methods for estimating fossil fuel resources and the strengths and limitations of each of these methods. Finally, it demands an explicit recognition of uncertainty. The often used concept of the 'best estimate' is a total fabrication by intellects needing certainty. At their best, resource estimators can only establish a defensible range of possibilities.

Understanding fossil fuel resources is not only a matter of understanding resource *quantity*, it is also a matter of understanding resource *quality*. Knowing the composition by relevant categories of each fossil fuel resource is essential to forecasting future production. The distributions of qualitative characteristics within each fossil fuel resource are the principal determinants of its supply curve.

In a demand-constrained world with excess production capacity, the means by which resources are converted to productive capacity are essentially taken for granted. In a supply-constrained world, understanding the means by which resources are converted to producing developed reserves is a crucial component of the forecasting process. In the early twenty-first century, with its very high rates of fossil fuel production, the scale of depletion, particularly of oil and gas resources, creates a particular predicament here. Simply maintaining production requires continuous large annual additions to productive capacity. Knowing the drivers of and the constraints upon the rate of capacity additions is thus a crucial element of the forecasting process.

The subsequent evaluation of the outlook for future production for each of the fossil fuels will follow a common outline. Each will begin with a review of production since 1950 and its geographical composition, examining both changes in overall production and in the geographical composition of that production. Each evaluation will discuss key factors in the reserves and the ultimate recovery of each fossil fuel resource. Each will conclude by developing three projections for production to 2050 that span the realistic range of possibilities and by discussing the key assumptions incorporated into each projection. The methodological considerations just discussed will be incorporated into each evaluation where relevant. The units of measurement used for each fossil fuel will be the most commonly used units internationally: metric tons (tonnes) for coal, cubic metres for natural gas and barrels for oil.

The projections of future supply shown here represent a long-term outlook. Few considerations of short-term supply and demand perturbations are incorporated within them. Actual supply and demand will most probably form an oscillating pattern around these projected supply trajectories.

3. COAL

For the first 60 years of the twentieth century, coal was the dominant source of energy for the world. After 1960, its lead was relinquished to petroleum liquids. In the year 2000, it slipped briefly into the third position, just behind natural gas. But with strong growth since 2000, it is firmly back as the second largest source, providing 26.6 per cent of world primary energy production in 2005.

From 1950 to 2005, world coal production of all grades (anthracite, bituminous, subbituminous and lignite) grew substantially, but irregularly (table 3). From 1950 to 1985, world coal production increased steadily, growing 144 per cent from 1823 to 4450 million metric tons (tonnes). From 1985 to 2000, world coal production essentially stagnated, growing slowly in the late 1980s and declining gradually during the 1990s as natural gas and other sources displaced coal. Since 2000, coal production has grown spectacularly, increasing 42 per cent by 2007.

The irregular growth of world coal production conceals dramatic changes in the composition of production by geographical area. Through 1990, Europe was the dominant coal producing region in the world. Since reaching its peak production level in 1986 at 1353 million metric tonnes, European coal production has nearly dropped in half in the ensuing two decades. Production in the Soviet Union grew steadily to 1990, only to collapse after the breakup of the Soviet Union, dropping more than 50 per cent by 1998. Subsequently, coal *production* in the countries of the former Soviet Union (now Eurasia) has begun a slow, steady rebound. Coal production in the USA, after declining during the 1950s when natural gas replaced coal as the preferred fuel for space heating, has grown steadily ever since with coal continuing as the primary fuel source for electrical power generation.

Growth in world coal production since 1950 is primarily due to major increases in coal production in China, India, and Australia. Since 1950, coal production in each of these three countries has increased by more than an order of magnitude. Combined, they have increased production 30-fold, spearheaded by unprecedented growth in China, particularly since 2000. Since 1970, 85 per cent of the growth in world coal production has come from these three countries. From 2000 to 2007, coal production in China more than doubled, growing more than 10 per cent annually on average. The average *annual absolute increase* in Chinese coal production during these

Table 3. World coal production, 1950–2005 (million tonnes). Adapted from Energy Information Administration (2008) and Mitchell (2000*a*,*b*,*c*).

year	China	other Asia/Oceania	USA	Europe	Eurasia	other	world total
1950	41	111	508	849	261	53	1823
1960	397	176	394	1059	510	60	2596
1970	354	248	518	1098	624	85	2927
1980	621	323	754	1212	718	178	3806
1985	874	449	803	1329	728	267	4450
1990	1082	547	935	1211	802	290	4867
1995	1397	660	939	872	438	336	4642
2000	1195	802	976	756	403	368	4500
2005	2209	1075	1029	702	457	429	5901

7 years—193 million tonnes—is greater than the *annual production* in 2007 of all but six other countries worldwide.

The conventional wisdom is that world coal production will continue to grow over the next several decades. This conventional outlook rests on two key arguments. The first is that recoverable reserves of coal are plentiful, unlike those of petroleum liquids or natural gas. Current estimates of recoverable reserves indicate a worldwide reserve-to-production (R/P) ratio of 143 years (table 4), a level clearly capable of sustaining at least modest growth for half a century. The second key argument is that world coal production has grown substantially (more than 40%) since 2000. Recent growth is believed to be a strong indicator of the potential for future growth.

These two considerations are not the only ones determining the future of world coal production. Other considerations, particularly those regarding the composition of coal reserves and of coal production, are of equal, if not more, importance.

Coal reserves are generally defined as the amount of in-place resources estimated to be recoverable under current economic and technological conditions. Operationally, this is defined by unambiguous limits. Internationally, the standard has been all seams greater than 30 cm thick and less than 1200 m deep. In the USA, the recent standard for reserves is all seams greater than 28 inches (approx. 70 cm) thick for anthracite and bituminous coal and greater than 60 inches (approx. 150 cm) thick for subbituminous coal and lignite. In addition, lignite reserves must be surface mineable and reserves for the other coal ranks must be less than 1000 feet (approx. 300 m) deep. The operational criteria for defining reserves used by different nations obviously incorporate different criteria for economic viability. For example, most current Chinese coal production and reserves occur between 300 and 600 m deep, a depth that would exclude them as reserves in the USA because they would be considered to be economically unrecoverable.

What is usually missing from estimates of coal reserves is a rigorous appreciation of how changes in economics (both prices and costs) and technology could affect reserve estimates. For example, given the distribution of potentially surface-mineable coal resources by both seam thickness and overburden, how would reserves increase or decrease following changes in prices and costs (the latter incorporating changes in technology)? In the latter half of the twentieth century, when coal was facing strong economic competition from oil and gas, such questions could be easily ignored. As prices increase in the twenty-first century, they become increasingly relevant.

Table 4. World production and reserves of coal, 2005 (billion tonnes). Adapted from Energy Information Administration (2008).

country/region	2005 production	2005 recoverable reserves	2005 R/P ratio
China	2.21	114.7	52
other Asia/Oceania	1.07	143.2	134
USA	1.03	239.8	233
Europe	0.73	46.2	63
Eurasia	0.46	226.5	492
other	0.40	75.4	189
world total	5.90	845.8	143

Coal reserves, unlike gas and oil reserves, have not increased over the past several decades. That this should be the case for in-place coal resources is not surprising. Coal resources, by definition, are limited to the shallower (generally 1000–2000 m) portion of sedimentary basins. In nearly all onshore basins of the world, this portion of the sedimentary section has been well known for decades from well cores and well logs. Thus, major discoveries of in-place coal resources are unlikely in the future.

Despite major improvements in coal mining technology over the past half century, world coal reserves have not increased by significant amounts. In at least one major producing region—Europe, the largest coal producing region worldwide up to 1990—reserves actually declined. As of 1966, measured reserves of coal (all ranks) in Europe were approximately 250 billion tonnes. Coal production in Europe from 1967 to 2005 was 41 billion tonnes, which should have left a reserve of 209 billion tonnes. Yet, estimated coal reserves in Europe as of 2005 were only 46 billion tonnes, 78 per cent less than subtraction of recent production from the 1966 reserve estimates would indicate. The largest uncertainty in projecting future world coal production is determining whether such reserve reductions might occur in other regions, or whether reserves could increase given substantial real price increases.

Coal reserves are popularly viewed as an homogeneous entity. Yet there are several major distinctions among coal reserves, the two primary ones being coal rank and mining method. Coals are distinguished by rank, the different ranks being defined by carbon content, volatile matter and heating value. The four ranks used in most coal statistics are, in decreasing order of heating value: anthracite, bituminous, subbituminous and lignite. Differences among ranks are substantial; for example, the heating value of lignite is approximately half that of bituminous coal. Lignite also has the distressing characteristic of combusting spontaneously, a property that makes it unsuitable for rail transport. The low-energy density of lignite means that it is consumed only at or near the mine mouth. Thus, its production is limited by the growth of mine-mouth facilities. Most (80% plus) of the coal reserves of Europe, two-thirds of the coal reserves of Russia and Ukraine and 30 per cent of surface-mineable reserves in the USA are lignite and thus subject to this constraint.

Coal reserves are also distinguished by mining method, depending upon whether they can be mined from the surface or need to be mined underground. Surface-mineable deposits are generally less costly to extract. Thus, where possible, surface mining has tended to grow at the expense of underground mining. The USA provides a good example of this. Reserves of mineable underground coal total 136 billion tonnes, 57 per cent of US coal reserves. But coal mined underground in 2007 amounted to only 319 million tonnes, 31 per cent of US production. (Underground coal mining in the USA peaked 91 years ago in 1918 when 598 million tonnes were mined.) Consequently, the R/P ratio for underground mineable coal is 426 years, nearly triple the 143 years for surface-mineable coal. This comparison illustrates some of the difficulties of converting measured reserves into reserves at producing mines.

Coal production, moreover, as noted earlier, is highly concentrated in a few countries and regions. China is the largest producer, providing 40 per cent of world coal production in 2007. More importantly, China provided 71 per cent of the increase in world coal production from 2000 to 2007. This spectacular increase came at a substantial cost. One major, but little noticed, consequence was that the R/P ratio for coal in China plummeted from 104 in 2000 to just 43 in 2007.

The state of Wyoming in the USA produced nearly 40 per cent of US coal in 2007 (410 of 1042 million tonnes). Production in Wyoming increased by 245 million tonnes from 1990 to 2007, compared with a 138 million tonne decrease in production throughout the rest of the USA. But by 2007, stated recoverable reserves of surface-mineable coal in Wyoming were only 15.2 billion tonnes, yielding a R/P ratio of only 37. These two areas—China and Wyoming, which provided 46 per cent of world coal production in 2007 and 77 per cent of the increase in world coal production from 2000 to 2007—have only 35–45 years of production at current rates of production and levels of reserves.

Forecasting future world coal production is a complex task, incorporating considerations of the amounts and the qualities of known and projected coal reserves, the ability to increase coal production capacity and the growth of coal demand. Because the relative importance of these considerations varies among countries and regions, the following forecasts are an aggregation of nine separate forecasts for China, India, Australia, other Asia, Wyoming and Montana surface mining, other USA, Europe, Eurasia (the former Soviet Union) and other (Africa and the Western Hemisphere less the USA). Excluding the very large production from China and the small production from other Asia, the remaining seven areas begin with roughly similar production levels (400–700 million tonnes per year).

Because there is substantial uncertainty regarding the considerations governing future coal production, three cases were developed to illustrate this range of uncertainty. The key differences among the cases are described in the following discussions of the key assumptions used in the forecast for each area. The three cases—low, medium and high—correspond approximately to subjective probability levels of 95, 50 and 5 per cent, respectively.

Future Chinese production is dominated by the amount of coal reserves China has, and can add by 2050. The three cases assume Chinese reserves and reserve additions of 120, 172 and 230 billion tonnes, respectively. These correspond to current (2007) reserves (with future additions being offset by losses from extensive coal mine fires), a 50 per cent increase over current levels and a 100 per cent increase over current levels. The medium- and high-case reserves roughly bracket what some Chinese sources have indicated to be their ultimately recoverable reserves of coal. All cases assume a slowing rate of increase in production until a peak is reached in 2015, 2025 and 2030, respectively, followed by a 5-year plateau and subsequent decline.

Future coal production through 2050 in both India and Australia is likely to be constrained only by the growth in market demand and by each nation's ability to increase production capacity continuously. All three scenarios assume slow rates of growth (1.5–2.5% per year) that decrease slightly after 2035. In sharp contrast, production elsewhere in Asia is so reserve-constrained that it can only decline continuously to 2050.

Future coal production in the USA will be determined primarily by the level of surface production of coal in Wyoming and Montana (Luupens *et al.* 2008). Instead of the current estimate of recoverable reserves for Wyoming, these projections use the estimates of coal resources in the Powder River Basin recently published by the US Geological Survey (Luupens *et al.* 2008), calculated to be recoverable at a cost of \$20, \$30 and \$40 per short ton (30.8, 54.0 and 61.1 billion tonnes, respectively). At these levels of resources, production of surface-mineable coal in Wyoming and Montana is projected to grow 1–2% annually to 2030 in all cases before reaching a peak

Table 5. Projected world production of coal, 2010–2050 (million tonnes).

year	low	medium	high
2010	6835	6835	6835
2015	7337	7468	7638
2020	7518	8021	8464
2025	7186	8441	9222
2030	6696	8705	9859
2035	6300	8415	10 363
2040	5973	7882	10 088
2045	5716	7528	9597
2050	5538	7334	9367
cumulative, 2006–2050	296 766	349 117	399 888

plateau in 2030 (low), 2035 (medium) and 2050 (high). In the low case, production declines slowly (approx. 1% year) after 2035. Production from surface mining in other states and from all underground mining is expected to stabilize by 2010 and (in the medium and high cases) begin a slow increase after 2020.

Production in Europe is projected to decline into the 2020s in all cases. With assumed higher prices, the medium and high cases for Europe assume stabilization during the 2020s and slow increases thereafter as former reserves are brought back into production. Production in the countries of Eurasia is expected to increase slowly but at declining rates, being limited primarily by the growth of their national markets. Because of projected population declines, production is expected to level out by 2030–2040 in the low and medium cases. Production in other countries (Africa and the Western Hemisphere excluding the USA) is projected to increase slowly throughout the period, primarily to meet the needs of national markets.

All three cases show world coal production peaking within the next 30 years (table 5). By case, production peaks in 2015 (low), 2030 (medium) and 2035 (high). These peak levels are only 18, 36 and 62 per cent more than 2007 production of 6397 million tonnes.

The most significant aspect of these scenarios is not the peaking of world coal production, but the immense amounts of coal estimated to be produced in the 45 years from 2006 to 2050. Cumulative production for this period is estimated at 297 (low), 349 (medium) and 400 (high) billion tonnes. By comparison, all of the coal produced worldwide in more than two centuries of coal production through to 2005 was only 287 billion tonnes, an amount exceeded by even the low projection of 2006–2050 production. Compared with remaining reserves of coal as of 2005 plus postulated additions to reserves to 2050, these cases predict that coal production from 2006 to 2050 will use up 34–40% of currently remaining ultimate world coal reserves.

Because China currently dominates world coal production, the path of future world coal production will be dominated by the path of Chinese coal production. When Chinese coal production peaks, world coal production peaks as well. The story of world coal production after 2025 is essentially the story of the struggle to replace stabilized and then declining Chinese coal production. By 2050, 75–85% of current Chinese coal reserves (including all the published additions to reserves by 2050) will have been produced. Thus, declining world coal production throughout the second half of the twenty-first century will be inevitable.

4. NATURAL GAS

World natural gas production grew spectacularly from 1950 to 2005, doubling nearly four times (table 6). Its growth was most rapid from 1950 to 1970, when it increased more than 430 per cent. Since 1970, world natural gas production has grown continuously, not undergoing any of the temporary declines in production that characterized oil during the early 1980s and coal during the 1990s. Underlying this pattern of continuous overall growth were major changes in the regional composition of natural gas production. During the latter half of the twentieth century, natural gas, compared with the other fossil fuels, best illustrated the constraints of demand on production.

In 1950, world natural gas production was essentially North American (specifically USA) production, the only locus for significant gas demand worldwide. In that year, North American production was 91 per cent of world production. By 1970, North American production was still two-thirds of world production. But after peaking in 1972, the North American share of world gas production has declined to less than 25 per cent by 2005, despite rebounding substantially from its 1985 low.

Other regions first emerged as significant sources of production beginning in the 1960s. The first of these was the Soviet Union where production grew by more than two orders of magnitude from 1950 to 1990. By the early 1980s, the Soviet Union became the foremost gas-producing region of the world, a position it has held ever since, except for a few years around 2000. Europe was the next region to emerge, growing first with the initiation of major production from the supergiant Groningen (Schlocteren) gas field in the Netherlands and subsequently from the expansion of gas production in the North Sea. During the 1980s, its production declined, followed by a slow rebound ever since.

Production in the other four regions did not reach significant levels until the 1980s and 1990s. Internal markets were not large; both the intra-regional and the inter-regional gas trade were limited. Since 1990, both the Asia/Pacific region and the Middle East have emerged as significant natural-gas-producing regions, each providing more than 10 per cent of world supply. The Asia/Pacific region is characterized by both growing internal demand and intra-regional trade, primarily from Australia and Indonesia to China and Japan. The Middle East is characterized by both rapidly growing internal demand and inter-regional trade, essentially to Asia and Europe. In both cases, growing production depended upon the

Table 6. World natural gas production by region, 1950–2005 (billion cubic metres). Adapted from Energy Information Administration (2008) and Mitchell (2000*a*,*b*,*c*).

year	USA/Canada	Eurasia	Europe	Asia/Pacific	Middle East	Latin America	Africa	world total
1950	178	6	5	2	0	5	0	196
1960	375	45	24	5	3	14	0	466
1970	691	193	88	16	20	31	3	1042
1980	628	435	259	69	40	60	19	1511
1985	552	643	260	113	67	78	53	1767
1990	614	815	244	158	105	83	70	2088
1995	684	705	279	216	141	100	85	2213
2000	726	715	311	272	214	137	126	2505
2005	697	816	323	368	317	181	173	2876

development, refinement and widespread adoption of liquefied natural gas technology.

Production of natural gas in Latin America and Africa has grown more slowly. Latin American production has been constrained by slow growth in both internal demand and intra-regional trade. Production in Africa has been constrained by slow growth in inter-regional trade and competition from other gas-exporting regions.

Sharp differences in the development of natural gas demand and its subsequent consequences for production have created a noticeable bifurcation among the gas-producing regions (table 7). In those regions with a long history of substantial internal demand (USA/Canada and Europe), cumulative production exceeds reserves and, at least for the low estimate, approaches half of the estimated ultimate recovery. In those regions with a short history of internal demand (all the rest), cumulative production is half or less of current reserves and less than a quarter of ultimate recovery. This bifurcation has major implications for the future regional composition of world gas production.

There are significant differences in the distribution of world gas resources among regions. As of the end of 2005, known world gas resources are estimated at 246.1 trillion cubic metres (Tcm) (table 7). Ultimate resources of natural gas, ranging from 356 to 571 Tcm, are 45–132% higher than known recovery. Three regions—Europe, Africa and Latin America—each have only 4–8% of world ultimate recovery (and only 14–18% of ultimate recovery combined). Asia/Oceania has 11–12% of world ultimate recovery. The USA and Canada, with 42 per cent of world cumulative production, has only 20–22% of world ultimate recovery. The Middle East and Eurasia dominate world natural gas resources. The Middle East has 26–28% of ultimate recovery; Eurasia (predominantly Russia) has 24–25%.

The differences in gas resource endowments among regions are largely explained by differences in the regional distribution of *supergiant* gas fields. Put simply, the Middle East and Eurasia have substantial numbers of these fields; the other regions do not. Supergiant fields are defined as fields with an ultimate recovery of at least 1 Tcm of gas. There are 10 supergiant gas fields in the Middle East with a combined estimated ultimate recovery of 55–60 Tcm. Another six large giant gas fields (with 0.5–1.0 Tcm ultimate recovery apiece) provide another 4.4 Tcm. Thus, approximately 80 per cent of the known gas recovery of the Middle East is concentrated in these 16 superlative fields.

One Middle East field deserves special mention. The North (Qatar)/South Pars (Iran) field is the greatest single gas accumulation in the world with an estimated 35–40 Tcm known recovery. It is thus the only *megagiant* gas field (a field with a known recovery in excess of 10 Tcm). This one field contains approximately half of the known recovery of natural gas in the Middle East and a staggering 14–16% of world known recovery. Its ultimate resources are in excess of the ultimate resources of three of the other six gas-producing regions worldwide. There are 12 supergiant gas fields in Eurasia, eight of which are in western Siberia. Together, these 12 fields have a known recovery of approximately 35 Tcm. Another dozen fields between 0.5 and 1 Tcm added another 8.3 Tcm to Eurasian known recovery. Together these 24 fields provide more than 60 per cent of Eurasian known gas recovery.

In sharp contrast to this high concentration of resources in a handful of fields, the other five regions combined have only seven supergiant fields and only six large giant gas fields. Together, these 13 fields contain 16 Tcm, only 16 per cent of the known recovery of gas in these five regions. The USA and Canada, the only other major gas-producing region in the world, have obtained most of their known recovery from several hundred 15–300 billion cubic metre fields.

Historically, natural gas production has come from what are termed *conventional* reservoirs. Since 1990, gas produced from *unconventional* reservoirs has emerged as a significant source of potential natural gas resources. Unconventional gas resources are generically defined as gas from poor-quality reservoirs, mainly reservoirs with low matrix permeability (permeability measures the ability of fluids to move through reservoir rock). The four major categories of unconventional reservoirs are listed in a declining order of importance: shale gas, tight (i.e. low permeability) sandstones, coalbed methane and tight carbonates.

Unconventional gas resources tend to be developed only when conventional resources are inadequate to meet gas demand. Thus, they are highly developed in the USA and Canada where they currently provide

Table 7. Cumulative production, reserves and estimated ultimate recovery of natural gas by region (Tcm as of 31 December 2005). Adapted from Energy Information Administration (2008) and Ahlbrandt *et al.* (2005); author's estimates and adjustments.

region	cumulative production	reserves	estimated ultimate recovery
USA/ Canada	33.20	7.39	75–95–115
Eurasia (FSU)	22.20	48.80	90–105–140
Europe	9.60	5.69	18–22–26
Asia/ Oceania	5.17	11.09	40–50–65
Middle East	3.34	73.01	100–120–150
Africa	1.84	13.76	20–26–36
Latin America	3.46	7.56	14–21.5–39
world	78.81	167.30	357–440–571

half of gas production. More than 80 per cent of the additional potential of natural gas in this region comes from unconventional sources. They could be significant in Europe, given Europe's declining conventional production, but major unconventional resources appear to be lacking in that region. During the next 40 years, unconventional potential is likely to be developed in significant amounts in Asia/Oceania, such as coalbed methane in Australia, China, India and Indonesia and possibly tight sandstones in China. Although the geological potential for unconventional resources appears to be substantial in Eurasia, the Middle East and North Africa, such resources are unlikely to be developed in the early twenty-first century, simply because conventional potential is so great relative to current and projected production that unconventional gas resource development is unnecessary.

Forecasting future world natural gas production requires careful differentiation among regions. In Europe, future production will be constrained primarily by the level of ultimate resources and the rate at which they can be developed. In USA/Canada and Asia/Oceania, production is projected to transition from being demand-constrained to being resource-constrained between 2015 and 2050, the timing of this transition depending on the ultimate gas resources in each region. In the other four regions, production is constrained primarily by growth in market demand and secondarily by the rate of development of production and transportation capacity. The following forecasts are thus an aggregation of seven separate forecasts for USA/Canada, Eurasia, the Middle East, Africa, Asia/Oceania, Europe and Latin America. Each separate forecast incorporates the considerations most relevant to that region.

Like coal, three scenarios of future production were developed to illustrate the range of uncertainty. These three scenarios—low, medium and high—correspond approximately to subjective confidence levels of 95, 50 and 5 per cent, respectively. The major differences among the cases are described in the following discussions of the outlook for each region.

Because of the potential of unconventional gas resources, production in the USA/Canada is expected to grow initially. The timing of the peaking of production and the level at which gas production will peak depends on the size of unconventional potential, particularly that of shale gas. (Estimates of shale gas potential vary from 22 to 55 Tcm.) Because the range of remaining potential is great, the timing of peaks varies widely as well, from the 2020s (low) to the 2030s (medium) to the 2040s (high). Production at the peak varies from just 16 (low) to 64 per cent (high) above 2007 production. In the low case, production declines substantially by 2050.

Because of the vast gas reserves of Eurasia, production is expected to increase to at least the early 2030s, and possibly beyond 2050. Production increases will however occur at a slow rate, generally 0.5–1.5% annually, largely because of the difficulties of developing gas resources on the Yamal Peninsula and in the Arctic seas. In all cases, Eurasia is the dominant producing region in the world until it is overtaken by the Middle East in the middle 2030s. Production is estimated to increase between 22 (low) and 54 per cent (high) above 2007 levels before reaching its peak.

Because Middle East reserves are so large relative to current production, no declines are predicted in Middle East production prior to 2050. (In the low case, production is expected to stabilize by the 2040s at a level roughly three times 2007 production, primarily because of political decisions to maintain production at high levels for the remainder of the century.) Growth is constrained primarily by the rate of growth in Asian and European export markets and secondarily by the rate at which production and transportation capacity can be developed. By 2050, the Middle East is projected to provide 30–40% of world gas production.

Production in Asia/Oceania is projected to peak between the late 2020s (low) and 2040s (high), primarily because of the extensive development of unconventional gas resources during the next three decades. Production is expected to peak between 37 and 109 per cent above 2007 levels. Because cumulative production of natural gas in Europe is already approximately half of estimated ultimate resources, in all cases gas production is expected to decline more or less continuously in that region to 2050. The only substantial uncertainty is the rate of decline.

The major constraint on the growth of African gas production is expected to be competition with Middle East and Eurasian gas producers for Asian and European gas markets. Because the growth rate in production is expected to vary (generally ranging from 2 to 4%), African gas production is projected to peak at roughly the same time (2035–2045) in all three cases before declining slowly thereafter. Production in Latin America is projected to grow slowly (1.5–3.0% per year), growing primarily to supply internal and intra-regional markets. Peaks are likely to occur between the early 2020s (low) and the late 2040s (high).

Table 8. Projected world production of natural gas, 2010–2050 (Tcm).

year	low	medium	high
2010	3.10	3.13	3.15
2015	3.36	3.44	3.54
2020	3.59	3.82	4.01
2025	3.79	4.14	4.52
2030	3.92	4.46	4.95
2035	3.91	4.68	5.38
2040	3.75	4.81	5.60
2045	3.45	4.76	5.81
2050	3.14	4.55	5.87
cumulative (2006–2050)	159.47	185.10	208.20
all-time cumulative	238.27	263.91	287.01

World gas production is projected to grow substantially beyond 2005 levels before reaching its ultimate peaks (table 8). Peak production is estimated to be 136 (low), 167 (medium) and 204 per cent of 2005 production. Natural gas is thus expected to take market share from oil and coal during the next 40 years.

Because this growth is so substantial, a very large proportion of the world's natural gas endowment will be produced between 2005 and 2050. Cumulative production during just these 45 years will consume 37 (high) to 45 per cent (low) of the world's estimated ultimate recovery of natural gas. Thus, despite a large remaining resource base relative to current cumulative production, world natural gas production is still projected to peak in 2030 (low), 2040 (medium) or 2050 (high).

5. PETROLEUM LIQUIDS

Petroleum liquids, as conventionally understood, include crude oil, natural gas liquids (NGLs), extra-heavy oil and bitumen and oil produced from so-called oil shale. They exclude hydrocarbon liquids produced from coal, natural gas or biomass. For convenience, petroleum liquids as defined here will be subsequently referred to as 'oil'.

World production of oil grew rapidly from 1950 to 1973, more than doubling every decade (table 9). This growth was the culmination of an amazingly long process of increasing oil production that began in 1870, shortly after the birth of the oil industry. On average, world oil production more than doubled every decade for a century. This continuous process of growth raised world oil production by three orders of magnitude from 1879 (58.5 thousand barrels per day) to 1973 (58.5 million barrels per day). Lifting world oil production to this level radically transformed the challenges of increasing production in the future. These challenges became highly visible during the oil price shocks of 1973–1974 and again in 1980–1981. As demand decreased in response to higher prices, growth in oil production ceased from 1973 to 1985. Following the decline in prices during the mid-1980s, oil demand and production resumed growing, but at much lower rates. From 1973 to 2005, world oil production has only increased 41 per cent, not coming close to even doubling once again, much less doubling every decade.

The growing production of world oil has been accompanied by an increasing globalization of oil production. Prior to 1950, world oil production was dominated by North America, essentially the USA. By 1970, North America had relinquished its leading role to the Middle East. Despite its immense oil resources, the Middle East has never reached the production dominance the USA once had. Instead, world oil production became increasingly dispersed geographically. All of the inhabited continents became substantial oil-producing centres by the 1990s.

Because oil has been the leading source of energy for the world since 1961, because substantial amounts of oil have already been produced (1087 billion barrels through to 2005) and because world oil production has levelled off between 2005 and 2008, an intense debate has arisen about the future of world oil. The key questions addressed by this debate are: 'how much oil remains to be discovered, developed and produced?' and 'when and at what level will world oil production peak?' An evaluation of the various answers given to these two questions shows that the answers given to the second question depend heavily on whatever answer is given to the first.

The resolution to this debate thus revolves around determining the ultimate level of world oil resources. Yet, like all broad resource issues, the problem is not just a matter of determining oil resource amounts; the distribution of qualitative characteristics of remaining oil resources is also a critical consideration.

The analysis of ultimate oil resources usually begins with estimates of published oil reserves. Yet, these reserve estimates are typically used with little understanding of what they mean. Thus, some basic distinctions and clarifications are necessary for understanding both the terminology and the estimates of oil reserves and resources.

The commonly accepted classification scheme for oil resources and reserves rests on four basic distinctions. The first is *discovery status*: is the resource discovered or undiscovered? The second is *economic status*: what proportion of the discovery is commercial and what proportion is non-commercial? The third is *technical certainty* of the reserve estimates: are discovered reserves considered to be proved, probably, or only possibly recoverable? (These three deterministic categories are gradually being replaced by probabilistic estimation.) The fourth and final distinction is that of *development status*: are the reserves developed, being developed or undeveloped? In the latest set of reserve standards, an important fifth consideration has been added. Discovered commercial resources can only be considered to be reserves if they are part of a defined development and production project.

This paper uses only *proved developed* reserves. This category provides the gold standard for both resource evaluation and the projection of future production. Proved developed reserves are the only reserves that can contribute to current production. All other categories of reserves require capital investment before they can do so. Including these other categories in

Table 9. World production of petroleum liquids by region, 1950–2005 (billion barrels). Adapted from Energy Information Administration (2008).

year	North America	South America	Europe	Eurasia	Middle East	Africa	Asia/ Oceania	world
1950	2.29	0.64	0.07	0.26	0.63	0.02	0.09	4.00
1960	3.23	1.27	0.21	1.07	1.91	0.11	0.23	8.02
1970	4.82	1.76	0.27	2.54	5.08	2.22	0.66	17.25
1980	5.16	1.39	1.09	4.39	6.95	2.28	1.84	23.09
1985	5.64	1.41	1.63	4.36	4.00	2.05	2.16	21.24
1990	5.09	1.70	1.68	4.16	6.38	2.45	2.44	23.90
1995	5.14	2.18	2.40	2.61	7.45	2.68	2.67	25.13
2000	5.21	2.64	2.49	2.99	8.59	2.94	2.92	27.71
2005	5.15	2.60	2.09	4.29	9.32	3.74	2.93	30.10

current reserve estimates thus obscures analysis of how much new production capacity can be added annually and how much resources remain to be developed.

The difference between proved developed reserves and reserves as usually published is striking. Assuming an average annual decline rate of 4.5 per cent, proved developed reserves of oil worldwide were 670 billion barrels as of the end of 2005. This is approximately only half of the usual estimates of world oil reserves. These usual estimates are more accurately termed as proved and probable developed and undeveloped reserves.

Estimated known recovery of oil worldwide as of the end of 2005 was 1757 billion barrels, 1087 billion barrels of which had already been produced (table 10). The basic fact of world oil occurrence is that oil resources are geographically widespread, yet highly concentrated. Conventional world oil resources are concentrated in two *megaprovinces* (the Middle East and Western Siberia) and 13 *superprovinces*. (An oil megaprovince is one with an ultimate recovery in excess of 100 billion barrels; a superprovince has an ultimate recovery of 25–100 billion barrels.) Moreover, within these largest provinces (as well as in most other provinces), oil resources are highly concentrated in a small number of supergiant (five billion barrels plus) and giant (500–5000 million barrels) fields. Unconventional oil resources, such as extra-heavy oil/bitumen and oil shale, are even more concentrated in a few massive deposits. This concentration greatly simplifies the task of estimating ultimate world oil resources.

In addition to proved developed reserves, there are three categories of potential oil reserves: (i) *recovery growth* from known fields, (ii) *future discoveries*, and (iii) unconventional resources. All are important for the estimation of ultimate resources. Current published estimates of ultimate world oil resources vary drastically. These variances do not stem primarily from disagreements about the potential of any one resource category. Differences among estimates depend primarily upon whether or not any specific category is even included in the total estimate. Recovery growth and unconventional resources in particular are frequently ignored.

From the standpoint of petroleum resource assessment, future discoveries are the best understood source of future additions to world oil resources.

Table 10. Estimated ultimate world potential petroleum liquids (billion barrels as of 31 December 2005).

	low	medium	high
cumulative production	1087	1087	1087
proved developed reserves	670	670	670
known recovery subtotal	1757	1757	1757
future discoveries	350	780	1310
recovery growth	800	1180	1570
unconventional	340	550	860
world ultimate total	3247	4267	5497

This is contrary to the common understanding that they are the least known (after all, they are still to be discovered). Future discoveries are the most extensively and thoroughly analysed source of future additions; their assessment has sound theoretical underpinnings; and the methodologies for assessing them have been rigorously developed over decades. Being best understood does not eliminate uncertainty in assessments; it does encourage the careful identification and specification of the uncertainties that do exist.

The estimates of future discoveries used here (table 10) are an augmented and amended version of the world oil assessments by the US Geological Survey (Ahlbrandt *et al.* 2005). Their estimates are augmented to add the Arctic regions of the world and the USA. They are amended to reflect 1996–2005 drilling results and to incorporate various reassessments of regional oil potential. This augmented and amended estimate of future discoveries ranges from 350 (95% certainty) to 780 (50%) to 1310 (5%) billion barrels.

From an exploration standpoint, most of the largest oil provinces of the world are moderately to highly mature. Only in a few is there any realistic chance of substantial future discoveries. The potential for future discoveries is highly concentrated in frontier provinces (such as in the Arctic or in deepwater offshore areas), or in a few lightly explored Middle East countries such as Iran, Iraq and Saudi Arabia.

Because of their locations, future discoveries are thus 10–40 years away from contributing to world oil production. The frontier provinces are at (and in some cases even beyond) the boundaries of current exploration and production technology. Middle East exploration is constrained for a variety of economic and political reasons. The potential for future discoveries is substantial; it however will not be immediately available.

Recovery growth is estimated here to be the most important source of future additions to world oil resources. Recovery growth is defined as increases over time in the estimates of ultimate oil recovery from discovered fields. Two types of increases are possible: estimates of in-place resources may increase or the recovery efficiency of an unchanged in-place resource may increase.

Although recovery growth is the most important source of both recent and future additions to world oil resources, it is the least understood and appreciated source of additions. It is poorly understood in part because it has been poorly explained by its few advocates and because it has no place in the calcified model of discovery, development and depletion that guides all too much thinking about the development of oil fields.

Recovery growth occurs because past oil field development was constrained. The two major constraints on development were the size of the oil market (demand) and the cost of the various phases of development (supply). Constraints on oil field development have been expressed through both formal and informal systems of production controls. These controls arose in order to keep oil prices declining to ruinous levels following the development of major discoveries. As noted earlier, oil resources are concentrated in giant and supergiant fields. Moreover, these fields tend to be discovered early in the history of exploration. If they had been developed fully shortly after discovery, their production could not have been absorbed in the market and oil prices would have collapsed.

Production controls, which begun in the USA in the early 1930s and spread to the Organization of the petroleum exporting countries a few decades later, had major effects on oil field development over the past 75 years. They retarded the timing of initial field development; they made initial development less intensive; and they focused development efforts on only the least costly developments. Where production controls were present, future growth opportunities from proved developed reserves are thus substantial. Where controls were not present, growth opportunities are more limited, being driven by both technology change and price (cost).

Future recovery growth will occur from a variety of sources. In declining order of importance, these are (i) more intensive development, (ii) the development of discovered, but currently developed fields, (iii) advanced secondary and enhanced oil recovery, and (iv) new reservoir discoveries and extensions to known reservoirs in discovered fields. The first three of these incorporate the approximately 600 billion barrels in proved and probable undeveloped conventional oil reserves.

World oil recovery growth potential is estimated here to be between 800 (95%) and 1670 (5%) billion barrels (table 10). This estimate assumes that ultimate recovery factors from known crude oil-in-place of approximately seven trillion barrels will reach 35, 40 and 45 per cent (plus additional NGLs). This potential increases ultimate world oil resources significantly. But because of a limited supply of engineering and geological expertise, annual additions from recovery growth will occur at a relatively low rate. Recovery growth will thus have only a modest effect on the maximum level of world oil production; it will however have a major effect on how long high levels of world oil production will persist.

There are three types of naturally occurring unconventional oil resources worldwide: (i) extra-heavy oil and bitumen (tar sands), (ii) oil from mature source rock, and (iii) oil shale. Each of these unconventional oil resources have immense in-place resources; 3.2 trillion barrels for oil shale, 4.1 trillion barrels for extra-heavy oil and bitumen and five to 20 trillion barrels for oil from mature source rocks.

The commonplace emphasis on these immense in-place volumes ignores the central problem for unconventional oil resources. These resources are unconventional because of poor fluid quality, poor reservoir quality or both. Thus, their primary problem is *recoverability*: how much, if any, of their immense in-place resources can be produced. All need less costly, more energy-efficient and less environmentally damaging technologies than those that exist today to unlock their resource potential.

The estimated contribution of unconventional resources to ultimate world oil resources is thus expected to be only a small fraction of their in-place resources. The estimates used here range from 340 (95%) to 860 (5%) billion barrels. Without major technology breakthroughs, only 10–20% recovery efficiencies will be achieved for extra-heavy oil and bitumen. Developing this resource will occur slowly because of its great expense. Recovery efficiencies from mature oil source rocks are expected to be only 1–5%, occurring only where natural permeability is present. Awareness of this resource only began this decade, so much research into its size, distribution and characteristics remains to be carried out. The existence of oil shale has been well known for decades. The necessary knowledge, however, for converting kerogen (an oil precursor) into oil and recovering that oil remains commercially problematic. At best, oil shale could begin producing oil in noticeable amounts by 2030; at worst, it could remain undeveloped forever because of its low net energy production.

Estimating future world oil production is not simply a matter of projecting from an ultimate level of world oil resources. It also involves consideration of the rate at which new producing capacity can be added. At current world-producing rates of 82.5 million barrels per day and with a current estimated world average decline rate of 4.5 per cent, 3.7 million barrels per day of new capacity is required annually simply to maintain production. To achieve a 1 per cent annual increase in production requires 4.5 million barrels per day of new capacity annually; a 2 per cent increase requires 5.35 million barrels per day of new capacity each year.

By comparison, the best sustained rate of new capacity additions ever achieved by the worldwide petroleum industry was an annual average of 4.7 million barrels per day from 1963 to 1973 when world production increased 114 per cent from 27.3 million

Table 11. Projected world production of petroleum liquids, 2010–2050 (billion barrels).

year	low	medium	high
2010	30.0	30.0	30.0
2015	31.5	31.5	31.5
2020	32.3	32.8	33.1
2025	32.3	33.6	34.0
2030	32.3	33.6	34.8
2035	30.8	33.6	34.8
2040	27.5	33.6	34.8
2045	24.9	32.8	34.8
2050	21.9	31.2	34.8
cumulative (2006–2050)	1331	1462	1510
all-time cumulative	2418	2550	2592
committed reserves	2904	3243	3365
(% of ultimate)	(89.4)	(76.0)	(61.2)

barrels per day to 58.5 million barrels per day. In contrast to this earlier period, when flush production was being added from new supergiant and giant discoveries in the Middle East, western Siberia and Africa, future additions to capacity will come from increasingly marginal resources with lower production and fewer reserves per well. Development of new discoveries will occur in increasingly more difficult environments such as deepwater and the Arctic. In addition, the supply of upstream professionals is expected to be contracting, thus placing a major constraint on the rate at which the petroleum industry can implement new capacity additions.

These considerations strongly suggest that the best rates of growth achievable in world oil production after 2010 are likely to be only 0.5–1% per year. Moreover, as the better quality resources are committed to production, new capacity additions will be drawn from increasingly poorer quality resources. Thus, production will level off and then decline when capacity additions no longer equal annual declines in the existing capacity.

The customary representation of this process is a sharp peak, instead of the broad plateau suggested here. A sharp peak in world oil production entails a sudden and sharp decline in annual additions to capacity. By contrast, a plateau implies a gradual decline in such additions, a pattern more consistent with how the world petroleum industry will work over the next several decades.

Like coal and natural gas, the projections of future oil production use three cases: low, medium and high. Each reflects the previously presented estimates of ultimate world oil resources (table 10). Each also incorporates estimates about the rate at which potential resources can be developed. For example, development of unconventional resources is considered to be a 75–125 year effort.

The three cases incorporate slow and declining growth in oil production from 2010 to at best 2030 (table 11). The ultimate plateau in production is reached in 2020 (low), 2025 (medium) and 2030 (high). Production rates at this ultimate plateau are estimated to be only 7.3, 11.8 and 15.7 per cent, respectively, higher than 2005 production. The duration of this plateau is forecast to be 10 (low), 15 (medium) or 20 years (high). Production declines at slow rates thereafter.

Table 12. Projected world primary energy production from fossil fuels, 2010–2050 (quads).

year	low	medium	high
2010	423.8	424.9	425.3
2015	452.1	457.8	464.9
2020	468.8	490.4	508.2
2025	469.2	515.3	547.7
2030	463.8	532.5	581.1
2035	446.8	534.6	607.3
2040	415.6	528.3	609.6
2045	384.7	514.6	607.1
2050	352.8	493.9	604.6

Maximum annual production is projected to be only 0.63 (high) to 1.0 per cent (low) of ultimate recovery. Because the maximum in each case occurs in the 2005–2050 time period, a substantial proportion—41 (low), 34.3 (medium) and 27.5 per cent (high)—of estimated ultimate world oil resources is estimated to be produced during these 45 years. Except for the high case, these high rates of consumption (indicated by committed resources as of 2050, the sum of cumulative production and proved reserves by then) leave relatively few oil resources to be developed after 2050.

6. CONCLUSION

World fossil fuel production has grown continuously, albeit irregularly, since 1950. That growth will continue, but only for the next 15–30 years (table 12). Combined fossil fuel production peaks at 469 quads in 2025 (low), 535 quads in 2035 (medium) and 610 quads in 2040 (high). These peaks are only 18, 35 and 54 per cent above the 2005 levels of world fossil fuel production. In each scenario, production stabilizes within 1 per cent of the peak for 10–15 years before declining continuously thereafter.

That this occurs should not be unexpected. Fossil fuels are non-renewable resources. Although their recoverable amounts are vast and are being gradually augmented by advances in technology and improvements in their economics of discovery, and development, they are not limitless. They cannot grow indefinitely, particularly when their production has already reached high absolute levels.

The overall pattern of each scenario is the same, varying only in the timing. Each scenario also exhibits the same pattern of change in the composition of fossil fuel production by fuel. In each, the relative share of petroleum liquids declines and the relative share of coal and natural gas increases. In the low and medium scenarios, oil maintains its dominance. In the high scenario, coal overtakes oil by 2030, and gas becomes dominant by the early 2040s.

Because fossil fuel production peaks and subsequently declines, production *per capita* will also decline. Comparing the three production scenarios

Table 13. Actual and projected CO_2 emissions from fossil fuel consumption, 2005–2050 (billion metric tonnes). Adapted from Energy Information Administration (2008) for 2005; 2020, 2035 and 2050 estimated from tables 5, 8 and 11 of this paper, using Energy Information Administration emission factors.

year	low	medium	high
2005	28.3	28.3	28.3
2020	33.7	35.3	36.6
2035	31.4	38.0	43.7
2050	25.1	34.8	42.7

here with their respective United Nations population projections (i.e. low/low, medium/medium and high/high) yields interesting results. The timing of peak production *per capita* varies among the three pairs of projections. The absolute level of *per capita* production at each peak is, however, approximately the same among all three pairs. The absolute level of production *per capita* peaks in the low/low scenario pair at 63.8 million Btu per person in 2020; in the medium/medium scenario pair, production *per capita* peaks at 64.3 million Btu per person in 2025; in the high/high scenario pair, production *per capita* peaks at 65.2 million Btu per person in 2030. None of these peak amounts *per capita* are more than 7 per cent above current *per capita* levels.

An illuminating corollary of the outlook for fossil fuel production to 2050 is its impact on future CO_2 emissions (table 13). Because fossil fuel production will peak and then decline, projected CO_2 emissions from fossil fuel consumption show no pattern of runaway increases. Instead, they too show a pattern of small to modest increases up to 2020–2035, followed by subsequent declines. In the low-production scenario, CO_2 emissions peak in 2020, 19 per cent above their 2005 level. By 2042, they have declined to 2005 levels; by 2050 they are 11 per cent below the 2005 level. In the medium-production scenario, CO_2 emissions peak in 2030 at 34 per cent above the 2005 level. By 2065, they will have declined to their 2005 level. In the high-production scenario, CO_2 emissions peak in 2035 at 54 per cent above 2005 levels and begin declining slowly to 2050 (after which the decline accelerates).

Two singular events in the world energy economy will occur during the first half of the twenty-first century. First, production of every fossil fuel, the dominant source of energy for the modern economy, will peak and begin to decline. Second, the transition from reliance on fossil fuels towards other sources of energy and more efficient use of energy will take off.

The conjunction of these two events is all too frequently assumed to mean that continued development of fossil fuel resources is unnecessary and can safely be disregarded. On the contrary, continued development of remaining fossil fuel resources is essential to provide adequate supplies of energy for the world economy across the many decades that this great transformation will require.

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