Our Energy Future:
Between Iraq and a Hard Place

A BRIEFING PAPER ON ENERGY
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Summary

There is little doubt that the world's total energy demand will grow substantially in the 21st century – most forecasts suggest between two and four times present demand (from 13 TW today to 25-40 TW in 2050, and 30-60 TW in 2100). What *is* in doubt is what fuels and technologies will be used to meet that demand, how these fuels and technologies will be chosen, and what the consequences of these choices will be for society and the environment. The question of energy path is if anything more salient today than it was when Amory Lovins posed it in *Foreign Affairs* a quarter century ago

The current global energy system is deeply implicated in the most serious problems the world faces. Fossil fuel combustion is the main driver behind the threat of climate change and numerous other pollution problems. Control of oil and gas resources underlies the most threatening geopolitical conflicts, including the war in Iraq. The unclosed nuclear fuel cycle poses the ongoing threat of nuclear WMDs, while centralized energy infrastructure such as nuclear power plants, transmission lines, and oil pipelines are prime targets for terrorism. Energy infrastructure, from mines and wells to hydro dams to transportation, has profound impacts on land use and fresh water supplies. Energy distribution is such that one-third of the world's population lacks fully modern energy services, including more than one billion people without electricity.

Fossil fuels are the backbone of industrial civilization, constituting 85% of global primary energy supply. Yet they must relinquish this role during the next century. Supplies of petroleum and natural gas are likely to dwindle within a few decades, leading to a permanent condition of scarcity and high prices. Coal supplies are plentiful, even in the largest developing countries, but must not be used (at least with present technology) if catastrophic climate change is to be avoided.

Yet what will replace fossil fuels in the long run is far from clear, for two main reasons: (1) There are no technical alternatives on the immediate horizon without substantial drawbacks of their own, whether for reasons of cost, hazard, or practicability. (2) It is impossible for markets and the private sector by themselves to adequately reflect the environmental and social dimensions of energy, but there do not yet exist public-sector governance institutions that can take these concerns into account in shaping a future energy system in the broad public interest. In addition, even the prospects of providential first steps toward a more sustainable energy system are clouded by the political power of interests that wish to protect the *status quo*. This is most obvious in the U.S., from the militant campaign of ExxonMobil against the Kyoto Protocol, to the energy bill now before the U.S. congress that has as its central feature a variety of favors to the fossil fuel industry. Indeed, much of Bush Administration policy seems best explained as an effort to maintain by military force and economic subsidy the present global energy regime.

If political barriers could be overcome and economic incentives put in place, there exist the outlines of a short-term energy path – from now until perhaps 2020 or 2025 – that could at least stabilize CO_2 emissions and buy time for longer-term solutions to

emerge. The technical features of such a path would include increasing industrial and residential energy efficiency through equipment standards and new building design; expanding the use of low-carbon transportation, including public transport systems and hybrid automobiles; promoting widespread conversion from coal to natural gas as a primary fuel; and increasing the percentage of renewable energy (especially wind and biomass) in electricity production (to a plausible maximum of about 20% by 2020). The institutional concomitants of such a path would probably have to begin with a dramatic shift in U.S. energy and foreign policy, and include such measures as the ratification of the Kyoto Protocol with strong, equity-focused measures for the second commitment period, beginning in 2012; some form of carbon tax or emission rights that provides the revenues for new energy R&D and deployment, including in developing countries; and the creation of a more secure geopolitical setting that would, for example, make China more willing to accept a degree of dependence on Russian and Central Asian natural gas.

In the longer run, it may be that no single technology plays the role of fossil fuels today. As the proponents of the Energy Apollo Project have argued, there are insufficient grounds for selecting technology winners in advance; rather, a strategy of supporting vigorous development of a number of promising alternatives to near-maturity, then exposing them to the rigors of market competition and consumer choice, will greatly increase the options available in 2020 or 2030 when the short-term cards have been played. Some of the likeliest contenders at present include next-generation nuclear fission (if the fuel cycle issues can be addressed); hydrogen fuel cells (if non-fossil fuel sources of hydrogen can be cheaply obtained); advanced biomass fuels (if land use requirements can be reduced); and advanced photovoltaics (if manufacturing costs can be lowered). Major contributions can be made at the systemic design level, for example with distributed generation and smarter transmission systems in electricity, with dematerialization and improved energy efficiency in production and consumption cycles, and with transportation systems corresponding to more rational patterns of settlement.

There exists the prospect of unexpected turns of event that will strongly affect the global energy system. Negative surprises might include evidence that climate change is more rapid and more severe than expected, or supply disruptions due to economic turmoil or war. Positive surprises might include quantum-leap developments in enabling technologies, such as superconductors, hydrogen-producing biomaterials, or the ability to put objects (such as PV arrays) in orbit cheaply. Yet despite the obstinance of many with vested interests, what should not come as a surprise is that continuing to follow the fossil-fuel *status quo* will lead to increasing conflict, vulnerability, and assault on the global commons. If "sustainable development" is to be the hope of the 21st century, it will have to begin in the energy sector.

Facts and Forecasts

Global Energy Demand Forecasts

The following forecasts for global primary energy demand are drawn from a number of sources, including the oil industry (Shell), environmental NGOs, and the U.S. government (DOE). The ranges are based on what the forecasters considered their most likely scenarios (as opposed to those assuming radical departures from current patterns). Forecasts embed many assumptions about population, economic conditions, and consumptions patterns that may not prove to be accurate. More distant forecasts are necessarily more speculative. Most forecasters assume that the shape of the curve is logistic, with little demand growth after 2100.

- 2000 407 EJ = 13 TW ± 0%
- 2025 700 EJ = 22 TW ± 15%
- 2050 1000 EJ = 32 TW ± 25%
- 2100 1400 EJ = 45 TW ± 33%

Global Energy Production

The world's primary energy production in 2001 was 425 EJ, of which 364 EJ, or 86%, were fossil fuels. (1 EJ = 1055 Quad Btu = 31.7 GW). The principal sources (not including traditional biomass) were:

- Total = 425 EJ (100%)
- Petroleum = 164 EJ (38.5%)
- Coal = 101 EJ (23.8%)
- Natural Gas = 99 EJ (23.2%)
- Hydro = 28 EJ (6.6%)
- Nuclear = 28 EJ (6.6%)
- Renewable = 6 EJ (1.4%)

Global Energy Consumption

The six top consumers (with the E.U. treated as a single entity) use two-thirds of the world's primary energy, with the U.S. alone consuming one-quarter. U.S. per capita consumption is more twice that of Europe, more than ten times that of China, and more than twenty-five times that of India.

- U.S. = 25% 365 GJ/pers
- E.U. = 16% 179 GJ/pers
- China = 10% 33 GJ/pers
- Russia = 7% 210 GJ/pers
- Japan = 5% 167 GJ/pers
- India = 3% 14 GJ/pers

- Global average = 70 GJ/pers

Global CO_2 Emissions

Total global CO_2 emissions constituted 6.6 billion tons of carbon in 2001. (CO_2 emissions *per se* can be calculated from the ratio of molecular weights, 44/12). The list of top emitters of carbon is identical to the list of top energy consumers. The global average per capita emission was 1.1 ton/person. U.S. per capita emissions of carbon were five times the global average, twice that of Europe, and nine times that of China.

Carbon intensity figures are also given, in metric tons of carbon per $1,000,000 of GDP. Very high carbon intensities in the Chinese economy reflect strong coal dependence and low industrial energy efficiency, while very low carbon intensities in the Japanese economy are a consequence of high energy efficiency and a high proportion of nuclear power.

national share of C		per capita C	carbon intensity
• U.S. =	25%	5.6 t/pers	170 t/$1M
• E.U. =	14%	2.5 t/pers	120 t/$1M
• China =	12%	0.6 t/pers	750 t/$1M
• Russia =	7%	3.0 t/pers	470 t/$1M
• Japan =	5%	2.5 t/pers	60 t/$1M
• India =	4%	0.3 t/pers	500 t/$1M
• Global Average		1.1 t/pers	200 t/$1M

U.S. and China Primary Energy Consumption by Sector

The table below shows consumption by sector in China and the U.S. in 1999. It illustrates the structural differences in energy consumption between industrialized and developing countries, and also indicates the likely direction of future developments: in China, the transportation share is expected to grow rapidly in parallel with private vehicle ownership, while the industrial share should decline with increased efficiency.

	U.S.	China
Transportation	28%	5%
Residential	20%	12%
Industrial	36%	72%
Commercial / Agricultural	18%	11%

Issues

Problems of Present Global Energy System

The gravest environmental and social problems associated with the current global energy scheme include the following:

- Global warming due to CO_2 emissions, risk of severe climate change
- Local/regional pollution (ozone, acid rain, particulates) due to SO_2, NOx, metals
- Land and water stress due to mines, dams, irrational transportation infrastructure
- Conflict/war over oil and gas resources (Middle East, Central Asia, South America)
- Vulnerability of centralized infrastructure to terrorism
- Nuclear WMD threat due to leaky/unclosed nuclear fuel cycle
- 2 billion people with inadequate energy, 1 billion without electricity
- Developing country debt strongly linked to fuel and infrastructure purchases & loans
- No clear pathway to the future – still tied to declining, dangerous fossil fuel resource

Advantages of Present Global Energy System

The advantages and disadvantages of the present global energy system are to some degree a matter of perspective. This is because few social and environmental externalities are reflected in the cost of energy, which allows those "upwind, upstream, and uptime" to enjoy convenient services at artificially low prices while those "downwind, downstream, and downtime" face the consequences. For those with purchasing power in locations that already benefit from developed infrastructure, the advantages include:

- Energy is cheap – 2-5% of GDP in industrialized countries
- Fossil fuels are very cheap
- Gasoline and diesel are ideal transportation fuels – portable, convenient
- Electricity is an ideal home energy source – clean, safe, convenient
- Thermal power plants are the cheapest source of electricity
- End-use equipment – cars, factory, home appliances – are mature and inexpensive

Questions That Will Shape the Future

How the global energy system should be optimized to meet future needs depends fundamentally on what question is being asked. Future choices look very different depending on how the following concerns are prioritized by those with the power to shape the system:

- Consumer preferences (e.g. convenience and low cost)
- Economic efficiency
- Climate protection
- Poverty alleviation / sustainable development
- Security and reliability

Predictable Determinants

Future energy demand is easier to imagine than the future supply mix. Most energy forecasts assume that regardless of supply options, future demand will be a relatively predictable function of the following variables:

- population growth
- economic growth and consumption in industrialized countries
- rapid development in LDCs – explosive growth in electricity and transportation
- fossil fuel inertia – both technological and political

Unpredictable Determinants

Both demand and supply mix may be strongly influenced by outcomes that are hard to predict with any degree of confidence at present, or that come as complete surprises. Such events could dramatically affect public perceptions, costs and availability of fuels, or institutional capacities, and facilitate major departures from current demand forecasts or the supply mix *status quo*.

- Resource scarcity – e.g., the ultimate stock of low-cost natural gas is unknown
- Dramatic evidence of climate change, such as changes in the Gulf Stream
- Outcome of the climate debate – implementation of the Kyoto Protocol
- Abrupt changes in control of fossil fuel supplies (e.g. Middle East or Central Asia)
- War or terrorism demonstrating unacceptable vulnerability of current system
- Major technological breakthroughs (e.g. carbon sequestration, fusion)

Energy Governance Matrix

The ultimate determinants of the long-term energy supply mix in 2050 or 2100 are likely to be progress in technology (hard to predict) and the nature of the controlling institutions, whether market or governmental.

Primary Sector Governance	Effectiveness Benefits	Ineffectiveness Drawbacks
Public sector	• can incorporate broad public interest & long view • could enjoy global legitimacy & ability to marshall social change • could create and police market institutions that guide private sector, reflect social hazards	• most public institutions are limited financially and in scope of action • goes against trend since 1980 of private sector political dominance, free market ideology, deregulation
Private sector	• profit motive is strong inducement for creativity • has the necessary money, technology, and expertise • can raise private investment capital and limit public risk	• resistance to changing profitable status quo • cannot easily internalize social and environmental externalities • skillful at privatizing profits, socializing costs and risks • focus on the profitable rather than

		the necessary

Technology and Resources

Fuel Concerns

- Cost
- Scarcity
- Security / competition for control of resources
- Convenience and safety of use

Technology Concerns

- Unit and capital cost
- Environmental impacts
- Time & cost horizon of development
- Complementary technology & infrastructure development
- Modularity

Current Supply Mix

- Oil
- Natural Gas
- Coal
- Hydro
- Nuclear

Medium-Term Supply Prospects

- Natural Gas
- Wind
- Biomass / biofuels
- Solar PV
- Solar thermal
- Next-generation nuclear

Long-Term Supply Prospects

- Hydrogen
- Advanced biomass / biofuels
- Advanced solar PV
- Advanced solar thermal
- Advanced fission
- Fusion
- Carbon capture and storage

Demand-Side Prospects

- Design and rational land-use planning
- Dematerialization / closed consumption cycles
- Energy efficiency
- Distributed generation

Fuel or Technology	Current Status and Future Prospects
Oil	Oil production may be peaking now or soon, as evidenced by a decade of decreasing returns on exploratory wells. Nonetheless, even under business as usual actual scarcity may not occur for three or four decades, because conventional oil can be extended by a combination of fuel efficiency and non-conventional fuels, such as biofuels, and coal or natural gas liquids. Oil price forecasts are notoriously unreliable, but production cost forecasts predict an increase to about $20/bbl on average by 2020 – with a backstop price set by biofuels – in contrast to $5/bbl for Saudi Arabian production today. The issue regarding oil is less resource scarcity than the scarcity of atmospheric space to absorb CO_2. Long before consuming the other half of the Hubbert curve, climate protection (and the need to retain some petroleum for chemical feedstocks) demands a switch to low-carbon alternatives. This requires decarbonizing transportation, by such means as carbon taxes, hybrid and electric vehicles, and (re)designing patterns of settlement for rational transportation systems.
Natural Gas	Natural gas is the premier fuel for home heating, and has become the preferred fuel for thermal power generation since the development of highly efficient combined cycle gas turbines in the 1980s. Gas is versatile and comparatively clean, and has the lowest carbon to hydrogen ratio of any fossil fuel, and thus lower CO_2 emissions for the same energy output. Because it is climate friendly relative to coal, it is perceived as the critical transition fuel to a true low-carbon regime in 2020 or 2030. However, there is great uncertainty about the magnitude of easily recoverable natural gas stocks, again evidenced by decreasing returns on exploratory drilling. The dependence of gas supplies on pipelines leave it rather vulnerable to terrorist attack, cutoff due to international tensions, and market bottlenecks and manipulation. Gas is touted as a hydrogen source for a vehicular hydrogen economy, but requires both a hydrogen infrastructure and the solution of the carbon sequestration problem if it is to address the climate problem.
Coal	Coal resources are adequate to supply several centuries of expected demand, though coal is geographically concentrated, leading eventually to transport and cost issues under business as usual. The issue – as with oil only more so – is less resource scarcity than atmospheric capacity to absorb the effluent. Coal has the highest C/H ratio of fossil fuels and is therefore the most climate unfriendly. "Clean coal" technologies – such as impurity removal or gasification on the front end, efficient fluidized bed and supercritical combustion, and flue gas desulfurization on the back end, can reduce local and regional pollution problems but remain climate unfriendly. A dream future for the coal industry and coal-dependent countries like China includes inexpensive minemouth gasification, piggybacking on natural gas infrastructure, and carbon sequestration.

Fuel or Technology	Current Status and Future Prospects
Carbon Sequestration (a.k.a. carbon capture and storage)	Carbon sequestration should not be counted on to come to the rescue of the fossil fuel industry in the short to medium term. Carbon capture – whether from the chemical processing of fuels or capture and chemical separation of combustion products – is a demonstrated but still expensive technology. Carbon storage on a large scale – in the deep ocean, in soils, in geological formations – is not yet demonstrated and raises many technical, economic, and ecological concerns. The extent of leakage from reservoirs and the possibility of catastrophic "burps" remain open research questions. A worrisomely imaginable scenario is one analogous to the nuclear waste problem, where captured carbon awaiting a safe long-term storage solution stacks up indefinitely in compressed-gas storage containers on power plant and industrial sites.
Nuclear Power	Current generation nuclear power is climate-friendly, but faces other major barriers. There is still no long-term high-level nuclear waste storage solution. Leakage from the civilian nuclear fuel cycle is a major proliferation and WMD concern. Finally, nuclear remains uncompetitive on cost grounds, which is the main reason no new plants have been ordered in the U.S. since the 1970s. Recent industry claims of competitive prices (2-3 cents/kWh) for existing plants in the U.S. are wildly misleading, as they reflect only marginal operating costs, and do not include a variety of public subsidies for R&D, plant capital cost ("stranded assets" under electricity deregulation), infrastructure development, insurance, and waste management. There is no civilian nuclear program in the world that is not highly subsidized, often in hidden ways; combined with lack of transparency, this makes accurate economic analysis of the nuclear fuel cycle very difficult even in 2003. "Inherently safe" and "passively safe" next-generation reactors, such as the High Temperature Gas Cooled Reactor, may be cheaper and safer to operate. Sealed reactors (like those in nuclear submarines) may be more proliferation resistant. But downstream issues remain and there is no industry consensus regarding next-generation choices, and no Admiral Rickover on hand to sort things out. If nuclear were to expand rapidly – as opposed to its current modest expansion, primarily in developing countries – scarcity of low-cost uranium ores could become an issue late in this century. Suggested long term solutions to that problem are either problematic on safety and proliferation grounds – breeder reactors with large-scale reprocessing – or are still quite theoretical – accelerator transmutation of waste products, or a thorium fuel cycle. A dream future for the nuclear industry is a nuclear hydrogen economy based on inexpensive nuclear electrolysis.

Fuel or Technology	Current Status and Future Prospects
Hydro	Hydroelectricity is climate-friendly but will not contribute substantially more to the long-term supply mix than it already does. There are relatively few technically superior sites for large dams remaining. New dam construction faces strong opposition worldwide because of damage to freshwater habitats and human communities in the reservoir footprint. The World Commission on Dams – a U.N. sponsored stakeholder process involving both the industry and its critics – may represent a watershed, in that its environmental safeguard and community participation guidelines may eliminate many possible future dams (while permitting the construction of a select few that achieve a broad consensus). Coming water shortages in many regions will also constrain hydroelectric operations more than in the past, as water management for human needs and crops grows in importance. Hydro will mostly play a local and regional role in the future, for example in China, where demand is growing, untapped hydro resources remain, social opposition is weak, and few other alternatives to coal use exist.
Solar PV	Solar PV costs continue their long-term decline, with installed costs now less than $5/W. For large installations, electricity production costs – which are a function of the local solar resource – are in the range of 20 cents/kWh. It is common, but probably erroneous, to treat PV as a competitor in the bulk power market, comparing 20 cents/kWh to 2-3 cents/kWh for the busbar production cost at the cheapest coal or natural gas plants. The appropriate comparison is actually in the rapidly expanding distributed generation market, for which PV costs only exceed market leaders by a factor of 2 in sunny climates. Because the diurnal and seasonal peaks in PV output matches demand peaks in many markets, PV provides high-value capacity as well as bulk electricity, making its intermittency much less relevant. To reduce costs by another factor of 2 will not require technology breakthroughs so much as increased manufacturing volume to reduce unit costs. In the longer term, especially if inexpensive energy storage is developed, PV could become a bulk power option. Dedicated silicon production suited to PV manufacture (rather than silicon from the semiconductor electronics industry) and highly-efficient (30%) multi-junction devices are quite plausible. Solar dreamers imagine a world of cheap spaceflight, with large orbiting solar arrays microwaving bulk power back to earth.
Solar Thermal	Solar thermal electricity is the overlooked step-sister of the renewable energy family, yet it is actually one of the most promising non-fossil technologies for bulk power markets. Solar thermal suffered a devastating financial debacle with the bankruptcy of the Luz parabolic trough thermal power plant in the Mojave Desert more than a decade ago, which still frightens investors away from the technology. Yet the Luz plant itself is still operating efficiently, producing power for the California grid at 10-12 cents/kWh, less than the cost of the long-term

Fuel or Technology	Current Status and Future Prospects
	power-purchase contracts signed by Gov. Davis to halt the California electricity crisis. The ability of solar trough systems to store hot water and use it later to generate power reduces the intermittency problem. In the medium to long term, a promising technology is parabolic concentrating mirror systems with Sterling engines, with air as the operating fluid. Sandia National Laboratories stopped R&D on this design several years ago, despite promising results. Recent cost improvements in materials, sensors, and control systems would seem to merit a new look (one technical issue pitted the greater expense of producing parabolic mirrors against efficiency losses with hemispherical mirrors, but sensor controlled, vacuum operated mylar mirrors might resolve this issue). With cost-effective energy storage, solar thermal could be a much more attractive option for bulk power than biomass: biomass production is inherently limited to the 1-2% solar conversion efficiency of photosynthesis, while solar thermal can be up to 25% efficient, which implies an order of magnitude lower land-use requirement for comparable power generation.
Wind	Grid-connected wind power is commercially viable (5 cents/kWh) and rapidly growing in many parts of the world, accounting for 17% of total capacity in Denmark (which has a target of 30%). The key to falling costs has been the scale of individual turbines, which has grown from the 10 kW range in 1980 to 1 MW at present. Wind's rapid improvement in performance and cost reflects a successful interaction between modest government subsidy that stimulated a profusion of competition and a rapid uptake of new technology, followed by market winnowing and the emergence of reliable, low-cost designs. Improvements in semiconductor power electronics have allowed the creation of cost-effective AC-DC-AC interfaces, which in turn permit sensor-controlled variable speed blade rotation, allowing turbines to operate near maximum thermodynamic efficiency (tip-speed ratio). The current technical challenge to further increasing rotor diameters is the problem of differential torques produced by non-uniform wind speeds across large swept areas (which was the downfall of the famous Boeing 2.5 MW experimental turbine decades ago). This is being addressed with new materials, sensor-controlled blade pitch adjustments, and circulation control. Another solution is offshore generation sites, which have less variable vertical wind profiles than sites on land. In the long term, wind requires incremental improvements in cost-competitiveness rather than major technological breakthroughs. The principal long-term challenge to wind is land use – wilderness areas, habitat fragmentation, bird kills, and aesthetics – which has already produced a public acceptance problem in the U.S. Recent studies suggest that maximum feasible exploitation of global wind resources (~ 10 TW) could affect climate due to the energy removed from the planetary boundary layer.

Fuel or Technology	Current Status and Future Prospects
Biomass	“Biomass” is a blanket term that incorporates many different technologies and types of organic material – corn, soybean, poplar and eucalyptus trees, switchgrass and hemp, along with crop and food processing wastes. The highest value application of biomass is probably as a carbon neutral transportation fuel to replace oil. Ethanol (for gasoline) and biodiesel (for diesel) are proven technologies within a factor of 2 in price of their fossil competitors, and requiring little or no modification of conventional vehicle engines. It is worth noting that biomass is not necessarily carbon neutral – it must be managed through its life cycle to ensure that it is (for example, soil carbon losses from poor harvesting techniques may erode other carbon improvements). The long term limitation confronting biomass is competition for land with wilderness, agriculture, and urban development. Extensive mono-cropping is also ecologically undesirable, especially under global warming. Given the land-use problem, biomass for bulk thermal power generation is less attractive than solar thermal or PV -- which are in principle more efficient in converting solar energy to electricity per unit area – if their intermittency problems can be addressed. For the short to medium term, 1-2 TW of biomass could be supplied with existing crop and processing wastes, without new dedicated biomass cropland.
Hydrogen	The hydrogen economy for transportation is the preferred option of the Bush Administration and the oil industry. However, whether hydrogen is climate-friendly depends on where the hydrogen comes from. If it comes from fossil fuels, there is no advantage unless CO_2 can be captured and stored. Other sources remain speculative. Hydrogen from electrolysis will be prohibitively expensive unless extremely low-cost sources of bulk electricity are developed. Biological sources – such as bioengineered anaerobic bacteria – are still highly experimental. Hydrogen fuel cells using gaseous hydrogen are already reaching commercial status, but large-scale application would require a new fuel distribution infrastructure to be built worldwide, with a vulnerability to terrorism similar to natural gas pipelines. In the long term, the creation of dense fuels in forms like metal hydrides, which could be packaged in small containers, could avoid the need for pipeline infrastructure
Energy Storage	For intermittent resources like wind and solar to play a major role in electricity, energy storage is required. There are a number of competing technologies under development for utility-scale electricity storage, including compressed air and superconducting magnets. Future technical developments, such as breakthroughs in high-temperature superconductors, may determine which (if any) of these become cost-effective. For transportation and distributed electricity storage, other competitors include advanced batteries, flywheels, and supercapacitors.

Fuel or Technology	Current Status and Future Prospects
Fusion	Fusion remains the physicist's dream for an unlimited long-term power source, but decades of R&D have not yet cracked the energy breakeven barrier. Containment requirements imply high capital costs even if the basic technology problems are settled. Fusion is unlikely to become commercially viable for many decades.
Transportation	The number of passenger cars has saturated in industrialized countries, but is growing rapidly in developing countries; this has made China a net oil importer instead of net oil exporter. The ultimate issue in transportation is what the public, and decision-makers around the world, are willing to sacrifice to maintain the primacy of private automobiles in planning decisions. The biggest potential gains in transportation are not on the supply side, but on the demand side: demand reduction through rational land-use planning and revival of freight and passenger trains and other forms of mass transit. Given the existence of lots of private cars, short-term options include higher fuel efficiency standards for conventional engines (politically difficult in the current U.S. climate), hybrids, and biofuel blends. In the longer term, options include all-biofuel internal combustion, hydrogen fuel cells supported by a massive new hydrogen infrastructure, and electric vehicles, which need less expensive, higher power density batteries and low-cost electricity to be commercially viable.
Distributed Generation	Distributed generation (also known as DER, Distributed Energy Resources) reduces transmission congestion and central station generating requirements by locating small generating units in close proximity to loads. DG is an outgrowth of the logic of PURPA (U.S. legislation opening wholesale power markets to small private generators) and the technology of backup generators, but has taken on a life of its own. While DG contradicts the traditional logic and culture of utility engineering, which favors central station power and economies of large scale, it has substantial advantages in areas like reliability, voltage support, coincident peaking capacity and reduced vulnerability to terrorism. DG substantially affects long-term electricity supply options by favoring technologies with useful features at small scales, such as microturbines, fuel cells, solar PV, and wind. In the near to medium term, in deregulated power markets characterized by price volatility, uncertain reliability, and declining power quality, DG is likely to grow rapidly. Questions remain regarding air pollution, urban land use, and electrical stability in grids with a high percentage of DG.

Fuel or Technology	Current Status and Future Prospects
Microturbines and Minigrids	Microturbines are small combustion turbines (25 kW to 500 kW) with very high rotation speeds (~ 100,000 RPM) derived from turbochargers in trucks and aircraft auxiliary power units. The microturbine industry is so far led by small manufacturers, of which the leader is Capstone, which has a few thousand units in the field. Microturbines – which are much cleaner and quieter than diesel generators – are expected to be the technology cornerstone of distributed generation. Microturbines could be a significant technology in the long term if there are low-cost hydrogen or carbon-neutral biofuels to burn, and the DG paradigm itself takes off. In the developing world, very high costs of grid extension may foster the widespread growth of local minigrids, using microturbines as the primary supply technology, or as a backup to intermittent renewable sources.
Energy Efficiency: Buildings, Lighting, Motors	Energy efficiency remains an enormous untapped resource. It is widely estimated that energy efficiency with off-the-shelf technology could cost-effectively reduce the world's primary energy demand by half (5-7 TW), and aggressive technology development could do so by perhaps three-fourths. The barriers to reaping the climate and other benefits of increased efficiency are neither technical nor economic but social and political – consumer and corporate purchasing decisions based on first cost rather than lifecycle cost, and little means of incorporating the positive externalities of reduced energy consumption. In addition to transportation, major opportunities for efficiency improvements exist in buildings, lighting, and motors. In buildings, the biggest gains are to be made in design, materials, and controls. Designs maximizing natural heating, cooling, and ventilation can replace much or all of the demand on HVAC systems, which can in turn be downsized and fitted with economizers and variable speed drives (VSDs). In U.S. states with strict building energy codes, automated, sensor-driven energy management systems have become common in new commercial buildings; an obstacle to wider adoption is that some building managers lack the skills to operate them. In lighting, natural daylighting by design is the preferred option. Compact fluorescent lamps (CFLs) and light tubes are more than competitive on a lifecycle cost basis, but face first-cost barriers. Dimmable fluorescents and LED lamps (a two order of magnitude improvement in watts/lumen over incandescent bulbs) are the likeliest long-term lighting solutions if manufacturing costs can be reduced. Great progress has been made in windows, including special coatings that adjust light transmission with conditions. In industrial motors, efficient VSD motors and right-sizing could result in enormous gains, especially in developing countries. For appliances, more efficient 3-phase motors could be used with the addition of existing converters than turn 1-phase house current into 3-phase. Education, investment, and government leadership remain the principal barrier to efficiency.

Next Steps

No-Regrets Energy Policy

Components of a no-regrets energy policy from now to 2020, which could stabilize CO_2 emissions and buy time for further technology development (in addition to producing net positive economic benefits in the medium term) would include the following:

- Decarbonize electricity through transition from coal to natural gas fuel for thermal power plants, efficiency standards for end-use equipment, and renewable portfolio standards (RPS) requiring increases in the renewable share of generation (a plausible maximum of about 20% globally by 2020).
- Decarbonize transportation through increased fuel efficiency standards, promotion of public transit and hybrid vehicles, support for clean developing country transportation
- Transition from coal to natural gas as industrial and residential fuel; improve security of Russian and Central Asian supplies to East Asia to encourage move away from coal.
- Ratify Kyoto Protocol, implement carbon taxes and emissions trading in way that will provide revenues for R&D and implementation, including in developing countries as part of a climate and equity global New Deal.
- R&D on longer-term technologies such as hydrogen transportation system, carbon capture and storage, superconductors, advanced nuclear, advanced solar PV, and advanced solar thermal.

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