

**Energy, Environment, Security:
Can We Have It All?
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CISAC Drell Lecture
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1. Introduction

There are multiple reasons why it is a particular *personal* pleasure for me to be giving a Drell Lecture. I've known Bud and Cicely Wheelon for some 15 years through Bud's service as a Caltech Trustee. Sid Drell has been my friend, colleague, and mentor for more than 20 years. And, beyond a common MIT heritage, the three of us share a passion for, and belief in, the application of a physicist's tools and sensibilities to important societal matters.

My subject today is the nexus among energy, environment, and security. Providing secure and sustainable energy to meet the world's growing demand is one of the most difficult tasks facing society in the next several decades. As energy issues are invariably a complex tangle of technical, economic, and geopolitical considerations, my topic is more than suitable for a Drell lecture.

My approach will be that of a physicist, following several previous Drell lecturers I know and admire. I will be factual, quantitative, and analytic, trying to clearly distinguish "knowledge and uncertainties" from my own opinions or judgments (which are not necessarily those of BP, plc). My time frame will be no more than the next 40 years or so, since it is difficult to project any further than that. And it's also most important to get the right level of resolution, identifying general principles and broad trends and understanding which details do (and don't) matter.

I've a three-part plan for the next 40 minutes. I'll start with the facts – something that is not always done with

* The judgements and opinions expressed here are those of the author and do not necessarily represent the corporate stance of BP, plc.

energy – and sketch the status and plausible projections of important energy aspects. I'll talk about what could be done to address the challenges we face. And I'll close with some thoughts on the necessity of broadening the energy discussion to other great problems facing the world.

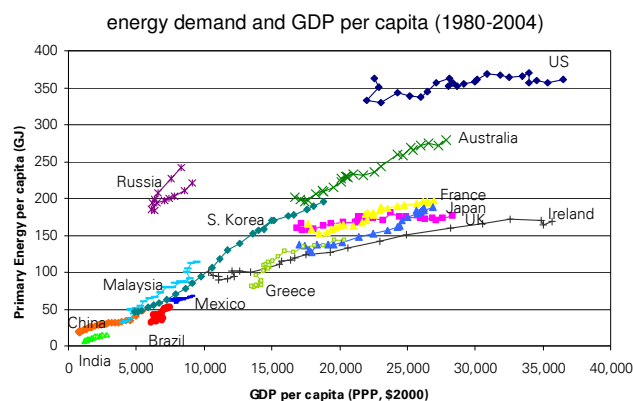
2. Energy Facts

There are many things to understand about energy, but given limited time, four broad statements should suffice.[†]

2.1 Demand growth

The first statement is that energy use will grow strongly during the next several decades. That fact is illustrated by **this chart**, which shows, for various countries 24 year trajectories of the annual *per capita* energy use against the annual *per capita* GDP.

energy use grows with economic development



Source: UN and DOE EIA
Russia data 1992-2004 only

The US is an outlier - a high, but slowly growing, energy consumption and a high GDP. There is another group of countries in the Developed World, the EU and Japan, whose energy per person is about half that of the US, but with a *per capita* GDP that's only about two-thirds the US. And then there is a swath of countries in the Developing World -

[†] A more detailed exposition can be found on BP's Energy Trends and Technologies video, available on DVD or streaming at <http://clients.mediaondemand.net/BP/#>

China, India, Brazil, Malaysia, Mexico - whose energy use per capita increases steadily and universally as their economies grow. **[Tell the China story.]**

Two general conclusions emerge from these data: first, nobody uses less energy as they get richer, and second, because there are about a billion people in the Developed World, another 2½ billion people in the Developing World, and another 2½ billion people who weren't even on that chart, one can expect demand growth as economic conditions continue to improve around the world.

That economically driven demand growth will be enhanced by the global population rising from the current 6.5 billion to a broad peak of about 9 billion people at mid-century. Most of that growth will be in Africa and Asia, so that Europe and North America will contain smaller, and relatively older, fractions of the world's people by mid-century.

Economic improvements and growing population will lead (indeed, are *already* leading) to a very strong growth in energy demand. Business as usual projections show energy demand increasing by some 60% to 2030 and doubling by mid-century, with about 75% of that increase coming from the Developing World.

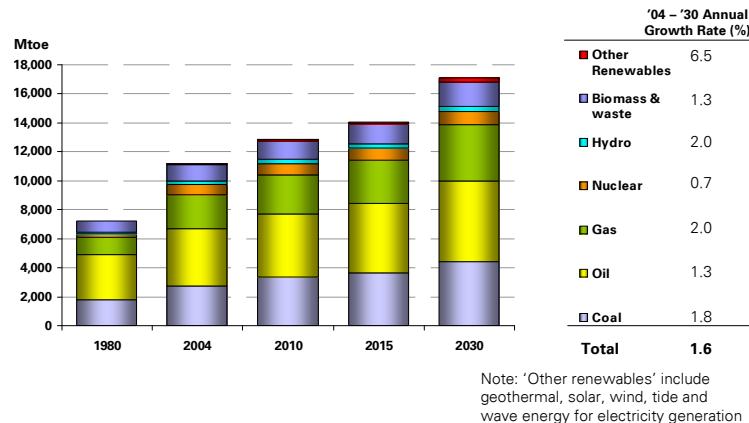
2.2 Fossil fuel dominance

The second statement is that today, and in the foreseeable future under plausible historic trends, the great majority of the world's primary energy comes from fossil fuels.

This chart shows the historical and “Business-as-usual” projected sources of the world's energy. The 2010 bar shows that coal, oil and gas provide almost 80% of today's primary energy. You can see that even though renewables are expected to grow strongly, by 2030 they will still account for a very small fraction of the world's energy. So, for the next many decades, most of our energy seems destined to

come from fossil fuels because of their availability, low cost, and ease of use.

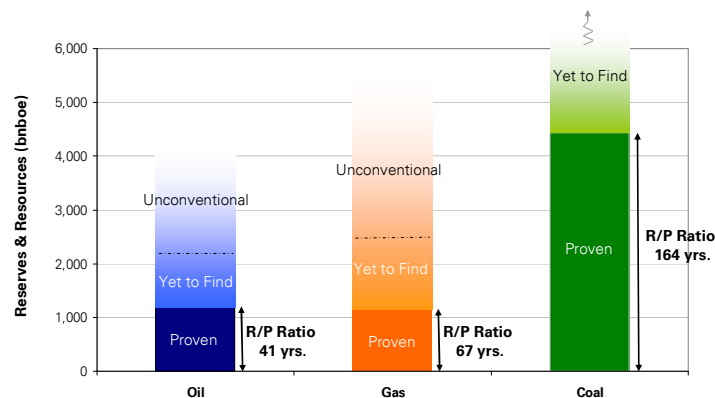
BAU projection of primary energy sources



Source: IEA World Energy Outlook 2006 (Reference Case)

That point of “availability” merits some elaboration. While fossil fuels are a finite resource, we will not run out anytime soon, as shown **in this chart**.

substantial global fossil resources



Source: World Energy Assessment 2001, HIS, WoodMackenzie, BP Stat Review 2005, BP estimates

At current consumption rates, there are 40 years of conventional oil and 60 years of gas known to be economically recoverable, with further equal amounts of each plausibly yet to be identified. And there is at least 150 years worth of coal, with plausibly much more- nobody has ever gone exploring for coal.

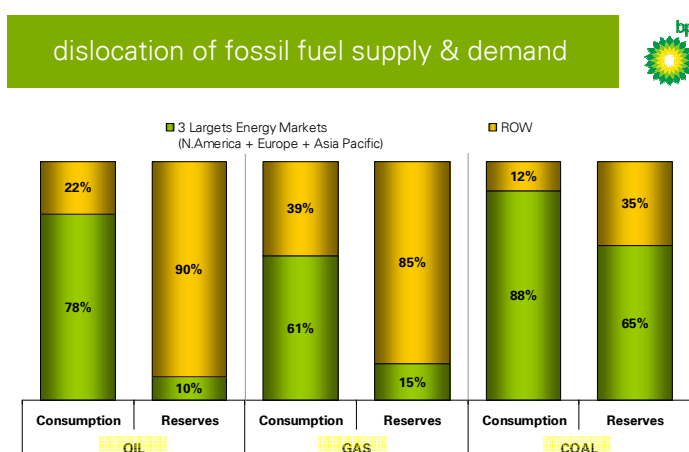
One aspect of fossil fuels you will hear much about is the peaking of oil production and the disruptions that will entail. Oil is distinguished among the fossil fuels in that it is the only fuel currently powering transportation, largely because of its high energy density.

If you've been around awhile, this is not the first time you will have heard people saying that "we're going to run out of oil." And one day, they'll be correct. But right now, the world plausibly has some 4.5 trillion barrels of oil recoverable at costs that are economic relative to today's price of \$90/bbl. This is some four times the total consumption expected over the next 25 years.

It is true that most of that oil will be more difficult to produce and of lower quality. However, it doesn't look to me like there is a shortage of hydrocarbons in the ground. Rather, as one of my BP colleagues says, oil production is determined not so much by the situation below the ground as by the situation above the ground - the demand, the technology, the economics, and the politics.

2.3 Maldistribution of fossil reserves

The third statement is that fossil fuels are maldistributed around the world, in that there is a dislocation between where the fluid hydrocarbon resources are and where the demand centres are.



Source: BP Statistical Review 2006

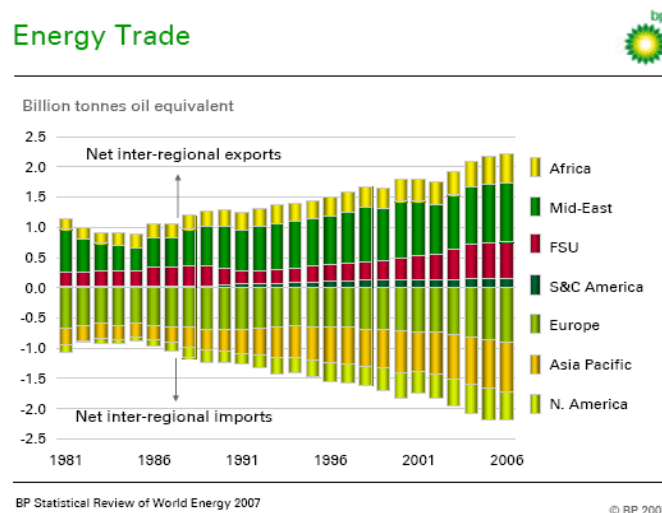
One sees from **this chart** that the three largest energy consuming regions (North America, Europe, and

Asia/Pacific), consume 80% of the oil produced every day, they have only 15% of the conventional reserves.

The situation for gas is a bit more evenly matched: 61% of the consumption and 32% of the reserves, while for coal, there is a fair alignment. Of course, not shown on this chart are so-called unconventional resources (heavy oil, tar sands, tight gas) all of which can make a material contribution to supply, although at increased cost, difficulty, and possibly emissions.

Another trend relevant to energy security is the increasing concentration of oil reserves in the hands of national oil companies (NOCs like Aramco or Petrobras) as opposed to the international oil companies (IOCs like BP, Exxon, and Shell). The IOCs have access to only some 10% of the conventional reserves, yet currently account for about 35% of the world's daily oil production. And, in general, the publicly owned and publicly scrutinized IOCs are more efficient and adept than the NOCs, whose strategies may have drivers beyond economics.

The growing energy trade depicted **in this chart**

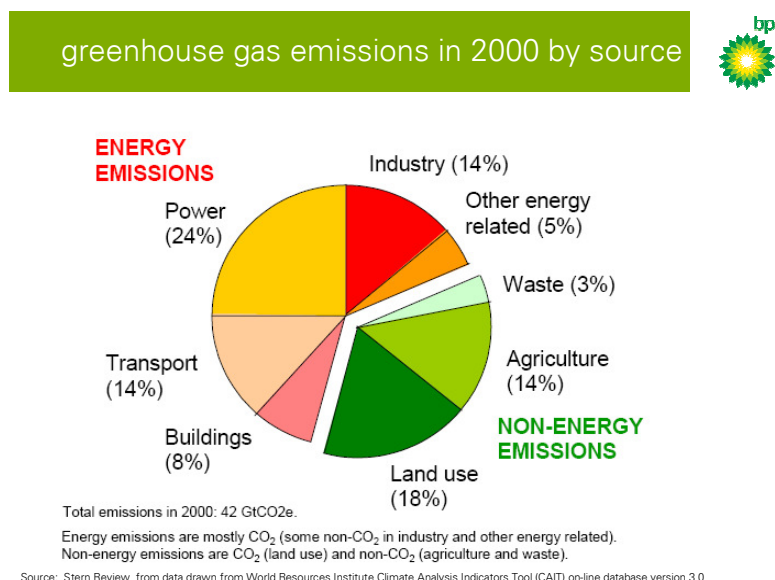


demonstrates that the world's energy security in oil and, to some extent, gas depends upon stable investment and production in distant lands with sometimes unstable

societies and a stable trade system to move those hydrocarbons around efficiently. But as the large consuming nations become worried about energy security, they will increasingly turn to coal and unconventional reserves.

2.4 CO₂ emissions

The fourth and final point is that the conventional use of fossil fuels adds Green House Gases (GHGs) to the atmosphere, as shown in the chart below. Indeed, 60% of anthropogenic GHG emissions arise from energy, of which roughly 40% each arise from power and heat and 20% from transport. Agriculture and deforestation make substantial non-energy contributions.

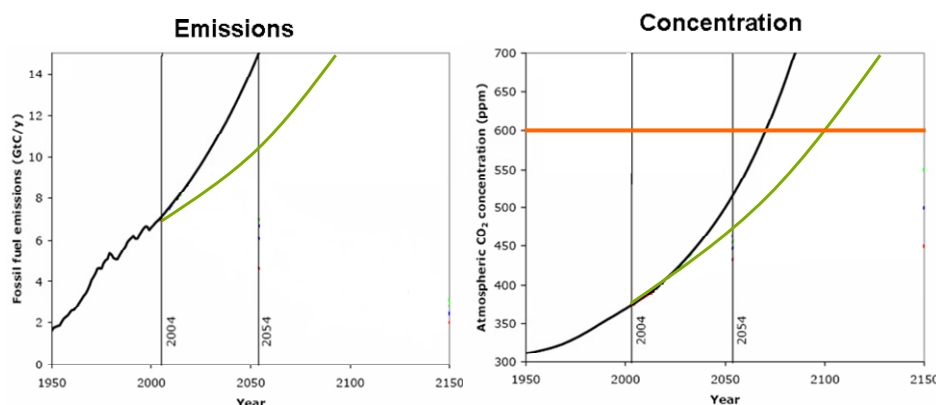


These GHGs have accumulated in the atmosphere to the point where they are very likely contributing to the climate change we are observing, and will likely influence the climate even more strongly as they accumulate further in the coming decades. While the detailed impacts of future anthropogenic climate change are not known, we do know broadly that they will entail disruptions and costs that could range from merely inconvenient to catastrophic. The much discussed increase in global temperature, whatever it turns out to be, is not particularly reflective of the possible consequences, which include increased desertification and

precipitation, shifts in vegetation and fauna, sea level rise, severe storms, and so on. These are not things we'd want to happen.

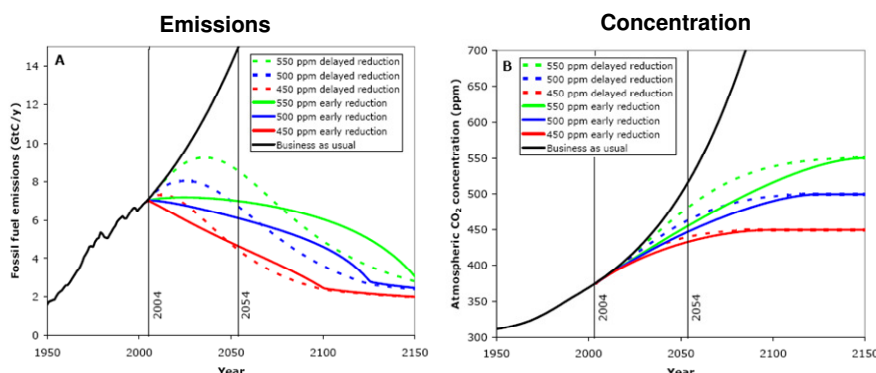
The cumulative nature of the GHG problem is particularly insidious, though little appreciated among the general public. The **left-hand graph** plots annual fossil fuel

crucial facts about CO₂ science



emissions, with the black line showing the historical data to 2004, and a “business as usual” 1.5% compounded annual growth extrapolated into the present century. Because about half of the CO₂ emitted each year remains in the atmosphere with a lifetime of more than 1,000 years, the atmosphere effectively accumulates emissions, so that the concentration rises at more or less the same rate, as shown in the right hand graph. Under business-as-usual, the concentration reaches levels deemed to be dangerous no later than mid-century. The problem caused by accumulation is that a modest reduction in emissions (according to that grey curve, for example) would only delay, but not prevent, the concentration from crossing thresholds deemed to be dangerous.

crucial facts about CO₂ science



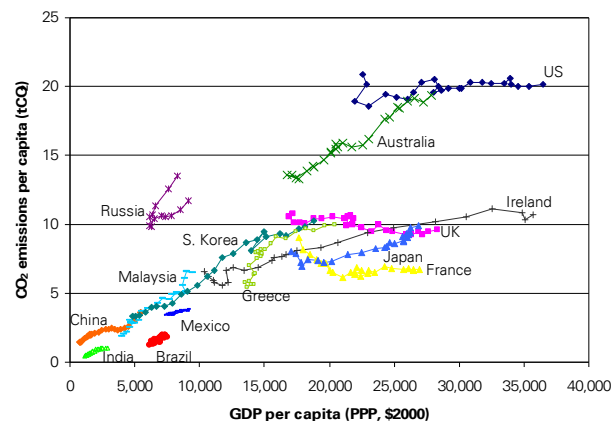
Drastic reductions in emissions are needed to make a material impact on the concentrations. For example, one of the green emissions trajectories above would stabilize the concentration at 550 parts per million, twice the pre-industrial value (note that there is a trade off between stabilizing emissions now or allowing them to grow for a while at the expense of more drastic cuts in the future). The blue and red trajectories allow stabilization at 500 and 450 ppm, respectively. These lower concentrations are those that an increasing number of scientists is talking about as being thresholds beyond which we would exert dangerous influence on the climate system.

These simple considerations also show that emissions by the end of this century must be reduced by about a factor of two from their current value if we are to have any hope of stabilization. That is in the face of an anticipated doubling of energy demand by the middle of the century. So we have to cut the carbon intensity of our energy system by a factor of four or so.

Beyond these global emissions challenges, one finds difficulties in the question of who is emitting and how much. **This chart** shows CO₂ emissions *per capita* vs. GDP. The situation looks much the same as in the energy trajectories I showed you - large but slowly growing emissions from the Developed World, and smaller but more rapidly growing emissions from the Developing World. Interesting outliers relative to energy consumption are France (since some 80%

of its electricity is produced from fission) and Brazil (with a large proportion of hydroelectric power and carbon-neutral biofuels).

CO₂ emissions and GDP per capita (1980 – 2004)



Since total (not *per capita*) emissions from the Developed and Developing worlds are just about equal this year, there are **three sobering implications** of these data

implications of emissions heterogeneities



- In the present Century, emissions from the Developing World (DW) will be more important than those from the Industrialized World (IW)
 - Each 10% reduction in IW emissions is compensated by < 4 years of DW growth
 - If China's (or India's) per capita emissions were those of Japan, global emissions would be 40% higher
- **in this Century**, cumulative emissions from the Developing World will be larger than those from the Developed World.
 - **with current trends**, every 10% reduction that the Developed World can make in its emissions (not something it has yet managed to do), is offset by less than four years of growth in the Developing World.

- if **the *per capita emissions*** of either China or India were to grow to be equal to those of Japan (one of the lowest of the developed countries), global emissions would *increase* by 40%, whereas GHG stabilization requires a 50% decrease by the end of this century.

To close off this discussion of energy trends, I **show** you world CO₂ emissions, which are growing rapidly, even as its energy supply decarbonizes slightly. But it is also disturbing that the countries who have signed up to the Kyoto protocol have actually increased their emissions in the past decade.

3. What needs to be done

The take-away from that whirlwind tour of the energy scene is that the world faces at two distinct energy problems: security and emissions.[‡] Addressing either or, ideally, both requires major changes in the ways we produce and use energy. To have impact on the scale required by these problems, the changes must be technically feasible, material, cost-effective, and politically acceptable.

Even with that stringent set of criteria, there *are* useful responses. But before going into specifics, it is important to enumerate some structural features that distinguish energy from many other problems facing society.

3.1 Distinguishing aspects of energy

The first feature is that of ***scale***. Energy is distinguished by large and costly infrastructure (a single power plant or off-shore oil field can be a multi-billion dollar investment), large amounts of material (globally measured in gigatons), and large numbers of units (vehicles, etc.). This scale requires large amounts of capital and/or the ability to

[‡] A third problem is energy poverty. This is largely decoupled from the other two I've discussed because plausible improvements in the lives of the 2 billion people afflicted would entail only small increases in fossil fuel demand and GHG emissions.

leverage existing infrastructure. For that reason, the existing energy industries must almost certainly be part of any changes.

distinguishing aspects of energy technologies



- **Scale**
 - Large infrastructure, amounts of material, numbers of units
 - Requires large capital, leverage of existing infrastructure
- **Ubiquity**
 - There are many players with sometimes divergent interests
 - Consumers, suppliers, governments, NGOs, ...
- **Longevity**
 - Lifetimes of large equipment and/or interoperability imply slow changes
- **Incumbency**
 - New energy technologies must compete on cost
 - May not provide any qualitatively new service to the end-user

The second feature is *ubiquity*. Energy enabling heat, light, and mobility is so ubiquitous that we hardly give it a thought as we go about our daily lives. Yet that very ubiquity generates direct interests from many different players: industry, consumers, governments, and NGOs. As interests are often not aligned, change occurs slowly.

The third feature is one of *timescales*. The lifetimes of large equipment (to a century for buildings, 50 years for power plants, 20 years for automobiles) make it difficult to effect rapid changes. The need for interoperability also inhibits change. For example, BP cannot make arbitrary changes in its fuels, as they must work with all existing vehicles. And consider that while the carbon problem has decadal to millennial timescales, the infrastructure lifetime is decades, the political timescale is a few years, the business timescale is a quarter, and the news cycle is a day (or even less). Society is not well equipped to handle problems of this duration.

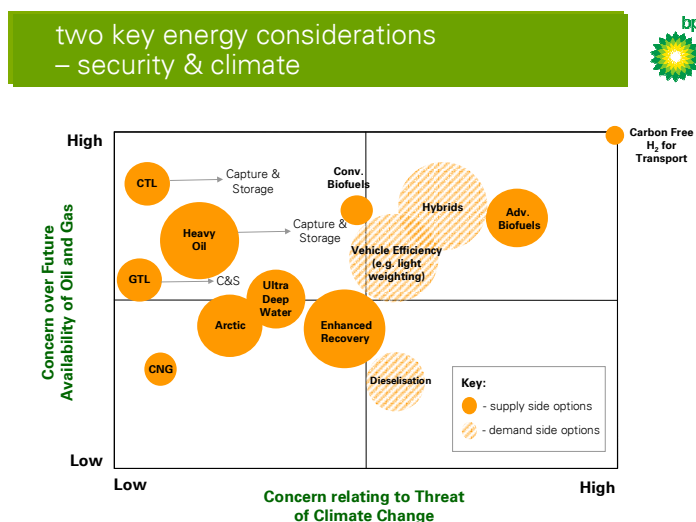
The fourth feature of energy is *incumbency*. From a consumer point of view, there are already perfectly fine technologies for heat, light, and power. Any new technologies introduced, which will not provide any qualitatively new services, must compete on cost and against existing interests.

3.2 Energy technologies

The levers available to make changes in the energy system are technology and policy. Policy types will say that the development and deployment of technologies is policy dependent and that is all one need consider. But we technical types know that there are powerful physical constraints that any technology must respect - you won't repeal the 2nd law of thermodynamics by taxing entropy! Moreover, one can make plausible judgments about technology evolution on a several-decade scale. And so let me consider energy technologies first, and then I'll turn to policy.

The commonly invoked “no silver bullet” approach to energy technologies is, to my mind, the wrong way to be thinking. The world has limited resources (whether financial, brainpower, or tolerance for change) and limited time in which to address the dual challenges of security and emissions. We must assess technologies against their ability to scale, their economics, and their technical headroom. The deployment of ineffective “feel good” technologies is doubly bad in that it both creates the illusion of doing something and also diverts resources from effective measures.

Let us start with transport technologies. Full electrification of the drive train may eventually happen, the limitation being electrical storage technologies. But for the next few decades liquid hydrocarbons are what will matter, because of their high energy density. It's useful to consider a **two-dimensional plot** where one axis is “security of supply” considerations (roughly read as oil price) and the other axis is carbon dioxide emissions (roughly read as carbon price). Technologies can then be plotted, the size of each circle giving some indication of materiality.



On the supply side, absent concerns about climate change, there are a host of material and cost-effective options that address security of supply through diversification away from conventional crude. These involve more difficult hydrocarbons, either because of access or quality – heavy and shale oils, tars sands, converting coal or natural gas into liquids. Most of these technologies will entail emissions at least as large as those of conventional crude, although the excess could be minimize by capturing and storing the CO₂ emissions that result from the processing.

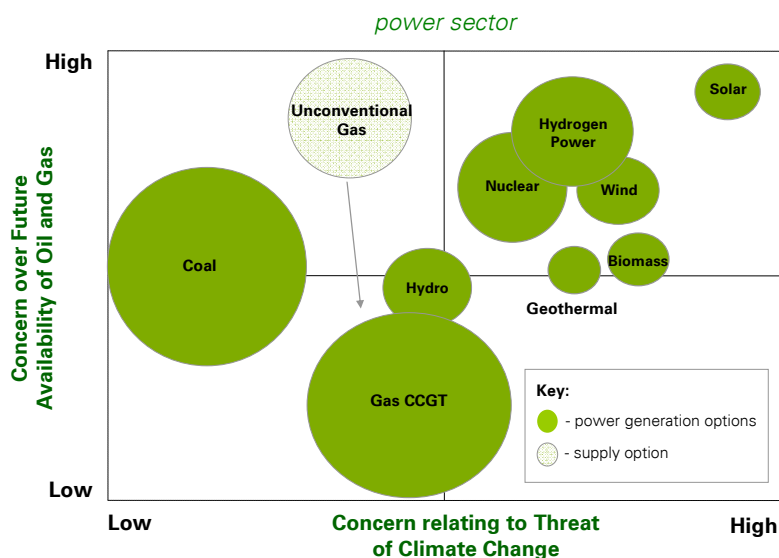
The only material supply option addressing both security and emissions is advanced biofuels. (Carbon free hydrogen is shown provocatively as a small circle). Conventional biofuels production (for example, ethanol from corn here in the US) has been piggybacked on food agriculture. As such, it has difficulty scaling to materiality and has limited GHG benefits. Advances in biology are opening significant possibilities for doing better – dedicated energy crops grown sustainably providing lignocellulose that is processed into fuel molecules superior to ethanol. There is great potential here and, as you may know, BP recently established the Energy Biosciences Institute with Berkeley and the University of Illinois to accelerate the development of these technologies.

Demand side transportation options can play an important role. Hybridisation and/or lightweighting of

vehicles can make a difference and there are other changes in engine technology that can be deployed. Plug-in hybrids seem an excellent idea on the horizon - a 40 mile electric range would cover 70% of the trips in the US. All of these technologies exist or are within reach - it's really a question of whether the political will is there and the economic forces can be arranged.

When one views **power technologies** in the same dimensions, absent emissions concerns coal is by far the favored option. It's available, it's where the demand centres are, it's easy to use, and it's inexpensive; however, it is most carbon-laden of the fossil fuels. Natural gas is better- it emits about half the CO₂ per unit of energy produced; however, there can be security of supply concerns. Hydroelectric power is effective, but the world's capacity is nearly exhausted.

evaluating power options



There are three material options in the upper right quadrant – wind, nuclear power, and hydrogen power. Let me remark briefly on each.

- Wind power is a quite mature technology that is competitive with fossil fuels at good on-shore sites. It is being deployed rapidly and is approaching 1% of the total electricity generated in the US. Cautions, though,

are the availability of good sites and their distance from demand centres, intermittency, and public acceptance of wind farms. It's plausible that wind could grow in the next few decades to 15-20% of US electricity produced, but larger fractions seem unlikely to me.

- **Fission currently supplies about 16% of the world's electricity (20% in the US or UK), but has not grown materially in the past two decades. It is a proven technology that produces material amounts of emissions-free power at competitive economics. So if the world is going address CO₂ emissions seriously, nuclear will almost certainly be a major part of the picture. Yet it is not without its drawbacks – concerns about safety, the management of waste, and the potential to accelerate the proliferation of weapons-relevant expertise, if not materials. However, most of these issues seem to me social and organizational, rather than technical. Renewed attention to these matters on both the national and international scale should significantly reduce concerns. And while fission is now used exclusively for power, newer and safer high-temperature gas-cooled designs, which are on the verge of being demonstrated at scale, offer interesting possibilities for heat to extract and process hydrocarbons for transport.**
- **Hydrogen power is BP's term for carbon capture and storage, where fossil fuels are burned so that hydrogen is produced to generate electricity and the CO₂ is captured and stored underground, where it is expected to remain for many millennia. Hydrogen power is more than a notion, as all of the above-ground elements have been demonstrated, but not yet integrated on a commercial scale. The integrity of the below-ground containment is plausible, but also remains to be demonstrated. The fully-mature technology is expected to have costs comparable to nuclear power.**

The set of hydrogen power demonstration projects proposed by BP and other companies will not only help refine the technology, but also to define the social and legal context in which hydrogen power would be deployed. Monitoring criteria, liability, and public acceptance are all crucial issues to be working on. But, together with nuclear and wind, this is one of the few material supply-side options for power.

3.3 Conservation and efficiency

Improving energy efficiency is a commonly invoked approach to reducing energy use and hence addressing both the security and emissions concerns. For example, about half of the world's energy is consumed in buildings for heat or light or ventilation, and there are already many technologies to enable that energy to be used more efficiently. Yet they are not aggressively deployed, the barriers being economic and social.

Urban energy systems are another potential big win. Today, half of the world's people live in big cities, by 2030, 70% will be living in big cities. Building cities with careful attention to building design, the integration of residential, commercial and industrial spaces, and the transport systems for people, goods, and information could, in principle, significantly reduce energy use.

However, it is important to realise that efficiency and conservation are not the same thing. Indeed, improvements in efficiency can even lead to increased energy consumption. For example, if gasoline prices remain constant, improving the mileage of an automobile could result in more miles driven, not less. And if you improve the operating costs of a refrigerator too much, households will start to have two or three of them.

In my opinion, the only sure ways to induce conservation, as opposed to efficiency, are to regulate its use or to raise its price. Both of these are difficult acts for governments to pull off and still remain in power.

3.4 Energy policies

That is a good segue into a brief discussion of energy policies. The desiderata here are rationality, effectiveness, and measures of continuity and stability. Easy enough to state, but difficult to realize in practice, I believe.

To address the security problem, one important step is to promote the effective functioning of global energy markets. Bilateral oil arrangements are increasingly common, but inefficient. The existence of the OPEC oil cartel and a nascent global gas cartel are problematic in this regard.

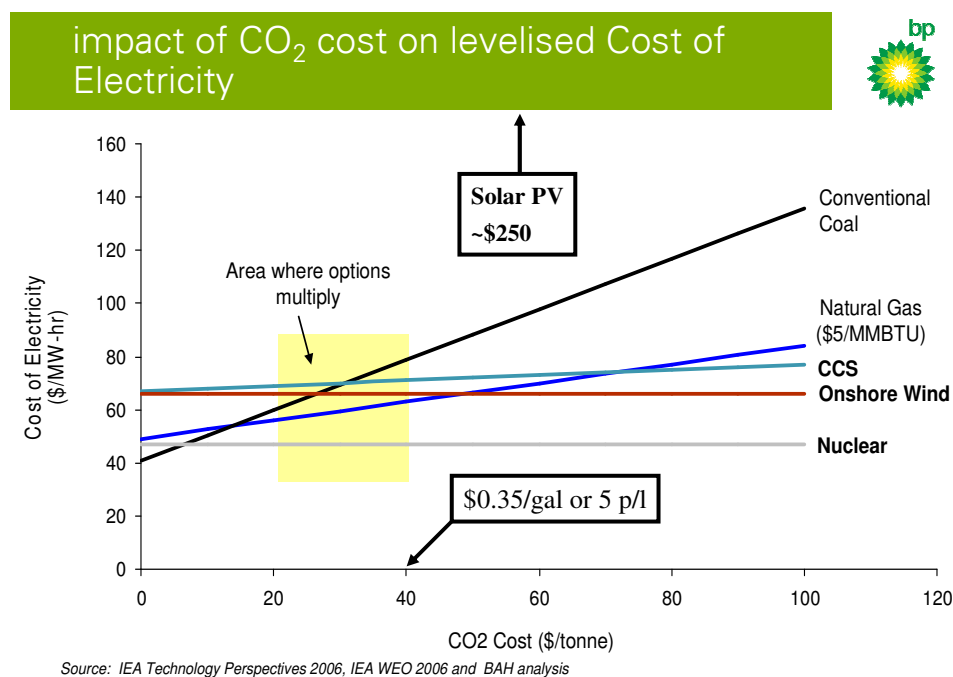
A second important step is to induce a favorable investment climate for production by promoting the stability and effective use of revenues in producing nations. All of this implies a greater and more productive engagement with the rest of the world than the US has had in the recent past.

Certainly there are responsible ways to increase US conventional oil and gas production, but they cannot be enough. So rather than the elusive energy independence, (in 1973, because of the OPEC oil embargo, President Nixon set 1980 as the date by which the US would achieve energy independence!) instead of energy independence, energy security should be achieved through a diversity of supply involving unconventional oils, coal and gas to liquids, and biofuels. Even here, there is a need to align foreign policies with energy policy. You'll know the US is getting serious when it drops its tariff on Brazilian ethanol imports or the UK drops import duty on Chinese high-efficiency light bulbs.

For the climate problem, some of the steps are more concrete. We must focus on the most cost-effective and material options for mitigating GHG emissions with a level playing field for all technologies, for example not confusing the goal of emissions reduction with that of promoting renewable technologies. Government support for precompetitive research in advanced solar, fusion, fusion, and biofuels is essential. And it is important to promote

deployment of a technology at the appropriate moment; we have seen some outstanding examples where premature deployment of technologies leads to great expense, but little impact.

Assigning a serious cost to GHG emissions is an almost essential policy measure now being implemented spottily around the world. Simple considerations show what the price needs to be in order to have an effect, at least in the Developed World. Let us plot the cost of electricity against the carbon price for various technologies. For zero carbon cost, which prevails is most of the world right now, coal is cheapest, yet it rises most rapidly with carbon cost. Natural gas or nuclear are somewhat more expensive at zero, but rise more slowly, if at all. The other technologies behave as shown.



A take-away from this graph is that the lines cross somewhere between \$20 and \$40 per tonne of CO₂, so that a carbon cost of at least \$20 per tonne is required induce serious decarbonisation and that if the price is more than \$40, the system is being stressed too hard.

Note that solar electricity is some six times more expensive than other emissions-lite technologies. Solar is

wonderful for off-grid applications, and for peak shaving in warm regions where electricity is very expensive by time-of-day. But in terms of having a material impact on carbon emissions, wide deployment of existing solar PV is not cost-effective.

If the carbon costs were \$40 a ton, coal in the US, which fuels roughly half of the power, would effectively be quadrupled in price, yet the price of oil would increase only by 25%. At the consumer level, gasoline would increase by only \$0.35 per gallon, small on the scale of recent price fluctuations. This implies that power is by far the most cost effective place to reduce carbon emissions, more so by about a factor of five relative to transport. It is therefore fortunate that far more carbon emissions come from power and there are multiple material options for emissions reductions.

A carbon price can be effected either through a cap-and-trade system, as is already in effect in the EU and will soon be implemented here in California, or through a carbon tax. There are many learned discussions about the relative merits of these two approaches. But either way, I think two aspects will be important. The first is long-term stability. If a company like BP is going to invest an extra billion dollars in an emissions-lite power plant, it needs a reasonable notion of what those emissions reductions will be worth three decades later. (Note that is 15 Congresses and 7 Presidential terms!) The second is an appropriate and transparent use of the revenues, including, for example, alleviating the impacts on the poorest. I am sceptical that the political system can pull all of that off. The carbon price must, of course, be universal to be effective, else in our globalized world carbon-intensive activities will simply shift to zero-price regions.

That brings me to the nub of the emissions problem. The Developed World has the resources to develop and deploy emissions-lite technologies. As I've shown, these currently have a considerable cost premium relative to conventional alternatives. The Developed World has started

down an emissions reduction path, although there are uncertainties about how much can be achieved. Yet, the Developing World has a host of more pressing problems facing it (including infrastructure, health, and education), so that emissions reduction necessarily has lower priority. Unless emissions-lite technologies can be developed to the point where they have essentially no cost premium, we must face the question “Who will pay the Developing World not to emit?” I have been asking this simple question to many people over the past few years and have yet to hear a convincing answer. Perhaps those of you knowledgeable in international trade or finance can help here?

3.5 Can we have it all?

Let me then turn to the question posed in the title of this lecture, “Can we have it all?”. My answer is that we *could*, and *should*, effectively address the dual challenges of security and emission, but I think we probably won’t. Let me explain.

The direct impact of energy security and its immediacy in time and place naturally make it the higher priority problem. Recall that security is largely about reliable and reasonably priced liquid fuel for transport and, to a lesser extent, natural gas for power and heat. I believe that market forces, the diversity of carbon sources, mileage standards, and the gradual electrification of transport will all contribute, although there will be bumps along the way due to the inevitable supply/demand mismatches. These could be smoothed if governments take a long-enough view to minimize disruptions. Sadly, we’ve been unable to do that in the US (or in most other nations, for that matter.)

I am much less sanguine about our solving the emissions problem. As I’ve shown you, there are certainly policies that *could* be implemented and technologies that *could* be deployed to stabilize GHG concentrations at 550 ppm, or even lower. Businesses like BP are making initial

steps at this, and could do much more, given the right policy framework.

Yet many things the world *could* do don't get done (the alleviation of poverty is just one example). In the emissions case, as I've discussed, there are formidable barriers involving scientific and technical realities, economics, politics, the way democracies work, and basic human nature.

So I think one has to consider the possibility, if not probability, that the world's best efforts at conserving energy and decarbonizing the energy supply will not solve the emissions problem, leading to the obvious question of **"What is Plan B?"** There has been a largely muted public discussion of this topic, for fear of distracting from the goal of mitigating emissions. Yet given the realities, I believe that it is irresponsible, particularly for academics, not to be studying this matter seriously.

Adaptation, which is already going on in parallel with mitigation efforts, must be a major element of Plan B. The degree of adaptation (which might include shifts in agriculture, hardening of existing infrastructure, building dams, dykes, and aqueducts, and perhaps even mass migrations) will, of course, depend upon the nature and severity of impacts, which are largely unknown. We have yet to see a taxonomy and quantification of the costs and benefits of adaptation measures analogous to the Princeton mitigation wedges. Despite this, I think the proportionality of adaptation, as well as its immediacy in space and time, make it likely the dominant societal response. There are reasons to believe adaptation will be effective, given the extreme range of environments that humans already inhabit. However, it will be more difficult in the Developing World, and particularly in regions close to subsistence levels.

And should the worst of the possible climate changes come to pass, geoengineering could emerge as part of Plan B. We are already intervening inadvertently in the climate system through GHG emissions. There are other, more

intentional, interventions that one can imagine, sucking GHGs out of the atmosphere through biosphere interventions or decreasing by a small amount the sunlight absorbed by the Earth. Apart from technical issues, geoengineering has difficult social dimensions, including questions like “Who gets to decide?” or “What are the trigger points?” or “What is the liability for unintended consequences?” It is a route that future generations might very reluctantly consider as a last-ditch response to catastrophic climate change.

4. Beyond energy security and climate

I would like to conclude by drawing some lessons from this energy discussion for other aspects of the world's condition.

This afternoon I think I've shown you that a straightforward accounting of the facts, trends, and technology leads to some powerful conclusions and a more or less obvious set of actions to respond to the challenges they pose. Sadly, as I've been presenting these thoughts for the past few years, I've found that they have perhaps been all-too-well received by general audiences and many decision makers, even though they are largely known to the experts. In short, I am amazed that the world can be, and indeed continues to be, so confused about energy matters.

So we need education. We need education of policy makers to foster wise decisions, education of the public so that they will allow (or at least tolerate), the decisions that have to be made, and education in the universities of people who will work these problems in the future. Technologists fluent in policy (or vice-versa) are particularly important.

Now to generalize. In the next several decades, the world will increasingly face (indeed, already is facing) a number of serious and unprecedented problems. Beyond energy and climate change, these include environmental degradation,

food and water availability, the finiteness of resources such as metals and wood, land use, public health, and emerging diseases,

These problems are driven, in varying proportions, by demographics, the economic rise of most of humanity, globalization, the finiteness and maldistribution of resources, and the advance of technology itself. And they are distinguished by having technical (scientific and engineering) issues, as well as social (economic, political, cultural) aspects. Many are therefore “systems issues” and all are global, most with long timescales.

Understanding how to manage these problems-providing clear analyses and response options and communicating them credibly and persuasively to decision makers and the general public - requires fusing the technical disciplines and the social sciences in unnatural ways. CISAC and other organizations tackling arms control problems are models for doing this, but the new problems facing us are even more complex.§ To find solutions, and I am optimistic that they do exist, we’ve got to focus the world’s prodigious problem solving ability on these issues.

But that is the subject for a whole other discussion and, since I expect I’ve already given you much to think about, it’s best that I stop here. Thank you for your attention.

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For a more complete presentation of Trends and Technologies material, there is streaming video at the URL shown here.

§ Consider how energy differs from nuclear weapons technologies, which are fairly well circumscribed, are in the hands of only a few organizations, don’t touch directly on most of society, and can be changed on a fairly rapid timescale.