

Dangerous Abundance

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David took first prize in Canada's national physics prize exam; he won MIT's prize for excellence in experimental physics; and was named environmental scientist of the year by *Canadian Geographic* in 2006. He has held the Canada Research Chair in Energy and the Environment and served as Professor in the Department of Chemical and Petroleum Engineering and Department of Economics at the University of Calgary since 2004 and remains an Adjunct Professor in the Department of Engineering and Public Policy at Carnegie Mellon.

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Dangerous Abundance

We are simultaneously threatened by both the scarcity and the abundance of fossil fuels. The scarcity of conventional oil poses a serious threat to economic and geopolitical stability, a threat that is intensified by the hugely unequal geographic distribution of the remaining easy oil. Yet, while oil grows scarcer, the very abundance of fossil fuel resources poses a threat that is at least equally serious: climate change—the greatest global environmental threat of our age—is rooted in the extraordinary abundance of fossil resources and the growing ease with which our technology can exploit them.

The scarcity of easy oil tempts many observers to assume that humanity faces an immediate and far-reaching crisis of energy supply, and it is not hard to see why. It is difficult to overstate the importance of energy in modern society. Coal, gas and oil enabled the world's industrial transformation. Many of the technologies and institutions of the modern world first emerged during the eighteenth century's "enlightenment," but it was access to cheap energy that played the central role in accelerating the industrial revolution a century later. Access to abundant fossil fuels—first coal, then oil and now gas—has driven the growth in human population and led to the mobility, high-speed communications and widespread—though grossly unequal—material abundance that are the hallmarks of our age.

Yes, oil is crucially important. But let's not confuse oil with energy. Oil may be scarce, but energy is not. A great deal of energy is stored in fossil fuel reserves which, in their abundance, pose a threat at least as serious as the prospect of running out of oil. There are enough fossil fuels beneath our feet to push atmospheric concentrations of carbon dioxide to well over ten times their pre-industrial levels. We may well have enough fossil fuel within the growing reach of our extraction technologies to nudge our planet's climate towards that found on Venus. Not Venus the goddess of love, but Venus the planet, where the atmosphere is 95 percent carbon dioxide and surface temperatures are hot enough to melt lead. So while it is possible to make a case that oil scarcity poses a threat to our civilization, I argue that fossil-energy abundance is where the more urgent threat lies.

In this essay, I explore the interplay between oil scarcity and climate change, shaping the argument around two alternative scenarios. In the first, we will assume that an oil peak is imminent and explore our options while ignoring concerns about climate change. In the second scenario we will assume the converse: a world with abundant oil in which carbon emissions must be swiftly eliminated to minimize the risk of dangerous climate change. The two scenarios bound the likely path to the future; enabling us to see some of the more onerous constraints and through them to imagine future opportunities.

Scenario One: Tight Oil, Loose Carbon

Suppose that we lived in a world where oil production declined sharply yet there were no concerns about carbon and climate. How might we reshape the energy system to answer this threat? To put some meat on the story, let's assume that the production of conven-

tional crude oil peaks today and begins to decline, at first slowly and then at an accelerating rate, so that production is a third of today's roughly eighty- five million barrels per day by 2050.

This is a strong “peak oil” scenario in which the decline in production is a little faster than the rate at which production increased over the last forty years. My view is that such a scenario is quite unlikely. As I will describe below, there are good reasons to expect that production of conventional oil would decline more slowly, unless demand is intentionally restrained. However, peak-oil advocates make some strong arguments, so it's worth considering such a scenario. In any case, my purpose here is to examine what we could do to manage a sharp oil peak— ignoring the climate constraint for now— independent of the probability that such a peak will actually occur.

On the climate side, one could assume— for the purpose of the scenario— that some cheap and clean method is found for removing carbon from the atmosphere. For argument's sake, suppose someone discovers a cheap method of accelerating the global weathering cycle that drives the permanent removal of carbon dioxide from the biosphere and so eliminates the climate threat. The mechanism is unimportant. All we have to do is envision a hypothetical world in which we don't have to worry about the climate. Could we manage an oil peak under this scenario?

The short answer is yes.

At this point, let us ignore the political economy of scarce oil and focus instead on technology and costs. The technical solutions to oil scarcity depend on transforming other energy sources into petroleum substitutes, and so all these options rest on one central fact: *there is no shortage of energy*. The age of conventional oil pumped from the ground will surely end, either as a gradual peaking and slow decline over a century, or the more dramatic decline I am considering here. Come when it may, the end of easy oil will not signal a shortage of fossil fuels or of energy. We have sufficient resources of coal, gas and unconventional oil to power our fossil- driven civilization at twice our current burn rate for more than two centuries.

How much fossil energy does the earth hold? In considering the question, one naturally imagines a tank with a fixed capacity, but this is a fundamental misconception that frustrates any attempt to make sense of the acrimonious debate about the future of fossil fuels. Imagine instead a line of fuel tanks stretching into an uncertain distance, each with a definite capacity and cost of extraction. Standing at the head of the line we see the conventional oil reserves that are producing today. Looking farther down the line, we cannot read the label with each tank's precise capacity and cost, but we can see that there are huge resources such as coal at depths too deep to mine with today's technology and oil that is in such small or hard-to-reach pockets that it is now uneconomic to extract. But it is there.

Economic geologists break the line of barrels into reserves and resources. Reserves are the amount of fuel that can be extracted at current prices using current technologies. If prices go up or if technology drives down the cost of access, then reserves expand without anyone discovering a drop of new oil. Reserve-to-production (R/P) ratios are the number of years that a reserve would last at the current rate of production. In contrast to reserves, resources are the estimates of the amount of fuel in the ground both discovered and undiscovered.

The gradual conversion of dimly seen resources to producing Reserves, the process that shapes the future of fossil fuels, is best seen in the United States, the country where the oil age began, and the country with the largest cumulative production of oil. A century and a half after production first began, and almost four decades after oil production peaked in 1970, the R/P ratio in the United States now stands at twelve years. Is the U.S. twelve years away from the end of domestic production? Not at all. R/P ratios have been similarly low for decades, and yet total petroleum production has been remarkably constant, falling only about 32 percent in the last twenty years. U.S. production is declining, but the rate of decline is far slower than that suggested by a glance at current reserves; we should expect similar dynamics for the world's oil production as resources are gradually converted into reserves.

So how big are these resources? By definition, we don't know exactly. Estimates are uncertain and contested. However, they are all immense in comparison with current consumption. Common estimates of the combined amount of reserves and resources of oil and gas range from three to six trillion barrels of oil equivalent, while for coal the total is between twenty and fifty. These estimates include unconventional resources, such as tight gas and bitumen in oil sands, but ignore gas hydrates that contain an energy equivalent of about 130 trillion barrels of oil. These resources estimates dwarf current consumption rates of oil, gas and coal, which now stand at twenty- even, nineteen and twenty-two expressed in billions (one thousandth of a trillion) of barrels of oil equivalent per year.

Put another way, the energy content of fossil fuel resources (ignoring gas hydrates) is equivalent to between four hundred and eight hundred years of global energy use at current rates of consumption. So it is a little early to say we are running out.

How can these resource estimates be squared with the evidence of resource scarcity given by advocates of "peak oil"? In general terms the answer is that those who argue for rapid exhaustion of oil, gas and coal do so primarily from curve-fitting analysis which ignores much of what we know about economics, geology and technological change.¹ The strongest arguments generally apply to oil where a good case can be made that Mideast oil reserves are systematically exaggerated. Likewise, the "Hubbert's Peak" resource production curves do a good job explaining the historical production of U.S. oil for which scarcity is clearly the driving force. However, the application of similar curves to U.S. coal production, for example, is virtually meaningless since they involve implausible extrapolations from early points on a curve to its endpoint; and, since they implicitly

depend on assumptions that coal production rates have been driven by resource scarcity while the history of U.S. coal prices (which have declined) contradicts this assumption, which in turn makes a mockery of the rationale behind the curve fits.²

There are multiple technological pathways to providing an increasing energy supply with a decreasing environmental footprint (ignoring carbon) at a cost that is a fraction of what we pay for health care. I will describe two of these important pathways: first, synthetic fuels and then, electrification, treating each in some detail to give a sense of the opportunities, costs and technical barriers to their large-scale implementation. Many other options exist, including biofuels, hydrogen and radically accelerated increases in efficiency, but I will ignore them here since they have been widely discussed in energy debates and may be more familiar to most readers.

Synthetic Fuels

Synthetic fuels are chemically similar to existing fuels such as gasoline or diesel but they are derived from a source other than crude oil.

Coal is the most common feedstock for synfuel production. A typical coal-to-liquids process starts by gasifying coal to produce a so-called syngas (synthesis gas) composed of hydrogen and carbon monoxide along with carbon dioxide and a mess of minor constituents. The hydrogen and carbon monoxide are then combined in a catalyst bed, composed of metals such as iron or cobalt, to make hydrocarbons such as octane, the central component of gasoline.

This is old technology. While gasification is sometimes portrayed as a high-tech challenge for the energy industry, it has roots extending back more than two centuries, when deforestation forced European iron makers to replace charcoal with coke made from coal.

Indeed, “natural gas” got its name because when it entered the market, it was replacing a syngas called “town gas” that was made from coal using a close relative of today’s gasification process and was then distributed through pipeline networks in many cities in North America and Europe. In these places, natural gas did not overtake town gas production until after World War II.

Synthetic liquid fuels also have a deep history. During World War II, Germany had little oil but abundant coal so it built huge coal-to-liquids facilities to enable fuel-intensive warfare with limited oil supply. Synfuel production supplied more than 90 percent of Germany’s aviation gasoline and half its total liquid fuels.

Coal-to-liquids turns a low-cost feedstock into a high-value product with the assistance of a large helping of expensive infrastructure. Coal costs five to ten dollars for the energy equivalent of a barrel of oil, and current synfuel technologies require about two energy units of coal to make one energy unit of gasoline, so the cost of coal required to make a barrel of energy should be less than twenty dollars. When interest on capital and produc-

tion costs are included, the long-run cost of refined synfuel products such as gasoline or diesel is in the order of one hundred dollars per barrel of oil equivalent.

While the process technologies are very different, coal-to-liquids and oil sands share a similar niche in the energy system. Both turn a low-cost energy feedstock into a high-value product: liquid fuels for transportation. Both require large inputs of capital and have high operating costs, and in both cases the cost of the raw material — coal or bitumen-rich sands — is a small component of the overall cost of producing the fuel. Finally, both take a high-carbon fuel as input and produce a lower carbon fuel and relatively large amounts of carbon dioxide emissions, a topic we will return to when we consider climate constrained futures.

Could synfuel plants be built quickly enough to fuel the growing transportation demand in a peak-oil world? The resources and technology are at hand, but the answer depends strongly on one's judgment about the investment climate for this kind of large energy infrastructure. For this reason, I will attack the question from three alternative viewpoints.

One could argue for the negative by noting that governments of the major industrial nations invested several tens of billions of dollars into synfuel development following the 1973 oil shock, yet there has been very little production to date. While this argument carries some weight, the lack of investment probably has had more to do with the decline in oil prices at the time this research would have been brought to market in the early 1980s than it has had to do with technological failures. Business has been sensibly shy about investing in coal-to-liquids, a high-capital-cost technology where the payoff depends so strongly on oil prices that lie outside the developer's control.

An argument for the positive is based on capacity and need. Current estimates of the investment cost for coal-to-liquids facilities are about one hundred thousand dollars for each barrel per day of capacity, so a million barrels per day of capacity could be brought online each year at an investment cost of one hundred billion dollars. The cost estimate above is inflated to reflect the high construction costs of the current energy boom, yet even if one assumes that capital costs were to double again because of the rapidity of construction, the United States could build enough coal-to-liquids capacity to eliminate the need for oil imports within twenty years at an annual investment cost of about 1 percent of gross domestic product (gdp). If oil security was truly seen as an existential threat to the welfare of developed nations, there seems little doubt that such investments would be made. Indeed, China is now making huge investments in coal-to-liquids plants because of the government's fear of oil scarcity.

Finally, could we build large-scale coal-to-liquids facilities without wrecking the environment? Putting aside carbon dioxide emissions for the next scenario, I expect it would be possible to produce fuel from coal with less environmental damage than current oil and gas production, because while it's locally destructive, coal mining and processing

disturbs less land per unit of energy than does modern oil and gas production. But my judgment hangs on an admittedly idiosyncratic view that sees land use as the central long-term driver of environmental damage. All the same, there is no doubt whatsoever that if coal-to-liquids plants were built quickly as a chaotic response to a real or perceived crisis, the environmental damage could be horrific.

Electrification

At current Canadian prices, it is about five times less expensive to provide a unit of energy to the wheels of a car using electricity than using gasoline, when one accounts for the higher efficiency of electric motors. Why don't electric cars dominate the market? Because the capital cost of batteries overwhelms this operating-cost advantage.

Transportation is the only important sector of industrial economies that has not been transformed by electrification. Electricity storage is the weak link that breaks the chain from power plant to wheels, limiting electricity to niches such as electric trains.

In the twelve decades since Nikola Tesla's invention of alternating currents opened the electric era, we have devoted an ever-increasing share of our primary (raw) energy inputs to electricity, so that now more than one third of all energy used worldwide is converted to electricity before being put to work. Electricity is an attractive energy carrier because at point of application the devices that transform it into useful energies, such as motive power, heat, light or computation, are generally efficient, compact, reliable, non-polluting and inexpensive. And, by decoupling primary energy inputs from energy use, the electric grid allows us to blend energy inputs such as coal, wind and nuclear heat into a uniform fuel. Your toaster or stereo can't tell the difference when you plug it in. Just as we can turn coal into oil, we can turn just about any energy resource into electricity.

The efficiency of modern electric systems is a marvel: the overall efficiency from power plant to wall plug exceeds 90 percent in most rich countries. That is, only 10 percent of the power leaving a big power plant is lost in the wires between the plant and an average consumer. Many small electric motors exceed 70 percent efficiency and large industrial motors have efficiencies of more than 95 percent; and finally, the round-trip (energy-out/energy-in) efficiency of common battery technologies, such as the lithium-ion that energizes the laptop on which I write these words, is roughly 90 percent.

The expansion of hybrid cars into the mass market and the announcement of battery-driven cars such as the Chevrolet Volt and the Tesla Roadster suggest that battery technologies may be within reach. Given the economic incentive from the oil-to-electric price differential and the depth of government support for reducing petroleum dependence, it seems plausible that, if oil prices stay high, half of all personal vehicles sold by 2020 might have partially electric power plants. Of these, most would be hybrids, a smaller number would be plug-hybrids and an even smaller fraction would be pure electric vehicles.

Cheap batteries are not the only way to electrify transportation. It is technically possible to transmit power to moving vehicles. Roads can be built with embedded wire loops that transmit power to vehicles by electromagnetic induction. As with the development of other new vehicle fuels such as hydrogen, the development of electrified roadways faces a chicken-and-egg problem: drivers will demand that their electric cars be “refuelled” at least as conveniently as they fill the gasoline powered vehicles they drive today. Yet it makes no economic sense to build a massive roadway or refueling network for a small vehicle fleet.

But the spread of electrified vehicles might open a new pathway for the economic deployment of electric roadways. Suppose hybrid vehicles spread widely, accounting for more than half of the vehicles on the road, and that short-range electric cars gain a small but growing market share. It might then be possible to introduce electrified roads on a limited basis, and make an economic return by charging cars as they drive. Work on electrified roadways has tended to assume that vehicles would need roadway power all the time, but the rising capacity of batteries means that it may be possible to have only portions of major highways and traffic arteries electrified and yet still supply power that allows all-electric vehicles to travel unlimited distances.

Moreover, we are not faced with an either-or choice when it comes to oil substitutes. Electrification and synfuels are two alternative paths beyond oil. Plug-in hybrids can burn synfuels, so we can mix these options within and between transportation sectors. And we have not even considered other paths, including biofuels and hydrogen. At one-hundred-dollars-per-barrel oil, alternatives are looking pretty interesting, electric cars are poised to enter the market and large synfuel plants are being built. At two-hundred-dollars-per-barrel oil, these alternatives would begin to look cheap, and the transition would accelerate. Given the steady reduction in oil demand per unit of gdp, industrial economies can now withstand prices in the one-hundred- to two-hundred-dollar-per-barrel range, albeit with some real pain if prices rise fast. But given the choice, of course, they would rather not, and so energy use will transition away from oil as prices rise, limiting demand and so, in the long run, limiting oil prices.

We have ignored the social and political complications involved in the transition away from conventional oil. But that is not the point. The fact that one could develop petroleum substitutes at a rapid pace without requiring major disruptions to the operations of modern industrial economies shows that oil scarcity in itself does not pose a catastrophic threat as claimed in some discussions of “peak oil.” Of course, with bad management or bad luck the security implications of oil scarcity could be horrific: one can certainly imagine scenarios in which the world blunders into war over scarce oil. But that is not necessarily our fate.

Scenario Two: Tight Carbon, Abundant Oil

Suppose oil was abundant, but we had to sharply reduce carbon emissions to limit climate risk. Could we do it? How, and at what cost might we re-engineer our energy infrastructures?

It is a difficult question. The case for urgent action to limit carbon emissions is inherently surprising given the slow-moving and uncertain link between our emissions and climate change. The worst risks of climate change are more than half a century off, and actions to cut emissions today will have little benefit over the next decades, so it is no small matter to argue that we should begin overhauling the entire energy system at a cost that will run to trillions of dollars. I will therefore present the case for taking climate risks seriously before delving into options to manage that risk.

To illustrate the range of time scales that link carbon to climate, I will frame the story around three important dates.

The first date is the end of the Eocene, not a historical date, but rather an era in the geologic record that ended about thirty-five million years ago. The Eocene was the last period in which geoscientists are confident that carbon dioxide concentrations stood above 1,000 parts per million, about four times their pre-industrial value of about 270 parts per million. The Eocene climate was far warmer than today's. Crocodilians walked the shores of Axel Heiberg Island in the present-day Canadian Arctic.

If we continue on our present course, then within this century — within the lifetime of my children — human actions may well push carbon dioxide concentrations to levels not seen since the Eocene. Global emissions of carbon dioxide now exceed thirty billion tonnes per year, an average of five tonnes per capita. An average Canadian is responsible for twenty tonnes, four times the global average. If twenty tonnes sounds like a lot, it is. The mass of carbon dioxide we dispose of in the atmosphere dwarfs the mass of garbage we send to landfills, and now exceeds all human-driven material flows, including the gigantic movements of mine overburden. We throw away forty times more carbon dioxide than we do garbage. If carbon dioxide were a smelly mass that had to be pushed around with bulldozers, we would have dealt with the problem long ago.

The root of the climate threat is that humanity is moving carbon from deep geological reservoirs to the biosphere approximately a hundred times faster than the corresponding natural process in which carbon from deep in Earth's crust escapes from locations such as volcanic vents. While significant uncertainty remains about the climate's sensitivity to increasing carbon dioxide and about the attribution of recent warming to the historical increase in carbon dioxide, the extraordinary human acceleration of the carbon cycle is an undisputed fact.

We cannot accurately predict the results of the experiment we are performing upon our planet, but it is safe to say that, if we continue on our present course, we are committing

our children to climate changes that will be extraordinarily rapid compared to those humanity has experienced over the ten millennia since the invention of agriculture, during which carbon dioxide concentrations stayed within about 5 percent of their preindustrial average. It is plausible, for example, that if we were to continue emitting carbon dioxide at the current rate, the sea level would rise more than five metres within a few centuries. A sea-level rise of just a few metres is enough to dramatically alter coastlines as seen from space. Low-lying areas such as Florida and the Fraser River Delta would be inundated.

There is nothing wrong with the Eocene climate; there is no inherent reason we should prefer our crocodiles in the Florida Keys rather than on Axel Heiberg Island. The climate risks come from the rate of change, not because the current climate is some magic optimum for life. Our infrastructures, our crops, the very locations of our coastal cities have evolved for the current climate. The slow adaptation that has anchored us to the current climate puts us at risk if climate changes fast. The climate has varied for billions of years, and would keep changing without us, but on our current high-emissions path, the rate of climate change over the next century will likely be about ten times faster than humanity has experienced in the past millennia.

While it is beyond the ability of social science to predict accurately the economic and social repercussions of rapid climate change, and while there will be some sectors or regions that will benefit from climate change, it is very likely that the losers will outnumber the winners. Economic analysis of climate impacts typically focuses on the aggregate economic damages which are thought to run to a few percent of gdp. Underneath this aggregate, some regions and industries have huge gains while others suffer huge losses, yet in focusing on the aggregate economists implicitly assume that the winners will compensate the losers. More likely, it is the sociopolitical tensions arising from this rapid reshuffling of the deck that will pose the largest risks.

The second date is 1965, the year in which the first scientific warnings about how the climate would be affected by fossil fuel combustion reached the ears of the world's most powerful politician. The report that President Johnson received from his scientific advisors related the same essential facts we know today: carbon dioxide concentrations are rising due to fossil fuel combustion; if left unchecked, substantial climate change is to be expected within a century; the exact amount of change and its consequences for humanity are uncertain.

I mention the 1965 report to emphasize the constancy of scientific understanding and to illustrate the absurdity of claims made by climate skeptics such as Canada's "Friends of Science." Such skeptics would have you believe that the climate story has been constructed by left-leaning Environment Canada scientists, or that the basis for concern depends on supercomputer models or on arcane details of the reconstruction of recent temperatures (the "hockey stick" debate).

Every one of these three assertions is nonsense. One of the best climate-research groups is at Lawrence Livermore, a top U.S. weapons lab, where atmospheric modelling expertise was built early to forecast where the fallout plumes would go in a hot war. Many of the Livermore scientists are not left-leaning enviros, and would be strongly motivated to report serious errors in the climate science to the U.S. government if they found them. Moreover, the scientists reporting to Johnson correctly forecasted warming, even though the globe was then cooling. So, contrary to common assumptions, the estimates of the climate risk have little to do with year-by-year temperature shifts, just as estimates of oil depletion have little to do with short-term movements in the price of oil. Finally, the basis for predicting a temperature rise in response to rising levels of carbon dioxide ultimately rests on foundations like the physics of atmospheric radiation, which has been known for more than a century, and does not depend on the details of the latest computer simulation. Using that physics in the 1890s, Svante Arrhenius was able to make a prediction for the warming due to carbon dioxide increases that fell squarely within the range of current computer simulations.

More than four decades have passed since scientists first sounded the alert about carbon-climate risks, and more than a decade has passed since climate change emerged on the international political stage with the negotiation of the Framework Convention on Climate Change and the Kyoto Protocol to that convention. Yet we have accomplished almost nothing. Far from reducing emissions, over the past decade, the annual growth of emissions has accelerated from just over 1 percent to more than 3 percent per year—though the current recession will cut or reverse growth for a while. If we are to reduce carbon emissions, what matters are actions, and meaningful action on this topic has been all but nonexistent. Sadly, perhaps the most measurable impact of the international negotiations has been the carbon dioxide emissions from participants' air miles.

The last date to consider is 2035. If the growth of carbon dioxide concentrations continues unabated, it will exceed 450 parts per million by about 2035. This concentration is roughly equivalent to a doubling of pre-industrial carbon dioxide concentrations when one includes the influence of other greenhouse gases such as methane and nitrous oxide. A carbon dioxide doubling has long been the benchmark for the level of greenhouse gases that would cause substantial climate change, posing real though uncertain risks to human society and the natural environment.

In the slow-moving world of carbon cycles, climate change and energy infrastructure, 2035 might as well be tomorrow. This fact is the centrepiece of the argument for urgent action to restrain carbon emissions.

I will return to the theme of uncertainty in the conclusion of this essay, but for now let us assume that we wish to reduce carbon dioxide emissions in order to manage the climate risk. What would we do?

As with the challenge of oil scarcity, I will focus on the technology and economics of cutting carbon dioxide emissions in a hypothetical world of omniscient and benevolent central planners, and leave discussion of real-world politics for the concluding section.

Because the carbon we emit persists in the atmosphere for centuries, stabilizing the climate means that emissions must be essentially eliminated. Like water dribbling into a bathtub, even a slow flow will increase the level to overflowing. It is the carbon in the air that causes warming, not the current year's emissions, so shutting off emissions instantly will not eliminate the climate risk, just as turning off the tap will not drain an overfilled tub.

Minor cuts in our emissions intensity will simply not do the trick. While it might be possible to achieve modest reductions in emissions through reductions in demand or improvements in efficiency, deep reductions require a different strategy. The only way to retain the myriad benefits that energy use grants us — from mobility to communications to plentiful food — while at the same time eliminating emissions is to change the way we make energy. We must decouple the production of energy from the emission of carbon to the atmosphere.

Cutting carbon emissions need not, therefore, mean cutting energy use. Indeed, one can imagine futures where emissions are cut and energy use accelerates.

Decoupling energy from carbon means either switching to non-carbon energy sources such as solar, wind, biomass and nuclear power, or finding ways to use fossil energy reserves without leaving the carbon in the atmosphere by capturing carbon dioxide from energy transformations and disposing of it safely underground.

None of these energy options is a panacea. At the scale of modern energy use, all energy technologies carry environmental risks and their implementation will have profound and far-reaching consequences for human societies. Large-scale use of biomass energy such as corn or wood carries profound environmental risks because land must be diverted from other human uses or appropriated from nature. At their root, these risks arise from the mismatch between the scale and intensity of human energy use and the diffuse energy production by biological systems. To a lesser extent wind, hydro power and some other renewables will produce risks for the same reasons: our civilization now uses energy at such a rate that diverting it from small or diffuse natural flows will necessarily cause significant environmental harm. Solar power is more plentiful and more intense, so it seems plausible that it could satisfy all human energy needs without unacceptable side effects. However, the high cost and intermittency of solar currently stand in the way of large-scale use.

Nuclear power and fossil fuels with carbon dioxide capture and storage pose risks of a different kind. These sources generally produce far more energy per unit of land than do renewables, so the diffuse environmental impacts can be less serious (for a given amount

of energy production) than the impacts of low-intensity renewables. The flipside of the coin is, of course, that these technologies pose some acute risk of accidents, and that the risks extend far into the future. Nuclear power poses a whole other class of risks because of its connection with the proliferation of nuclear weapons.

If well managed, all of these technologies could provide energy with substantially less overall environmental risk than the current energy system. There are no risk-free energy systems, and in considering the risks of these low-carbon-emission options, we must bear in mind the extraordinary environmental impacts — from climate change to air pollution — of our current energy system.

While there is no certain path to a carbon-free energy future, there are many steps we could take today that would take a substantial bite out of our carbon emissions. In most countries, a serious attempt to cut emissions would likely start in the electricity sector, the source of more than 40 percent of the world's carbon dioxide emissions, almost all of which are from coal-fired power plants.

There are three major options for producing near-zero emissions electricity that could be implemented on a large scale at costs that are less than twice as expensive as current generation technologies: wind power, coal with carbon dioxide capture and storage, and nuclear power would each allow us to make rapid and deep reductions in emissions from electric power systems. Technologies like hydro, solar-thermal and geothermal can be competitive where there are rich resources, fast-flowing rivers, geothermal hot spots or sunny deserts, but they cannot now be widely deployed at costs comparable to the big three.

When transmission, distribution and marketing costs are factored in, generation costs amount to between one-third and one-half of an average electricity bill, so even if decarbonizing electricity doubled the cost of generation, it would increase a typical bill by less than 50 percent. Costs might well be lower if regulations were implemented slowly enough to allow new technologies to reduce generation costs.

No one wants their electric bills to increase, but one does not need a fancy economic model to understand that if carbon controls were implemented with deliberate haste, our society could easily afford such an increase in electricity costs without significant disruption. We can afford to protect ourselves from climate risks.

It's easier to squeeze the carbon out of electricity generation than it is to squeeze it out of transportation. This is because in electricity generation the costs of cutting emissions are less per tonne of carbon and because electricity generation technologies can be freely mixed, albeit with some constraints. The chicken-and-egg linkage of cars to their refueling infrastructure makes it harder to mix novel fuels such as hydrogen or electricity. Nevertheless, there are credible routes to making deep cuts in the carbon emissions from transportation beyond what can be achieved by efficiency improvements alone.

For personal vehicles, electrification may well be the leading option, though its effectiveness depends on the decarbonization of electricity. It seems unlikely that hydrogen can be a serious player in the transportation system beyond minor niches. Both its relatively poor end-to-end energy conversion efficiency and the inherently poorer fuel handling characteristics make hydrogen's large-scale use unlikely.

Despite the challenges of managing the environmental footprint of biofuels, they remain a serious contender. There are interesting options beyond incremental improvement of the current fermentation-based biomass-to-liquids technology. One such example would be to use biomass as a feedstock in a synfuel process much like that used for coal, while providing external inputs of process heat and hydrogen from a non-biomass source. These non-biomass sources could include nuclear power, coal with carbon capture or a future solar-to-hydrogen technology.

The input of external energy makes these hybrid biomass systems very efficient at converting the carbon in raw biomass to carbon in the final hydrocarbon fuel. Early studies suggest that this method could roughly triple the biofuel yield per unit of biomass input, making it far more plausible that limited biomass resources could be stretched to provide a substantial reduction in transportation emissions. This option does not depend on some undiscovered technical magic. It simply means using biomass as the carbon source for making hydrocarbon synfuels using energy supplied by some more abundant energy resource, rather than using biomass as the source of both carbon and energy, as is the case with current biofuel production.

The hydrocarbon fuels (that is, primarily gasoline and diesel) produced by such a system would still contain carbon, and would have all of hydrocarbon's advantages such as high-energy density and compatibility with existing energy systems, but the carbon content of the fuel would have been drawn from the atmosphere when the biomass feedstock was grown, so the fuels would be, paradoxically, carbon-neutral hydrocarbons. The carbon would simply be a re-useable energy carrier, like a beer bottle that is recycled hundreds of times. The amount of high-energy carbon produced as hydrocarbon fuel would be matched by the input of low-energy carbon in the plants (such as agricultural and forest product wastes) that provided the biomass feedstock.

It is also possible that carbon needed to synthesize carbon neutral hydrocarbon fuels could be captured directly from the atmosphere by a technological carbon-scrubbing process, "air capture," allowing the production of carbon-neutral hydrocarbon fuels without use of biomass feedstocks. While I am personally involved in the development of such technologies, I would be the first to concede that they are a long way from commercialization. Also, as with the biofuel synthesis described above, making a hydrocarbon fuel from carbon dioxide would require large inputs of energy and hydrogen.

Restraining emissions will not be free. Contrary to some overly optimistic assertions, the economic side benefits from developing and deploying low-emissions technologies, while real, will not eliminate the costs of action. But these costs are manageable. In a world with omniscient global governance, the climate problem would be easy enough. With wise investment, it seems likely that one could transition to a zero-carbon economy in less than a century at a cost of 2 percent of gdp — comparable to the amount we spend on the military and far less than we spend on education or health care. This does not mean reducing growth rates by 2 percent, which would have a catastrophic economic impact; it simply means forfeiting a few years of growth out of the next half century. In this light, climate change seems like a far lesser problem than the challenge of managing nuclear or biological weapons in a world in which war is still the ultimate method for settling disputes between nation states.

Finally, it's worth mentioning that Canada's greenhouse gas emissions are exceptional in many respects. Because we have so much carbon-free hydro power, electricity accounts for only 20 percent of our emissions, about half as much as in a typical industrial economy. Since electricity generation is typically the easiest sector in which to begin cutting carbon emissions, the fact that we have a relatively low-carbon electricity sector makes it comparatively harder to cut Canadian emissions than it would be in a more typical industrial economy. This fact combined with the fact that Canada has a rapidly growing and resource intensive economy makes it harder to cut emissions here than it would be in the U.S. or Europe. This is one of the reasons why Canada's choice of Kyoto target was particularly challenging, though this fact is not, of course, an excuse for inaction.

Oil and Carbon in an Uncertain World

Isolating the oil and carbon challenges is a convenient fiction, but in reality, of course, we face both simultaneously along with a host of other related challenges, from air pollution to the seemingly irresistible spread of nuclear weapons.

Before turning to the economic and political factors that shape our responses, it's worth considering some of the technical challenges of jointly managing carbon constraints and oil scarcity. While efficiency improvements reduce emissions and oil consumption simultaneously, the development of substitutes such as synfuels or electric vehicles does not. Just the opposite. Coal-to-liquids — one of the easiest large-scale petroleum substitutes — has life-cycle emissions that are roughly twice as large as conventional oil. Accelerated development of extra heavy oil such as that found in Canada's oil sands will also increase emissions, though several new oil sands operations now have well-to-wheels emissions within 20 percent of conventional oil. Even electric vehicles will not provide significant carbon benefits if the electricity that charges their batteries is supplied by coal.

Moreover, oil scarcity will tend to focus money and political attention on the transportation sector, making it harder to sustain the investments needed to lower the carbon footprint of electricity, the most efficient place to focus if carbon were our primary challenge.

During the recent oil-price surge, for example, many commentators have argued that high oil prices made carbon policy unnecessary. This is wrongheaded for at least two reasons. First, if, as seems likely, oil scarcity drives a switch to extra-heavy fuels and coal, high prices will increase emissions; and second, most carbon emissions worldwide, though not those in Canada, come from coal, and it has not seen a similar rise in price. High prices and oil scarcity will not solve the carbon problem; on the contrary, the high-carbon emissions associated with a shift to ultra heavy oil and coal-to-liquids as we “scrape the bottom of the barrel” will counterbalance the demand reduction spurred by high prices.

The upshot of this interplay between oil scarcity and climate risk is that we cannot hope that politicians will be able to craft wise energy policy if we lack agreement on the goals which that policy must address. It is naïve to imagine that there is a generic “good” energy policy. Policy must be designed to address specific goals, and we must agree on the relative importance of potentially conflicting goals such as supply security and climate security before we can make sensible energy choices.

As a first step towards the real world, consider the differences between the oil and carbon challenges that arise from the fact that oil is a commodity while climate protection is a global public good.

Meeting either challenge requires a massive investment in infrastructure in order to reshape our energy system so that it can supply the energy services we need — such as mobility, illumination and communication — while eliminating the need for oil or the emission of carbon. We have technologies near at hand that could provide a substantial step to resolving either problem at costs that would make a scarcely discernible dent in our economic fortunes, yet the central distinction between the two is economic, not technical.

The transition away from oil will be aided by the market’s magic. As oil becomes scarce, prices will rise and it will be in the self-interest of individuals, corporations and nations to find substitutes. While governance and collective action will be needed, they will be greatly aided by self-interest that tends to make oil scarcity self-correcting.

Unfortunately, naïve self-interest cannot be relied on to help solve the climate problem. For carbon as for oil, the costs of technical substitutes are local, yet for carbon the benefits of reduced climate risk are spread globally. It is in each nation’s direct self-interest to leave their emissions unchecked while exhorting others to reign in their emissions. In the language of economists, climate stability is a global public good.

Consider our family’s recent purchase of a super-efficient furnace. We bear the full cost (net of fuel savings) of our climate friendly hardware, while the benefits of its reduced emissions are spread worldwide; and worse, because of the slow dynamics of the carbon cycle, the benefits are nearly zero over the rest of my working life. The global climate benefits from our furnace, but only as the reduction in emissions gradually produces an

(infinitesimal) reduction in climate change that extends more than a century into the future. It's a lousy deal. We can only justify it by the hope that our family's purchase will spur others to make the same choice, thereby amplifying the climatic benefits beyond those achieved by our furnace alone.

Humanity has solved global public-goods problems before, the most notable example being the near elimination of ozone destroying chemicals from the global marketplace. The trick involves national and international mechanisms to reduce the incentive for free riders who would let others shoulder the burden of reducing emissions. But there is no magic formula to ensure success. Moreover, despite the grand statements issued by the current round of climate negotiations, current attempts to cut carbon emissions are more like the "phony war" that preceded World War II than real actions of the kind and magnitude necessary to attack the problem.

Uncertainty makes both the climate and oil problems harder, and it is uncertainty in combination with the public goods problem that makes the carbon-climate problem so dangerous.

Substantial uncertainty about the climate's response to our meddling will remain unresolved for decades. At the low end of current estimates, the global average temperature would rise one degree Celsius, a bit more than its rise since 1900, while at the high end, the average temperature would rise about five degrees, a global climate shift more than half as large as the shift from the ice age to the present day.

If the climate risk could be quickly eliminated, we could wait until the uncertainty about the degree of climate risk was resolved before taking action. Upon discovering the extent of the climate sensitivity to carbon, we could then choose an appropriate response, one that balances the cost of response against the environmental benefit.

Unfortunately, we cannot sensibly postpone action until we know the exact degree of climate risk. The problem is the enormous inertia between our decision to respond and the benefits of that response. The inertia arises from the long lags in the climate's response to our carbon emissions — more than half of the carbon we emit today will be retained in the atmosphere a century hence. Similarly, our carbon-emitting energy infrastructure is not going to be replaced overnight. The turnover of energy infrastructure is relatively slow; power plants are not replaced yearly like iPods, they often last half a century.

It is the combination of high uncertainty with high inertia that makes the climate problem particularly dangerous. We cannot wait to find out if the climate dice have rolled against us before we act. Planning our response around the most likely outcome is reckless overconfidence. However, we seem particularly unable to manage problems that combine high uncertainty and high inertia. The tendency to procrastinate is just too strong. This fact, combined with the climate's status as a global public good — the benefits of cutting

emissions are spread globally while the costs are felt locally — goes a long way to explaining humanity’s near-total failure to act in the face of the climate threat.

Uncertainty in the face of the climate threat should not be a justification for inaction any more than uncertainty in the battlefield is a reason to delay decisions about the movement of troops. We should make decisions in the face of uncertainty, accepting that the consequences of climate change may turn out to be more or less severe than our best guess. We must hope for the best while laying plans to navigate the worst.

So, on the one hand, we have an energy problem that, while potentially dangerous, is largely self-correcting by the normal market incentives that arise from scarcity. As oil dries up, the self-interest of nations, firms and individuals will automatically drive the implementation of substitutes from coal-to-liquids to electric vehicles. That underlying self interest does not justify complacency. Navigating the oil transition will be dangerous and clear-headed actions by governments will be needed to provoke energy innovation and to manage the energy-system transition; but for the oil transition, government action will be pushing in the direction that the economy naturally “wants” to go.

On the other hand, we have a planet-altering problem in which current actions pose growing risks to future generations. For climate change, the self-interest of nations, firms and individuals will work to drive measures to ease adaptation to the changing climate since the benefits of adaptation can be captured locally where money is spent, whereas cutting carbon emissions demands coordinated actions to secure a global public good. Far from being self-correcting, this problem may well be self-reinforcing. If actions to limit emissions continue to fail and climate change accelerates, then governments may focus their efforts on adaptation, abandoning a coordinated attempt to control emissions with potentially disastrous consequences.

The oil and climate challenges are both rooted in our energy system. Abundance of fossil and other energies enables the energy substitution that is the path beyond oil scarcity, yet it is the very abundance of fossil fuels that drives the climate threat. Fossil abundance means that low-cost high-carbon fuels such as coal and ultra-heavy oil tend to out-compete the lower carbon alternatives and create the carbon emissions that drive climate change.

Climate is therefore the arena in which government action is by far the most important. The innovations and investment that limit carbon emissions will be (mostly) made by firms and individuals, but their efforts cannot be harnessed unless governments act to put a price on carbon and to build international mechanisms that trigger the myriad small investments that must be made to limit emissions worldwide. Investments that will be repaid many times over if we are able to leave our children with a climate like that in which our civilization evolved.

End Notes

1. Estimates of future resources are highly uncertain. One could credibly defend estimates several times smaller than those I used here as well as estimates that are significantly larger. These estimates are drawn from the studies IIASA/WEC world energy studies (while there are more recent versions, the following is a good summary: Rogner, H- H, *An assessment of world hydrocarbon resources*, Annual Review of Energy and the Environment, 22: 217–262, 1997). I used this study because it uses reasonably transparent methodology and attempts to take systematic account of the technological and economic drivers that convert resources into reserves.

2. Estimates of resource scarcity often discount technological change that works to facilitate access to resources even as the average quality of the resource declines. Discussions of coal scarcity, for example, typically do not even consider advanced autonomous mining technologies or underground gasification, yet underground gasification has already been used successfully in several commercial or near-commercial demonstrations. Likewise, arguments for scarcity typically discount the possibility of accessing methane hydrates on the seabed. The most radical claims about scarcity of fossil resources implicitly depend on the assumption that a whole set of technologies— any one of which could greatly expand the reserve base— will each separately fail in the next century. While no sensible person expects all these technologies to succeed, the probability of them all failing seems vanishingly small. Underestimating technological change is the underlying reason why so many historical claims about resource scarcity have proved false over the last century and a half.

3. Perhaps the strongest arguments for coal scarcity are made by David Rutledge, a professor of electrical engineering at Caltech. Most of the arguments rest on fitting historical data to a logistic production curve (see <http://rutledge.caltech.edu>). This method might be convincing when one is well past the peak of production, but prior to the peak the method interprets any downward deviation of production from a logistic/exponential as a reduction in the ultimate resource. This might make sense if there was a convincing reason that the production rates should “naturally” follow an exponential growth trajectory and if any deviation from exponential growth was due to resource scarcity. If scarcity were playing a role one would expect prices to be rising, but in fact U.S. coal prices have remained remarkably constant (aside from any peak in the mid-70s) since the 1950s during which time annual production has more than doubled. This price history contradicts the assumption that resource scarcity is driving the production rate. Far more plausibly, other factors in the U.S. electricity markets have caused production to increase linearly rather than exponentially, factors that have little to do with coal price or scarcity. If coal production rates have had little to do with coal prices and scarcity, then there is no reason to expect that the logistic fit would mean anything, even assuming that there was sufficient data to make a high-quality fit (which there is not).