

Turning Black Swans Green: *The Vittorio Santaniello Memorial Lecture*

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This article argues that the severe (or Black Swan) event of a financial crisis provides the opportunity to address other threatening issues—energy insecurity and climate change with the associated extreme weather events. The financial crisis has been catalytic in reassessing risk and the likelihood of extreme events—whether in finance or energy or climate. Already, a large part of expenditures from the global stimulus has been directed to diversifying the energy base of economies toward less carbon-intensive energy. Public expenditures, in an attempt to compensate for the fall in consumer spending, are stimulating a reformation of the capital and energy infrastructure of nations toward a lower carbon path of growth. Likewise, and consistent with this reassessment and transformation in energy, are the efforts to combat climate change and the prospects of extreme weather events. International negotiations and domestic legislation for cap and trade are moving towards providing more market-based incentives for this diversification of energy and at the same time stimulating lower-cost solutions for reducing carbon emissions.

In both energy and climate, it is increasingly recognized that the economies of the world need to move to even greener technologies, which offer zero or even negative emissions. The 50-80% reduction in carbon emissions by 2050 currently called for by scientists can only be achieved through using energy-rich crops as a major source of fuels. Biofuels and biomass offer near zero emissions and when combined with carbon capture and sequestration could result even in negative emissions—providing energy while capturing carbon from the atmosphere. But advances in biotechnology are needed to reengineer plants to become more fuel rich and have lower cost in harvesting and processing if these ambitious reductions in carbon emissions are to be attained by mid-century.

Key words: environmental economics, government policy, energy, climate, global warming, biotechnology, agricultural technology, financial markets, black swan, green energy, risk management.

We live in a time of extraordinary opportunities but also extraordinary risks. The world's economies have become more interdependent, linked by global markets in capital and commodities, creating enormous benefits but also systemic risks. Capital flows freely across national boundaries as banks and capital markets have become increasingly international. But failure of the financial system in one economy can be transmitted to other financial institutions as contagion sets hold. As the recent financial crisis has shown, only a concerted global effort across central banks and governments can dampen contagion being transmitted between economies.

Likewise, energy trades relatively freely across borders through international shipping, pipelines, and elec-

trical grids, creating interdependence but also substantial risk for countries dependent on importing energy. Supplies of fuel are largely concentrated in a few locations in the world with the passages for naval shipments limited to several narrow straits; electrical grids and pipelines cross borders making any one nation vulnerable to the sovereign decisions of others. In addition, we have a planet whose climate is changing rapidly due to anthropogenic activities. Most coastal cities, nearly half of the planet's species, and the livelihoods of billions of people are under threat from climate change. As the planet warms, weather becomes more unstable, threatening food supplies, with floods and droughts being more severe and frequent. The actions of one nation in permitting carbon emissions affects the well-

being of others as greenhouse gases freely disburse in the atmosphere. Furthermore, through feedback, emissions in one country can trigger higher emissions in others as higher temperatures trigger the release of trapped greenhouse gases.

In a world economy so interlinked and with uncertainty and new risks increasing over time, history becomes a poor predictor of the future. In addition, contagion which can be transmitted through interlinked global markets becomes more likely, resulting in severe events once thought to be rare. But with the threat of such severe events also comes opportunity—specifically the opportunity to dramatically transform economies and how risk is managed, accelerate the development of clean energy technologies, and build paths to low-carbon growth.

Recent extraordinary and severe events in the financial sector have initiated extraordinary action by governments to change the way risk is managed and regulated in the global financial system. It has also reemphasized that governments must work together to address common issues while at the same time triggering the desire for more independence. The recent spike in oil prices to record levels and the interruptions in natural gas supplies have made governments more concerned about their dependence on externally supplied energy. In addition, governments have come together through the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol to establish international markets that cause the source of anthropogenic climate change—carbon emissions—to be internalized into national policy and private economic decisions. Motivated by the need for greater energy security and to reduce carbon emissions, investment and incentives provided by governments are increasingly offering the opportunity to transform the energy and transport infrastructure of modern and emerging economies and save much of the world's forests. In addition, the financial crises of 2007 and 2008 have begun to accelerate public investments in new and more efficient infrastructure and have provided the catalyst for a lower carbon future. The threat of future Black Swan events in energy and in climate have created new global green initiatives whose full consequence on the capital structure of nations are just beginning to be felt. Heightened by the financial crisis, the public has become conscious that the improbable is more likely than once assumed. Governments have responded by seeking greater security in energy and lower carbon paths of growth for their economies.

In this article, I will elaborate on this transformation that is now just emerging and discuss their ramifications. I will describe three Black Swan events: one occurring but hopefully dissipating—the financial crisis; another potentially pending—an energy crisis; and a third forthcoming—a climate crisis with severe economic consequences. I argue that the current financial crisis has created the catalysis for investments and incentives to counter a potential energy crisis and to mitigate climate change. The financial crisis has demonstrated the vulnerability and terrible costs of Black Swan events. I will argue that the occurrence and threat of further Black Swan events in energy and climates has stimulated another rare but transforming event—specifically a green swan event—essentially a transformation of economies toward a lower carbon, more diverse energy economy. I will then conclude that biotechnology plays a crucial role in combating climate change—in energy through improved biofuels with the potential of negative emission, in sequestration with more carbon-hungry plants, and in adaptation through crops more resilient to extreme episodes of drought and floods. I argue that biotechnologies provide the possibility of reaching the significant reductions in carbon in the atmosphere needed by 2050 to keep global temperature in the 2-4° centigrade range. In fact, without the breakthroughs in biotechnology, the goal of 50-80% reduction of carbon emissions by 2050 is extremely difficult and costly, if not impossible. Although biotechnology has risks, those are low compared to the risk of climate change for livelihoods and biodiversity.

The Seemingly Improbable

A Black Swan event is a seemingly improbable but highly consequential and far-reaching event. The misjudgment of the likelihood of the event can come from a psychological blindness to the actual probability of the event. Nassim Nicholas Taleb, who made popular the term, elaborates:

“What we call here a Black Swan is an event with the following three attributes. First, it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable. I stop and summarize the triplet: rarity, extreme impact,

and retrospective (though not prospective) predictability. A small number of Black Swans explain almost everything in our world, from the success of ideas and religions, to the dynamics of historical events, to elements of our own personal lives” (2007, pp. xxi-xxii).

A Black Swan event may actually result from a probability distribution with “fat tails” but, in assessing risk, is assumed to be highly rarer, fitting a more normal distribution consistent with recent historic data. For example, using history as a basis, it is assumed that the event occurs with a probability two standard deviations from expected occurrence and therefore with a probability of 1 in 40—for example, once in 40 years—but actually have a frequency of once every 10 or even four years or less. And because risk is measured and managed incorrectly, a Black Swan event will have a severe consequence. As a point of reference, we refer to this as a Type I Black Swan event—a misassessment of the actual probability of a severe consequential outcome.

In this article, I extend the definition of a Black Swan event such that the actual event may have a very low probability of occurring with any one participant but because of the number of participants and contagion, it actually has a higher probability of leading to a severe outcome. For example a flu virus jumping from a swine to a specific farmer has an extremely low probability of occurring. This event of a single farmer being infected has little or no consequence to the other inhabitants of the earth (except for family and friends); however, due to contagion (which will depend on other factors, such as the number of people with which the farmer is in contact, etc.), the virus could jump from the farmer to others and have severe global ramifications. If this potential for contagion is not assessed accurately, then the probability of a global epidemic could be misjudged and the world’s health system would be unprepared. Likewise the failure of any one investment bank could be unlikely but because of interlinkages the low probability event could have severe consequences. With many such participants facing low probabilities, the aggregate probability of a severe event could be high, as contagion spreads the effects from one institution to another. I label this as a Type II Black Swan event—a mistaken assessment of the actual probability due to contagion of many low-probability events leading to a severe outcome.

I will also argue that both types of Black Swan events do not occur without having the conditions to breed them—an incubator that increases the likelihood of their occurrence. This can be excessive leverage, lack

of diversification, or just false sense of the improbable that leads to complacency in risk management.

The Current Black Swan Event: The Financial Crisis

From 2007 through 2009, the global financial system suffered the most severe crisis since the Great Depression. This event was one of four that occurred in the last 27 years—ranging from financial failures in Latin America to those in East Asia. Contrary to the others that preceded the recent crisis, the latest struck at the heart of the financial system in New York and London and then transmitted to the peripheral of the financial world by contagion. The previous financial failures, although occurring at the fringes of global finance, had the potential of contagion but were dampened by relatively mild actions (in comparison to today’s interventions) of treasuries and central and multilateral banks.

Such frequency of financial crises is unprecedented. But, in each case the sequence in manifesting the crisis were similar. The breeding grounds were macroeconomic imbalances, an appreciating exchange rate, an inflow of capital and liquidity, a bubble in asset prices, the bursting of the bubble, and a banking and credit crisis as the financial system is drawn deeper and unsustainably into financing the bubble. As the bubble strengthens, banks increasingly take on more risk, some of which is eventually recognized and other parts badly underestimated. In each financial crisis, it was not that the risk instruments were not in place in the banking sector but that they were not calibrated to the actual probability of a fat tail event fed by contagion.

Despite the series of previous financial crises—in some ways the tremors before the large event—the widespread magnitude of the current financial system was largely unanticipated. The improbable, as based on recent historic data, was badly misjudged or ignored. Most financial institutions that were assessing risk did not anticipate that the collapse of the subprime mortgage market would lead to a series of deeper and more severe liquidity crises transmitted through interlinked markets, eventually leading to unprecedented interventions by central banks and treasuries. It was not that banks were not assessing risks, as sophisticated models had been developed throughout the banking system to adjust portfolios and balance risk with reward. But these were well behaved models, not geared to take into account contagion between banks driven by illiquid markets. Risk models were built based on assumptions of rational markets and well behaved probability distri-

butions—mainly normal or log normal distributions when the reality turned out to be distributions more closely resembling Black Swan events—that is, distributions with fat tails.¹ While credit risk could be taken into account on the failure of any one institution and priced, the contagion effect was largely not accounted for. Although the probability of any one institution failing was small, the number of institutions with potential contagion effects taking leverage positions lead to an aggregate probability significantly higher, with potential to trigger through contagion a Black Swan event in the global financial system.

With the 2008 and 2009 financial system in crisis and consumer expenditures severely curtailed, governments needed to fill the gap through public expenditures and investment; but, the question was on what. This is where the recognition of the two other potential Black Swan events pushed public expenditure to not only stimulating the economy in a classic Keynesian fashion but to direct a large part—in the United States about \$80 billion and in China more than \$400 billion—of the expenditures toward energy security and combating climate change.² A Black Swan event in the financial system provided the opportunity to attack with unprecedented vigor two other potential Black Swan events in energy and climate and thereby contributed and, more importantly, potentially stimulated more investment toward a future with lower carbon emission.

The Opportunity: The Renewed Quest for Energy Security

The recent wide swings in the price of crude oil are similar to only two other periods in recent decades—the Gulf War of 1990-91 and the OPEC price wars of the 1980s. But the recent volatility is even more severe—peaking at \$145/barrel, down to a trough of \$33/barrel, then back toward \$80/barrel—and without any apparent external event in the market affecting fun-

damental supply and demand or uncertainty. For governments and the public, it has become increasingly obvious that the oil market and the supply of natural gas are vulnerable, and it does not take much to cause a disruption in supply and a price spike. The rise of oil prices to unprecedented heights was one signal that the market was potentially vulnerable to further severe price rises³. Few now expect that the future consists of a well behaved random normal distribution of oil prices around some long term trend of an equilibrium supply/demand price. Increasingly governments recognized that a Black Swan event in energy is not beyond possibility.

With energy such an important component of economic well being and growth, such volatility and possible further spikes in prices creates unacceptable economic and political risk. It generates the perception and perhaps the reality that the current sources of energy supply feeding economic growth may become more scarce and vulnerable. While only a few economies can become energy independent, most governments have come to realize that diversification of energy supply is a public good—it lowers the perceived risk profile of economies and increases the willingness to invest. This realization has set off a wave of public initiatives to diversify the energy supply of economies. With fossil fuels still relatively cheap, this diversification needs to be driven by public expenditures and incentives. In normal times and with budgets constrained, such public monies would be difficult to find. Not so after the reality set in from the financial crisis that government needed to intervene and manage risk while stimulating the economy. Energy security has become the mantra of not only the rich countries but also the poor. In both finance and energy, risk is increasingly seen from the possibility of extreme events. Black Swan events are considered not as the distant outlier that can be disregarded for all practical purposes but as a real threat and likely in the near future. As long as that awareness holds, the drive to

1. *It is good practice in risk assessment to stress test risk positions by triggering the models toward the extreme. It is unclear whether this actually took place in the institutions that failed or whether these stress tests were considered to be replicating such low probability events that the results were ignored.*
2. *Although not attributable to stimulus packages but certainly motivated by the fat tail risks to the global economy of climate change, Secretary Hilary Clinton announced at the Copenhagen Climate Summit \$100 billion a year of private and public money by 2020 for developing countries to combat climate change and invest in clean energy.*

3. *For example, of the approximately 85 million barrels per day that are transported from producers to consuming nations, about 50% of this is shipped on fixed maritime routes. Of this shipped oil, about half of it goes through the Strait of Hormuz, which is about 21 miles wide. It has already been subject to mines and terrorist threats. About 40% of the maritime shipments pass through another narrow passage—the Strait of Malacca—which at its narrowest is 1.7 miles wide. It has been subject to poor visibility, collisions, and a terrorist attack as recently as 2003. The remaining supply goes through the Suez Canal (1,000 feet wide), where two oil tankers ran aground in 2007. Any disruption in these passages would have a significant effect on supply and world oil prices.*

diversify energy will continue. It will be reinforced by climate change and the associated extreme weather events.

Global Warning: The Climate Crisis

This sense that the improbable may not be so improbable is carrying over into national and international policy in combating climate change. Although global warming is in itself not an unanticipated Black Swan event, it will produce many severe events through unstable weather—droughts, floods, hurricanes, blizzards; in other words, it will create a climate that is potentially much more extreme and unpredictable. And this instability in weather will raise significantly the risks to businesses and economies, as well as to lives. Because history does not provide a good basis for measuring these risks, scientists have turned to large and elaborate simulation models to guide public policy. Although these models have large degrees of uncertainty built into their simulations, they point to a climate much more variable and extreme, with the critical link being between the amount of carbon stocks accumulating in the atmosphere and temperature rise.

Using these models and simulations of the link between carbon accumulation and temperature change, scientists have set 450 ppm of CO₂ in the atmosphere (or less) as an amount that could create a rise in global temperature of 2° centigrade with a 0.7 probability and of exceeding 3° with a 0.5 probability. This 450 ppm target has been generally accepted as an amount of CO₂ in the atmosphere—a rise of about 65 ppm from today's levels—to be an achievable limit if action to mitigate emissions is taken now and increased dramatically by 2020.

As already indicated by the probabilistic nature of the simulation results, the probabilistic distribution of temperature changes also have fat tails. As the planet warms, positive feedback loops are likely. For example,

- as the frozen tundra melts, it will emit more methane (a greenhouse gas), which is more than 20 times as toxic as CO₂;
- as atmospheric temperatures rise, warmer oceans absorb less carbon; and
- as snow cover is reduced, less radiation is reflected.

With such feedbacks operating, a nicely stable log-normal distribution of temperature change is unrealistic. The likelihood is that as some yet unknown level of CO₂

is approached, positive feedback (or contagion) between events could be reached. Many climate-related events, perhaps in themselves relatively insignificant in emissions, in aggregate will accelerate the accumulation of the amount of carbon in the atmosphere; these then result in subsequent rounds of rising temperatures. Such “contagion” of the consequences of temperature rises would be the fat tail of much more extreme temperature changes. At what threshold of carbon accumulation when such feedback would be reached can only be simulated very imperfectly.

The possibility of such a feedback mechanism being triggered should be weighed against the likelihood of governments taking action at a magnitude and sustainably over time to achieve reductions in carbon emissions. Even with concerted government effort, the feasibility of achieving the target of 450 ppm is far from obvious. To peak at this level of carbon in the atmosphere requires emission reductions of 50-80% from current levels. To get a sense of the enormity of this task, take the United States as an example. Current emissions are around 20 tons of CO₂ per capita. In a business-as-usual scenario, emissions are projected to increase to 40 tons per capita in about 40 years. To reach the target of an 80% reduction means that emissions would need to fall to about 4 tons per capita against a projected business-as-usual emission 10 times that amount. In comparison, India's current emissions are around 1.2 tons per capita and China's are about 6 tons per capita. But like the United States, these emissions are projected to more than double under a business-as-usual scenario.

Another way to look at this challenge is from the perspective of wedges—that is, what does it take to get a billion tons of emission reductions from current inventories of energy production? Currently the United States emissions are around 7 billion tons per annum on a path to about 14 billion tons. To get this reduced to 50% (less than the 80% target) of emissions means that more than 7 billion tons needs to be cut from the business-as-usual scenario.

Pacala and Socolow (2004) have suggested that seven wedges of a billion tons each

1. build 700 gigawatts of nuclear power to displace coal power (twice current global nuclear capacity);
2. decrease car travel for two billion 30 mpg cars from 10,000 to 5,000 miles per year;
3. capture and store greenhouse gas emissions at 800 large coal plants;

4. improve energy efficiency by one-fourth in buildings and appliances;
5. produce 100 times current US ethanol output;
6. produce two billion cars that travel 60 miles per gallon of gasoline instead of 30 miles per gallon; and
7. build two million 1-megawatt wind turbines to displace coal.

A few of these measures standing alone may be feasible or halfway achievable, but most in aggregate are formidable challenges even over 40 years. Note that the longer the delay in doing any of these measures (which is likely), the more will need to be done later, as the atmosphere will be further accumulating stocks of carbon dioxide.⁴ The target cannot be reached just at the end of the 2040s or 2050s—emission reductions must be a process taking place continuously and beginning as soon as possible. Delay just makes the problem larger and the costs higher.⁵ And the contagion created by global warming creates the prospect for more global warming through positive feedback loops and with it even more extreme weather events. What was a once in a (say) hundred year event could become an event of much greater frequency, such as once every few years. The direct and indirect costs of such extreme weather events could be enormous—well above the costs of vigorously mitigating carbon emissions.

What is clear is that 450 ppm is a formidable target. Scientists estimate that global emissions must peak by 2015 or at the very latest by 2020 to achieve this target, a feat which is difficult in the least. But even if met, scientists predict much more severe weather events—from storms and floods to droughts and crop failures—as the planet continues to warm. Each of these events will have contagion effects and be viewed from the perspective of historic data as Black Swan events. The management of

risk will be even more challenging, as the underlying probability distributions for modeling risk will be non-stochastic—that is, not stable and be more consistent with fat tail distributions of unknown and unstable distributions. Stressing risk models will not be testing unlikely events but more likely occurrences than given by historic data.

To combat these threats, it is clear that we need many technological solutions and they must come quickly or the buildup of CO₂ in the atmosphere is going to result in temperature rises much closer to 4° centigrade (based on current simulation models) and therefore result in much more severe extreme weather events. But the bulk of research funding is directed at making existing fuels such as coal cleaner through carbon capture and sequestration or is focused on much more distant solutions such as fusion. While this is important as the dependence on coal will continue in industrial countries and certainly in the emerging economies of Asia and Africa, the possibilities are limited for capture and sequestration. Capture and storage of carbon emissions from coal plants are based largely on underground storage and therefore will be dependent on local geology.

While fusion provides an ultimate solution for power generation, the day when it will be economically feasible seems very distant, well beyond the time period when a cleaner solution to the world's energy needs must be found. Major hurdles in fusion need to be overcome and even then what nuclear fission has taught us is that the economics are not simple or easily surmounted.

The feasible solution rests with technologies that sequester carbon from the atmosphere while producing a substitute for fossil fuels. Biofuels almost reach that criterion if you do not take into account the emissions from fertilizer, soils, and transporting the biomass to plants. They emit just about what they absorb so they are almost a neutral fuel—that is have a near zero balance.⁶

Biotechnology directed at making biofuels more efficient and more easily converted into fuels using existing refinery infrastructure has received much less attention than sequestration of carbon from fossil fuels. Yet biotechnology—when viewed against the enormous

4. *Even with substantial reductions, the delay would result in even higher temperatures. In other words, the current necessary targets would need to be increased even more substantially.*

5. *With cap and trade, some of these emission reductions do not need to occur in the United States, which could purchase the emission reduction from, say, China. Pending legislation in the United States recognizes the challenge of this reduction and provides for the potential of 10% of US emissions being offset by carbon emission reductions abroad. With international emission trading, these targets are feasible, especially with the introduction of avoided deforestation being one of the potentially lower cost offsets (deforestation and other land use accounts for about 25% of all global emissions).*

6. *Nuclear is another option that does not emit any carbon except in the production of the plant and the gathering and disposal of the fuel (except for the emissions associated with building of the plant and transporting and disposing of fuel). But nuclear—while part of the solution—has its limitations and has yet to receive wide public support.*

challenge of achieving 450 ppm—has a crucial role to play in mitigation, sequestration, and adaptation. Examples of this include: (a) mitigation, which, through more productive biofuels such as more oil-rich algae and faster growing trees, would ideally behave as annual plants that wilt when reaching maturity, thereby reducing harvesting cost and overcome the costs of breaking down cellulose into sugar;⁷ (b) sequestration, which, through plants that absorb much more carbon from the atmosphere, would produce either biofuels such as ethanol or biomass or just sequester the carbon in the atmosphere; and (c) adaptation, which, through crops that are much more resilient to severe droughts and floods, would extend the temperature tolerance of existing crops. Also by using biotechnology to increase yields of food crops, more land area can be devoted to biofuels while not impacting food supply.

Biofuels and biomass also offer the potential of negative emissions when combined with carbon capture and storage.⁸ No other source of energy offers this potential. While sequestration and capture of coal provides the possibility of near neutral emissions (although at the cost of energy efficiency), it pales in comparison to biofuels and biomass combined with capture of emissions, which offer negative emissions. If ejected into greenhouses, captured CO₂ from biofuels could even feed into accelerating the growth of carbon-hungry energy crops.

Venture capital has seized upon the prospect and is funding experimental biotechnologically engineered biofuels. But if viewed against the enormous challenge of avoiding the fat tails of climate change, biotechnology directed at fuels is not receiving the focus that it deserves. While the engineering of plants does present risks, they are small compared to the risk of catastrophic climate change.⁹ Combating the fat tails of climate change will require accelerated action, which may go

beyond the precautionary principle and the risk of doing some harm. It may well be a matter of weighing the risks to livelihoods and biodiversity of climate change with that of a bioengineered crop.

The Green Event: The Confluence of Technology, Risk Management, and Climate Change

The future will not be easy but is manageable. Public expenditures and incentives in response to the financial and economic crisis have already accelerated investment to meet the challenge of these potential severe risk events. The recognition coming from the financial crisis that Black Swan events are not rare and that the seemingly improbable is indeed much more probable has been penetrating energy and climate policy.

The stimulus packages initiated by work from the economic crisis in the Organization for Economic Cooperation and Development (OECD) and in emerging markets have already been directed at diversifying the energy infrastructure and seeking higher efficiency in energy use through many means—from buildings and transport to lighting. Furthermore, a more ambitious international policy regime to regulate emissions and diversify energy is moving forward, although slowly. In the United States, legislation is in process to provide comprehensive incentives to diversify the energy base. In response, venture capital is quickly moving from the “old” technologies of IT and software to clean technologies—from electric cars to algae and carbon capture and storage. The number of patents for inventions in clean technologies has already accelerated with the signature of the Kyoto Protocol. As documented by Dechezleprêtre, Glachant, Hascic, Johnstone, and Ménière (2008), the transfer of technology has increased dramatically with the UN Clean Development Mechanism. And this is only the beginning. Venture capital is moving to China to meet the enormous challenge there and hopefully to profit from the opportunity of helping the largest emitting country to achieve extraordinary efficiency gains. Already, China is investing heavily in wind, including the use of super conductivity in turbines. It also has an ambitious program to increase the use of nuclear energy sources. Likewise, India has a wide and ambitious program of energy efficiency and diversity, ranging from wind and solar plants to solar lamps and efficient cookstoves.¹⁰

This remaking of the energy landscape in industrial and emerging economies is driven by the recognition that the potential Black Swan events in energy supply

7. *Biotechnology research is working directly at producing an enzyme that could process cellulose without using energy or chemicals. If this research is successful, it would greatly expand the sources of biomass that can be economically converted into biofuels. Algae have already been modified to increase its efficiency in producing oil and strengthen its resistance to chemical substances potentially contained in the feedstock.*

8. *The biomass can also be co-combusted with coal or other fossil fuels.*

9. *Synthetically engineered algae is being used in enclosed fermentation, thus reducing the risk of spreading to the outside biosphere.*

and weather will be nowhere as rare in the future as in the past. When the risk of the effects of Black Swan events are incorporated in the economic calculus, seemingly uneconomic solutions to the energy supply may not in fact be so.

Having a cap and trade system translating national targets on emission reductions into market prices will help drive technological change. Further, if allowances or permits to emit carbon are auctioned, they provide government revenue to further motivate public investment in support of the new energy regimes. Adaptation to climate change will demand more expenditures, as even a 2° rise in temperature will precipitate the need to protect coastal areas and manage water supply. Some adaptation investments will create opportunities for mitigation, as they create protection from climate change. Examples include new and more efficient transportation systems protected from severe weather and more water storage to generate renewable electricity while at the same time control floods and supply water during times of drought.

The bottom line is that the entire base of energy and infrastructure will be going through a profound transformation in the next 40 years. Ironically, the economic crisis—the once-in-forty or perhaps four year event—has motivated governments to dramatically increase public investments to accelerate this transformation of the capital structure of nations. Research is critical—today we do not have all the solutions—particularly in achieving negative emissions in the generation of energy.

Summing Up

The world governments and financial institutions have already suffered the effects of misjudging the probability of Black Swan events in the global financial systems with severe costs to the public. Policymakers should not misjudge the potential of Black Swan events in energy and climate change. Governments tend to be slow in foreseeing crisis but often quick in reacting to them when crisis strikes. There are positive signs that governments are reacting coming out of the financial crisis with government stimulus money directed toward energy diversification and more efficiency, thereby pro-

viding incentives for new clean technologies needed for a lower carbon growth path. National legislation and international negotiations on climate change are proceeding with the likely re-endorsement of global cap and trade of emission reduction certificates.¹¹

But the time needed to transform economies is the issue for governments and international bodies. Black Swan events catch up to present as the past has shown. A significant part of economic stimulus packages of the United States, Europe and the emerging economies are being directed at efficiency and diversification of energy. This stimulus money is providing the catalyst for transforming the energy infrastructures of nations. The question remains as to whether it will take more Black Swan events to further accelerate investment, or even more dire, whether we will reach the day when the necessity of investment in adaptation overwhelms that for mitigation.

To achieve the future energy needs of both developed and developing countries without accelerating climate change, energy sources that produce near zero or negative emissions will be needed. Biological sources of energy offer this possibility. Biotechnology must become a priority of research funding for mitigation, sequestration, and adaptation. As carbon accumulation and climate change reengineers the planet, we must also reengineer plants. If the scientists and their models are right, we have little choice. Black Swans once thought rare must continue to be the impetus of a greener future.

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10. JP Morgan Climate Care is investing in cookstoves both in Africa and South Asia. These stoves reduce carbon emissions while at the same time reduce health risks of smoke and other particle inhalation by the family. These projects illustrate that emissions can be reduced, and at the same time communities can benefit not only from a financial payment but also from improved health.

11. *The first commitment period of the Kyoto Protocol has shown that global trade of carbon emission reduction certificates is possible and does reduce the costs of compliance. To continue this success requires a second commitment period to be agreed by governments. The Copenhagen Conference of the Parties made the political commitment, but much of the detail still needs to be worked out to continue the trading post 2012 when the first commitment period ends.*