Black Swans thesis of energy transformation

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Introduction

The looming twin challenges of climate change and energy production are too big to be tackled by known solutions and time-honored traditions. Incremental remedies are fine for incremental problems, but they are insufficient for monumental, potentially life-altering threats, which need to be approached with a disruptive mindset. There are 5 billion people coveting the energy-rich lifestyles currently enjoyed by 500 million people, mostly in the developed world. Incremental technology progress will not satisfy this craving. We need non-linear jumps in technologies – Technological Black Swans![1] We can invent these future technologies.

Environmentalists have done a superb job identifying the problem, but often push impractical idealistic solutions at high cost or inconvenience to consumers. I believe that capitalism and self-interest driven models of new technology adoption are the lowest risk way to achieve a low carbon social infrastructure and plentiful energy. The solution cannot be pushed by legislation or governments; it must be pulled into the market by consumers, corporations and aided by encouraging policy. The environmentalist solution is often one of "deploy the technologies we have as quickly as possible" combined with idealized hopes that the business community will start to value un-priced environmental and health externalities.

These thoughts are noble, and occasionally work, but distract from our best "broad" hope: robust unsubsidized market competitiveness of "green" technologies against their fossil competitors. This should be the mantra and goal of Black Swan technology development. After all, the logic of business is to externalize as many costs (like using public roads or not reducing emissions) and maximize profits, as it should be. "Green" should be a feature that follows – rather than defies – the "laws of economic gravity," which in essence declares that economics trump everything when it comes to mass adoption of a technology. In fact, the mindset of clean energy always costing more can be turned completely on its head in many, even most, areas; economic energy-focused innovations could save consumers hundreds of billions over the next 10 to 15 years!

My basic thesis is that investment in true innovation is the key to reinventing the infrastructure of society and enabling 5+ billion people to sustainably live the energy affluent lifestyle that 500 million enjoy today. While there is no shortage of existing technology providing incremental improvements – whether today's thin film solar cells, wind turbines, or lithium-ion batteries – even summed, they are not likely to address the scale of our problems. While these technologies will continue to improve and sometimes this incremental ecosystem will result in products compliant with the laws of economic gravity, such as wind in certain locations or lithium-ion batteries in certain applications, I suspect this will not be enough. Regulation and clever accounting will help many pundits justify and push these technologies, but in order to drive the necessary resource multiplication, we need to (and can) reinvent the infrastructure of society through the creation of Black Swan energy technologies.

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[1]Credit for this "Black Swan" concept and the inspiration for this paper goes to Nassim Taleb and his book, *The Black Swan: The Impact of the Highly Improbable*.

These Black Swans are technologies that are market competitive without subsidies once scaled, and hit the Chindia price point (the price at which people in India and China will willingly purchase without subsidy) while providing sufficient scale to have measureable impact. They may have up to a 90% chance of failure, but if they succeed, everything changes. Ironically, many appear to have a high probability of failure mostly because they have not been given sufficient scientific focus. Because of this, the skeptical questions such as "wasn't this tried before?" or "why now?" keep many people from even trying.

Author Nassim Taleb defines a Black Swan event as (1) an outlier—it lies outside the realm of traditional expectations in that evidence from the past did not predict the future event; (2) it carries a significant impact; and (3) in spite of its outlier status, it is justified by explanations that are derived and accepted after the fact. To summarize, "rarity, extreme impact, and retrospective (though not prospective) predictability."[2] So these technological Black Swans engender shocks that have retrospective, but not prospective, predictability and material impact in at least one large domain. So-called once in a hundred year events actually happen all the time! There is a lot of error in estimating tail probabilities and they tend to be systematically underweighted, particularly in complex systems.

Thus, with several thousand Black Swan technology "shots on goal," where most predict that each individual shot will fail, I predict we'll see at least 10 incredible successes. Together, they will completely upend assumptions in oil, electricity, materials, storage, agriculture and the like. Improbable is not unimportant in my view. In fact, very likely, the most successful technologies will be the ones considered improbable, not those known to be safe and incremental. While the world expects lithium-ion batteries to get better, the most prevalent battery by 2020 to 2025 may be what I call a "quantum-nano-thingamajigit" battery that is 10 times cheaper and 10 times more energy dense. Technically it may not even be a (chemical) battery, but rather another sort of electricity storage device. This is the essence of the Black Swan thesis of energy transformation!

Consider this: most projections of future oil use are based on linear extrapolations of the past. However, the reality is quite different: for instance, as personal income (PPP GDP per capita in 2010 dollars) in South Korea went from $10,000 per person to $20,000, over 10 years, per capita oil use quickly jumped from a mere 0.014 barrels per day per person to nearly 0.05, an increase of 3.5 times. Now consider that in 2009, China was at ~$12,500 PPP GDP per capita and growing by at least 10 percent. If China continues to grow at 10 percent, they'll reach the $20,000 threshold in 5 years and $30,000 by 2020. In order for China's oil consumption to track South Korea, or Taiwan, the world oil output would need to double, and China would go from 10 percent of demand to nearly half.[3]

In reality, we won't run out of oil overnight. We can produce a lot more oil than many pundits believe; if prices go up, oil sands, oil shale, coal-to-liquids and a handful of other processes will scale up – oil reserves are more of an economic concept than a geological one. However, most of these technologies are far more costly and damaging to the ecosystem than traditional oil extraction and have increasing

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[2] "*The Black Swan: The Impact of the Highly Improbable*." Nassim Taleb
[3] http://blogs.cfr.org/geographics/2010/08/23/chinasoilconsumption/

costs as we try and access more of these resources. Demand shocks like this, as well as supply shocks such as the Arab Spring in the Middle East, can make clean technologies economically viable by increasing the marginal cost of fossil technologies. Add to it Black Swan innovation and we have an interesting but unpredictable mix. And, in a world where carbon legislation is forever an imminent possibility, the financial risk of investing in these fossil-based high-capital technologies makes them potentially uneconomical, offering Black Swan "green" alternatives an opening. Investors should consider "low carbon risk" investments for any asset with multi-decade lifetimes and green economic technologies should have a lower risk premium than their higher carbon risk traditional competitors like oil sands.

The only way to create 5 billion energy-rich lifestyles economically without complete environmental destruction and geopolitical conflict is through resource multipliers: technology or techniques that dramatically increase our ability to create and use energy efficiently. More specifically, the technology will have to achieve 5 to 10 times our current energy productivity (GDP output per BTU consumed or 80 to 90 percent improvement in efficiency overall) over the next few decades while dropping carbon emissions per unit energy by a similar factor, by increasing supplies of economic low carbon energy (BTU per carbon emissions). In simple terms, we need more light per unit of electricity and lower carbon per unit of electricity, more engine horsepower per gallon of fuel and lower carbon fuel, etc. (I have written about how best to structure a global carbon framework previously in my paper "Whose Rules?" and a recent foreign policy article.[4])

As one example, given energy related 2005 emissions were roughly 29.7 billion tons in 2007[5] (all human related emissions are actually closer to 44 billion tons CO2-e),[6] in order to achieve 80 percent less emissions from 2005 levels, with ten times the number of people living energy rich lifestyles, we would need 10 times energy productivity, and then 5 times energy carbon efficiency on top of that. Not accounting for methane and other greenhouse gases, we need roughly a 50 times "carbon productivity"[7] improvement. **Provided we deal with the non-CO2 greenhouse gases separately, our only hope of reaching this goal is with a combination of energy productivity (how efficiently we use the energy we can make/extract/collect) and carbon energy efficiency (how little carbon we emit to make the energy we use) using substantially superior - cleaner, yet economic - technologies.**

Focusing on short-term incremental solutions as the answer risks distracting us from working on the home runs that could change assumptions. This is the real danger because only when we break down current assumptions can we begin to confidently look for those game-changers. Incremental improvements have their place as part of a complex ecosystem of innovation, but mostly as catalysts or stepping stones to larger innovations that end up changing assumptions.

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[4] http://www.khoslaventures.com/presentations/080924_Global_Carbon_Caps_Proposal.pdf; http://www.foreignpolicy.com/articles/2010/12/10/long_shots
[5] http://www.eia.doe.gov/oiaf/ieo/emissions.html
[6] http://www.wri.org/chart/world-greenhouse-gas-emissions-2005; http://www.ipcc.ch/publications_and_data/ar4/syr/en/mains2-1.html
[7] Utility (e.g., GDP, lumens, miles driven) per unit carbon emissions

Sometimes it is hard to predict when a seemingly incremental innovation leads to large changes. It is similarly difficult to predict when multiple incremental generations will compound into large changes over multiple iterations in time. Both of these forms of unpredictability emphasize connectedness across the diverse technologies of the innovation ecosystem because only through denser and denser connections can we increase the likelihood (or auto-catalysis) of these extensive adjacent possibilities.[8]

Unique combinations of these incremental innovations can become an enabler for a Black Swan innovation, because innovation ecosystems are complex and hard to predict. At the very least, incremental innovations are training wheels for larger innovations. Still, while valuable, there is a dangerous false comfort in focusing our time, money, and energy on scaling incremental improvements to the exclusion of searching for Black Swans. I still believe, despite the above mechanisms, that radical innovation in energy technologies needs a much stronger focus.

Therefore, I personally believe we over-value incremental steps at the expense of Black Swan innovations that have a better shot at economically addressing problems at scale. As an example, wind power makes economic sense in certain applications but will remain a niche solution until energy storage takes a quantum leap. A Black Swan in storage would change the outcome for wind (and solar) more than any innovation in wind, which is why I think that subsidy dollars are better spent encouraging storage innovation than wind adoption.

Solar, given the current trajectory and rate of technology innovation, may get substantially more economic through technology change into the adjacent possible. While the adjacent possible in wind is generally incremental, in solar, if one defines the adjacent possible to include structures and materials different than traditional solar cells, then large improvements are possible. Though often a matter of definition and semantics, "incremental" upgrades and tweaks to most current technology merely reinforce the erroneous generalized belief that "everything" has already been "figured out," and tomorrow's solution is simply today's technology with a few tweaks.

Less consumption or conservation, though useful, is another incremental path but not a 5 to 10 times multiplier of resources. People will not choose to just "use less" when it stunts their own prosperity or convenience. Simply, we need to cost-effectively produce usable energy with a smaller carbon footprint, and we need to use that energy far more efficiently; radical new technologies, Black Swans, can get us there.

That said, uneconomic solutions simply will not succeed at scale. The only scalable solutions are economic ones that hit the "Chindia" price point. After all, a rural Indian farmer won't buy a more efficient widget because it emits less carbon; he'll buy it because it saves him money, or enables him to do something he couldn't do previously. Remember that this farmer doesn't have access to cheap credit, which many environmental or academic "economic" calculations assume to be a 3 to 5 percent interest rate, but rather he borrows at the rate of the local moneylender.

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[8] Coined by Steven Johnson – in his words: "The adjacent possible is a kind of shadow future, hovering on the edges of the present state of things, a map of all the ways in which the present can reinvent itself."

Any new technology must have a path to unsubsidized market competitiveness if it's going to have a chance to scale. ***To have any hope of rapid adoption, this new technology must pay for itself in a year or two for individuals or have at least an 18 to 20 percent IRR for corporate investments. This is the reality of consumer and corporate behavior against all the arguments of what consumers or corporations "should" do.***

This focus on what people or countries "should" do is firmly entrenched. I believe what the consumers "will" do is more important, and fairness, prosperity, and reason get lost in political debate. User behavior, especially in the developing world, where most demand growth will happen should be our guide to acceptable technologies. If we just develop expensive technologies that only eco-minded San Franciscans or rich Germans will adopt, and somehow succeed in making San Francisco carbon neutral overnight, the ecosystem won't notice (it would remove 4.1 million tons of CO2 per year or ~2 percent of China's annual *increase* in emissions).[9]

The bias in many environmental prognostications, including from the IPCC, make the problem of trust and reliable information even harder. The majority of the world's population does not yet believe climate change is a critical problem, despite the well-positioned and carefully crafted polls that say they care. They care, but not enough to make it a top five priority. And the only prognostications that work in my view are based on game theory and the self-interest of the various populations, given their top five priorities! Groups like the IPCC (does anyone, in real, daily decision making, really care what the UN, World Bank or IMF have to say?) have lost enough credibility that they are unable to convey the fact that their models, based on early data, are more likely to underestimate rather than overestimate the changes. I do believe climate change risks are very real and need urgent attention, but what matters more than my opinion are the beliefs and priorities of the consumers and corporations.

My call is to a safer approach to the problem instead of relying on what we "should do." We should rely on self-interest of people (cheaper energy, less short-term spending through efficiency) and countries (national competitiveness through more energy-efficient economics, jobs, GDP growth in new segments!). While the Stern Review[10] talks about reducing GDP by 1% to 1.8% now in order to address climate change; can you see many countries making this political trade-off? This is as unlikely as it is ineffective. I advocate investing instead in the efficiency and clean energy innovation race which speaks to countries' self-interest and desire for job creation. Proof points are clear: look at the growth of the countries that willingly jumped into the information technologies race! Environmentalists often talk of rich countries taking more responsibility by spending directly and helping developing nations reduce emissions; even if this is the moral thing to do, can we practically triple the equivalent of foreign aid to India and China while people think they are "replacing" US/European jobs with low-paid foreign workers? Equally importantly, my arguments work even if one discounts the probability of climate change. The investments I suggest are warranted as much for energy security, as for increasing affluence generally and market competitiveness specifically.

[9] EIA

[10] http://www.hm-treasury.gov.uk/sternreview_index.htm

Many claim that the world cannot innovate significantly in energy; that there are only incremental improvements possible. Many believe energy innovation only happens on a long time scale. This is all nonsense. At least in the US, more likely globally, the energy sector suffers from a particularly bad case of "incumbency capitalism," which protects the interests of the incumbents, to the detriment of the innovators. Innovation is artificially repressed in the energy sector by anti-innovation structures.

In fact, innovation in the energy sector is vastly easier, in a technical sense, than in the rest of the economy – if we get rid of the barriers built into the sector beginning in the 1920's and now reinforced by the incumbent monopolies, cartels and their well-funded lobbyists. For example, the IEA identified roughly $550 billion annual in global dirty energy subsidies.[11] Every depreciation schedule, royalty rate, pollution requirement or other economic factor is influenced by the incumbents during policy making all over the world. But the Black Swan approach is robust against political reality and does not count on any of this being rationalized or "done the right way" or "on a level playing field."

Innovators seldom show up at the influence table, another part of why "incumbency capitalism" is an apt way to describe the kind of capitalism we practice. It may yet be true that without energy market reform, ONLY drop-in innovations deployed by the ultimate consumer have an easy pathway to scale. Innovations up the supply chain, or disruptive in a non drop-in way, are often blocked by enormous cartel and regulatory barriers.

Nuclear is a classic example of an incumbent technology that claims to be cheap, but this illusion swiftly breaks down without government loan guarantees (capital cost subsidies), waste disposal subsidies, subsidized insurance and the like. If solar, wind, storage and other technologies were on a level playing field with nuclear and got similar loan guarantees and similar subsidies, I would welcome the competition. The fact is that the nuclear industry received tens of billions in cumulative subsides when it was nascent to get down the cost and technology curve, and still continues to do so. Much of the miracle of France's nuclear power could not be replicated today at the 12 to 15 percent rates of return commercial investors want or the national insurance and waste disposal commercial vendors would demand. Nuclear power in those "level playing field" conditions would not be the cheapest alternative, though I am a fan of letting nuclear power compete with renewables.

Wind and solar for their part need to recognize that we cannot supply power only when the wind is blowing or the sun is shining, but when the consumers want it! Averaging renewable resources over large areas doesn't get there since it works only in an idealized situation with enough sources, but not along the path of development, and power needs to be delivered almost 100 percent of the time it is demanded. We need to be pragmatic on all sides; reliable peak power matters. It is difficult to have policy biased towards innovation, or "innovation capitalism," but it will help assuming it can get past the existing influencers. Having good policy in place will help, but again, in my view, it is not necessary to drive Black Swan innovations in the US.

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[11] http://www.ft.com/cms/s/0/27c0ff92-7192-11df-8eec-00144feabdc0.html?ftcamp=rss#axzz1ES0IQfay

It's also a question of focus and motivation; we have not had either in the last thirty years. In 2005, Rick Newton (then Dean of Berkeley School of Engineering) and I conducted an informal survey to determine academic interest in energy research, and virtually no professors were interested in energy technologies. Starting in 2004, I was giving energy lectures at universities around the country, yet the rooms were mostly empty; there were almost no PhDs interested in energy at MIT, Stanford, Caltech and other top-tier schools. Without mind-share, the outlook was dim for exciting game-changing technological leaps in this arena. Just eighteen months later, a similar informal survey showed 50 percent of the professors were interested in energy technologies.

How times have changed – oil topped $150 per barrel briefly, energy geopolitics has become mainstream news and recently we've witnessed the potential for devastating catastrophes associated with increased deep-water drilling or natural disasters like the Japanese tsunami. Energy is now the #1 priority at top-tier institutions globally. The world's best minds are targeting this challenge, coming up with crazy ideas and getting funded to explore new and often crazy possibilities. University energy programs are now attracting the best and brightest PhDs from around the world, all focused on this problem.

Ten or twenty years from now I expect we won't recognize our world because of their efforts. If that sounds like hyperbole, remember that 10 years ago Google was a small-time search engine, and Facebook and Twitter hadn't even been conceived. In the 1980's pharmaceutical companies looked skeptically at biotechnology, buying non-IBM computers was career threatening, while in 1995 media seemed unaffected by the Internet. Fifteen years ago, when we were starting Juniper networks, there was zero interest in replacing traditional telecommunications infrastructure with internet protocols. After all, there were hundreds of billions of dollars invested in the legacy infrastructure, and it looked as immovable as today's energy infrastructure. In fact, most major telecommunications carriers told me they would never adopt internet protocols given the humongous investments and complexity of the legacy infrastructure. After all, a new voice switch in San Francisco had to work with a fifty-year-old telephone switch in Oklahoma.

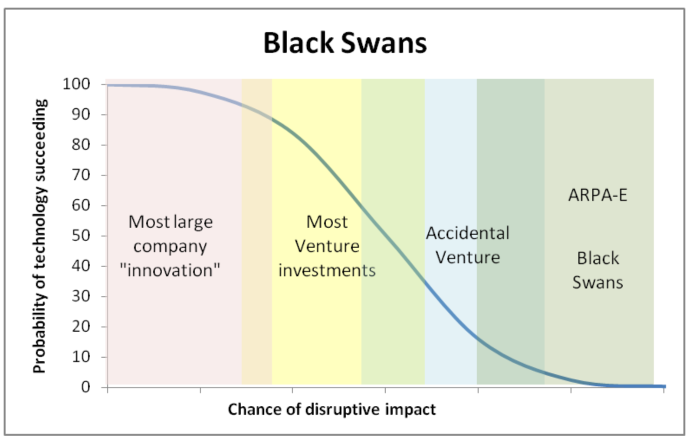
Energy is an even bigger challenge and opportunity than information and telecommunications. Market forces will drive reinvention of the infrastructure of society. If we harness and motivate these bright new minds with the right market signals, a whole new set of future assumptions, unimaginable today, will be tomorrow's conventional wisdom. I predict there will be 10 or more Googles in the energy space in the next two decades.

We don't yet know what new technologies will change the world; it may take 10,000 different start-up efforts to find those 10 Googles. There is no easy way to predict these 10,000 new efforts, as witnessed by the dotcom "Cambrian like" explosion. The fact that most failed did not impact the fact that the few that succeeded transformed the landscape; nor that it was difficult to predict which ones would have an impact! In the end, improbable is not unimportant if there are a sufficient number of improbables. An improbable venture can become the Black Swan that overturns conventional wisdom. AT&T offers this cautionary tale: this Fortune 500 company went from dominance in 1995 to being sold to tiny Cingular

Wireless and others in 2004, and now mostly the brand remains. If mighty AT&T can be impacted, then so too can Exxon!

Consider every far-out energy idea with the potential to be a Black Swan as a shot on goal. Just like in the lab, most experiments do not succeed, yet someone still wins the Nobel Prize. We need that in energy; we will need a lot of shots on goal in order to get these transformative successes. The easiest way to picture this is through a probability distribution.

In general, I have observed a trend that the more impactful technologies are less likely to succeed, but the more disruptive an impact they will have if they do succeed! Most large companies focus in the safest area, while most VCs focus on moderately risky bets that offer decent returns, but not much likelihood of true disruption. Almost certainly, though institutions like Congress and the Department of Energy pay more attention to the larger corporations, these same corporations will be minor players in the large innovations ecosystem. They generally work on the short-term needs of their current customers and like to schedule innovation timelines and offer little reward for "good" failure. Most, but not all, of the Black Swans reside on the far right of the curve, where the likelihood of technology success is low.



In order to create the right environment, it will help to have the right structures, like carbon pricing, to avoid the "tragedy of the commons"[12] and assure that people pay the cost of increasing the risk to the climate and reap rewards from reducing that risk. Still, Black Swans will emerge even if the Government doesn't do anything, though it may reduce the total shots on goal and take longer as a result. The capital community, aside from a few funds like Khosla Ventures, currently focuses on reasonably high likelihood of returns, and thus tends to ignore the potential Black Swans. With the right structures in place, we could get 100 funds like ours, each investing in 100 long shots over the next decade.

Many argue that the twin objectives of Government are to keep its people safe and allow them to be prosperous; climate change risk is a huge threat to both of those objectives. Rather than trying to pick

[12] This is the dilemma arising from the situation in which multiple entities, acting independently and rationally consulting their own self-interest, will ultimately deplete a shared limited resource, even when it is clear that it is not in anyone's long-term interest for this to happen.

winners and decide what the right path is (which it isn't qualified to do), the Government can specify objectives and make "more shots on goal" a key policy objective. The ARPA-E program in the United States is an excellent example of funding dozens of shots; revolutionary technology ideas compete for grants providing the freedom to either fail early or chart a path to fantastic success. Though the program is not perfect, it is far better than not having any program at all. This is why if the US Department of Energy ARPA-E program is discontinued, for instance, then the Government will reduce the number of shots on goal which reduces the probability of success, though it won't kill the chance of Black Swan innovations completely.

Furthermore, we can also bias the "incumbency capitalism" system, for example, towards "innovation capitalism" by creating an R&D tax credit that favors innovative research over accelerated depreciation which favors capital investment. We need more of this! In the 1990's, private money poured into dotcom and telecom companies, creating a tremendous amount of wealth as well as some spectacular failures, such as the optical telecom bubble and the dotcom bust. I hope the same – but faster – progress will happen in energy if the long-term policy frameworks to create the markets and set the goals are put in place. Despite the failures and bubbles in telecom and the Internet, both areas are much further along than they would have been without the frenzy. At the end of the day, you can't brute force innovation; we don't know what the best ideas or even the right directions will be yet. By creating markets and the right incentives, we can foster the healthy ecosystems to drive unexpected results.

Meanwhile, fast-growing countries like China, Brazil and India are not standing still. Where the United States has an already affluent population and slow growth, these countries are asking themselves how they will provide energy and prosperity to their quickly-growing economies in the face of limited technology solutions. It is thus not surprising that they have adopted their own ways of encouraging innovation and development of technologies that will change the equation for energy security, productivity and prosperity in their own countries.

China for one has been reinvesting its trade surpluses on a huge scale to foster domestic innovation at universities, incubators and tech parks. Simultaneously, it has been attracting innovative foreign companies through incentives and a chance to gain better access to one of the fastest growing large markets in the world. In 2009, China put over $34B in public and private money into cleantech while the US invested just over $18B, and all indications suggest that this number in China is growing quickly in 2010 and 2011. But the more important thing China is doing to attract these new technology efforts, in my view, is to create larger markets for them than exist in the west! The leading LED companies have larger markets in China than in most western countries, and that is the right way to compete.

Despite the criticism of many national government efforts, be they in the US or China, there is a larger future economy that is up for grabs and the race for the next trillions in GDP growth is there to be won. As compared to the politics of "limits, cost increases, subsides"[13] that environmentalists push, there is

[13] Nordhaus & Shellenberger: *Break Through: From the Death of Environmentalism to the Politics of Possibility.*

an economic world of "possibility," GDP growth, and jobs that will go to the creators of Black Swan technologies and economic rationale exists for investing in this race.

This is a race for hope and economic growth, not a world of limiting growth for the sake of the environment! This is not about burdening the economy with additional costs but rather making an economy more competitive with much lower energy costs, and making a country the leader in the race for new "green" GDP growth. In the end, these efforts cannot defy the laws of economic gravity or hope to change consumer or corporate behavior away from the technologies that deliver the best value.

The goal is to leverage what consumers do, not what they should do. Technology can provide economic solutions that are also green and not just "green" solutions. The companies or countries that develop these technologies will be the epicenter of the new foundation technologies that reinvent the infrastructure of society. They will benefit just like the US benefited from the re-invention of information and communication technologies: the so-called ICT.

Countries and companies should not pursue this goal because it is the right and moral thing to do, but because it is in their self-interest; it is a guarantee for capturing this growth in their GDP and providing jobs for their citizens. It is not about the shared sacrifice that Europeans laudably envisioned when they signed the Kyoto Treaty (which few if any have complied with), but rather about global competition of these new markets. It is about making their economies more energy efficient (lower energy use per $ of GDP) and hence having a competitive advantage!

Still, there are those who claim that it's not worth expending the effort because climate change is a myth. To those skeptics I ask, is the chance that your home might face a flood, fire or break-in a myth, just because it might not happen? Huge climatic shifts have happened in the earth's geologic history and are linked to mass die-offs, so there is precedent for the down-side risk. Of course, the problem is magnitudes worse today, as thousands of years ago, an earthquake, hurricane or flood wasn't a big issue because society's infrastructure investments were tiny.

In fact, the impact of catastrophic climate change today, whether you believe there is a 10 percent or 90 percent probability, could range between 1 percent and a concerning 12 percent of GDP (that's $500 billion to over $5 trillion assuming the worldwide GDP this year),[14] so putting money into climate "insurance" is a rational business decision. It makes even more sense when the technology outputs of these investments should compete economically with the next best available technology. Thus, we should treat climate change as risk - much like we treat terrorism, nuclear proliferation, national defense, epidemics, and many other global risks. We insure against these others at substantial cost.

If most people insure their homes because of a supposed 0.1 percent probability of it burning down, why not insure our planet if there is even only a 1 percent probability of catastrophic climate change? One does not have to believe in the certainty of climate change to insure against the risks that it brings

[14] http://media.swissre.com/documents/rethinking_shaping_climate_resilent_development_en.pdf

with it. Most climate models and experts, even skeptical experts, compute a far higher probability of serious climate change.

Further, the debate on whether this potential climate change is manmade or not is academic. Whatever the cause, we have invested a lot as a society in our cities, transportation, agriculture and many other areas – investments that may be destroyed or rendered less useful if the climate picture changes. We no longer have the minimal-investment society we had centuries or millennia ago when the world last endured global temperature changes. If climate change was not manmade but global warming was happening naturally, like tsunamis are natural, would we still not want to insure against it by investing in technologies that improve our efficiency and resiliency?

Part I: Entrepreneurs versus experts, pundits & econometrics:

Just because we don't currently know which technologies will change the world shouldn't keep us from trying to invent these technologies. Brainstorming, day-dreaming and wild-guessing are fundamental activities because they drive technological innovation. The boldest are those who dream the dreams, and are foolish enough to try and make them come true. These entrepreneurial dreamers don't require a lot of data to make their guesses. They may know a lot of science, "facts" and data, but they don't let what's already been done, or what might have failed in the past, constrain what they think might be possible.

More importantly, they don't let what the "experts" say can't be done dictate their activity. The best among them take every market projection with a grain of salt, or as encouragement that nobody will be prepared when they completely disrupt the very concept of their target market (assuming that market even exists yet!). The entrepreneurs, technologists and scientists that we need to encourage and motivate are the ones who don't want to extrapolate the past assumptions, but in fact want to violate them and invent a new future. These intrepid, often naïve, visionaries get themselves into "must solve" situations that usually discourage experienced technologists who are deterred by the known problems. By backing themselves into a virtual corner with seemingly impossible obstacles, they find a way around the issues driven by their ego, smarts, knowledge and the instinct to survive. In these situations, necessity is the mother of invention.

On the other hand, I view experts cautiously. Experts are handmaidens to hindsight, whereas dreamers are mothers to progress. Experts apply existing data and trends to analyses and projections; they focus on past trends, known drivers, known technologies, and large public company announcements. They often ignore the wild claims of startups in the same space. As a result, they generally derive linear, incremental predictions that work well until they are wildly wrong; as Karl Marx famously said, "When the train of history hits a curve, the intellectuals fall off." The trouble with predictions of this sort is that it can create closed thinking in otherwise creative people, making them believe there are no opportunities left.

The real tragedy occurs each time a creative mind turns away from a challenge because enough experts tell them it's unsolvable. The number of times prominent experts have claimed that there is no possible innovation left in a market, an area or even all of science, is hard to count. In 1900 Lord Kelvin, having just retired as president of the Royal Society, was reported to have said, **"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."** Meanwhile they had started to shut down patent offices all over Europe. As John D. Barrow describes in his book, *New Theories of Everything*, "Near the end of the last century, many also felt the work of science to be all but done. The Prussian patent office was closed down in the belief that there were no more inventions to be made. But some work carried out by a junior at another patent office in Berne changed all that and opened up all the vistas of twentieth-century physics."[15]

[15] "New theories of everything: the quest for ultimate explanation" John D. Barrow

In the decade between Kelvin's claim and the popularization of the new theories of Einstein, the aforementioned patent clerk, who knows how many budding scientists picked up other pursuits because of Lord Kelvin's close-minded statement. Newer versions of such blanket statements of what will or will not work are abundant today, ready to be disproven in areas as diverse as energy, biotech, and data storage. Another famous example occurred in 1969, when the Surgeon General claimed to Congress that "we can close the book on infectious diseases."[16] Then we were hit with HIV, MRSA Staph infections and countless other infectious disease challenges, as a result of which new drug discovery and treatment methods accelerated dramatically. Experts and pundits suffer from a number of scientific biases, like confirmation bias, the decline effect,[17] and others. In the end, their prognostications aren't worth as much as the paper (or screen) they're printed on.

Extrapolation is often wrong when new approaches are invented. Failure to predict "needs" creates opportunity for those who challenge conventional wisdom. Nearly every major company built from a startup in the last 30 years flew in the face of big company conventional wisdom: take the case of Juniper Networks that succeeded against Cisco's conventional wisdom. In 1996, no telecommunications company thought it needed the bandwidth and flexibility that internet protocols (TCP/IP) would give them. When starting Juniper, we were told by almost every major telecommunications carrier that they would NEVER switch to TCP/IP. Cisco meanwhile declared they would only develop a different technology their customers were demanding, called ATM. Five years later, AT&T was struggling,[18] their leadership split the business into 4 chunks and sold much of it to Cingular, while Juniper flourished and Cisco struggled to catch up.

Notice that it is possible that Juniper, a single small startup, changed the direction of Internet technology, and was indirectly responsible for the impact of the internet as we know it, though of course the "internet without Juniper" adjacent possible is hard to predict. Similarly, IBM did not predict Microsoft's emergence. Microsoft had several opportunities to get into keyword driven ads (1995, 2000, 2003 as Google did), but aborted each attempt. Facebook simply didn't exist 10 years ago, and no expert could have anticipated the demand. This phenomenon is not exclusive to information technology; biotech companies such as Genentech innovated where old-line pharmaceutical companies spent billions pushing old ways. Technology Black Swans changed the dynamics here and in many other places, primarily driven by small innovative companies, be it in media, telecom, pharmaceuticals, or other areas.

AT&T commissioned a study with McKinsey in the 1980's asking them to project the market size for cell phones in the year 2000. The answer was a market potential of just under 1 million phones by 2000. What was faulty was the projection of technology and what the phone in 2000 would look like (see picture below). It was probably not McKinsey's fault per se; like so many models and projections, they

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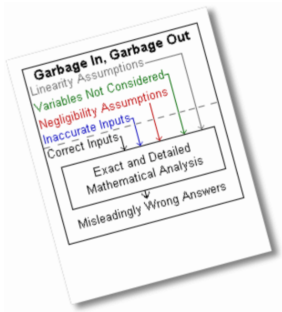
[16] Surgeon General of the United States William H. Stewart, 1969; speaking to the US Congress – cited in *The Killers Within: The Deadly Rise Of Drug-Resistant Bacteria* by Mark J. Plotkin and Michael Shnayerson, 2003, ISBN 0316735663.

[17] http://www.newyorker.com/reporting/2010/12/13/101213fa_fact_lehrer

[18] http://www.forbes.com/2000/10/26/1026topatt.html

started with bad input assumptions and thus created bad output: garbage in, garbage out. AT&T did not focus on wireless as a result and missed what turned out to be a 109 million subscriber market by 2000.



Source: Avinash Kaushik Blog (Left image)

McKinsey's mistake was that they didn't predict the dozen major innovations that hadn't yet occurred and would work together to take phones from suitcase sized floor mounted monstrosities (by today's standards) to the elegant Startac and beyond. It took digital networks, CDMA/GSM, lithium-ion batteries, ultra-low power processors, low-cost high-resolution color displays, TCP/IP and several other innovations. This is where a bunch of white swan parents gave birth to a genuine Black Swan! Each individual advance was a small step forward, but, taken together, they yielded a phone that weighed less than the phone cord of the 1980's era briefcase-sized phone, and recast the mobile market a hundred times greater than McKinsey had dared to imagine. Technology was the driver, and has driven even greater change from 2000 to 2010, where today the mobile device is no longer a phone, but a gateway to the vast resources of the web. And tomorrow it may be your personal assistant that knows more about you than you do.

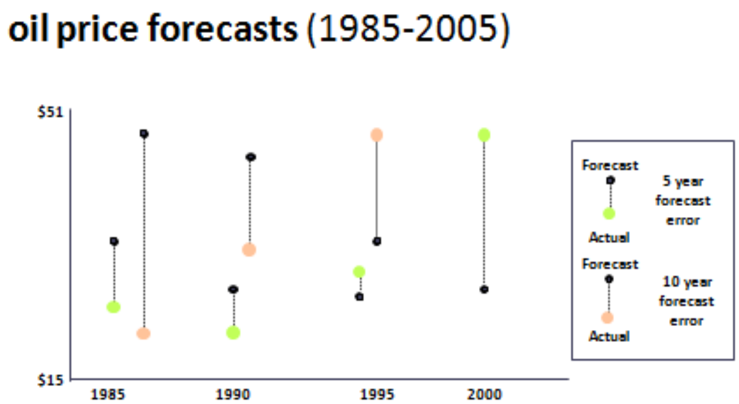
Who could have forecast just ten years ago that India would have more than 600 million people with access to cell phones in 2010, but less than 350 million with access to toilets or latrines![19] Much of this is not knowable or forecastable and is not the forecaster's fault other than their mistaken and sometimes arrogant belief in their forecasts, which provide society the comforting illusion of knowing.

It's easy to come up with anecdotes where experts are wrong (or where they're right), but it's important to recognize that in certain realms (technology-reliant areas like energy in particular), experts make systematic errors. The most obvious perhaps is the EIA oil price forecasts; they're based on a decades-old projection and adjusted for wherever the oil price happens to be that year. They bear little to no resemblance to reality, and even their 90 percent confidence interval is violated every few years (Graph 2)**.**

For instance, the EIA currently projects that oil prices will grow at 2.8 percent annually over the next 20 years, and demand will grow at about 0.8 percent annually.[20] Either the EIA is right or the brief oil

[19] http://www.businessweek.com/ap/financialnews/D9J67E500.htm
[20] http://www.eia.gov/forecasts/aeo/source_oil.cfm

analysis at the beginning of this essay (not an original analysis[21]) is right. But each projection, both with reasonable assumptions, differs by hundreds of percent! And the consequences of this difference of assumptions can be catastrophic to society's plans and forecasts. If we look at the EIA forecast below, both the 5 and 10 year forecasts are off by huge margins. During one talk I gave on this subject, in order to try to discredit my slide, an energy analyst went through each deviation and explained the "one-off unpredictable event" that led to each difference. He simply proved my point.



Graph 2: the black dots represent the forecasted price of oil 5 (green) or 10 (red) years forward from the forecast date. The colored dot represents the actual price of oil once the date arrived. (source: EIA)

The central reason for these huge deviations is that every few years, something completely unexpected happens, recalling Nassim Taleb, to whom I owe the basic thinking, and his book, *The Black Swan: The Impact of the Highly Improbable*. Black Swans engender shocks that have retrospective but not prospective predictability. So called "one off" or "once in a hundred year events" actually happen all the time because there is a lot of error in estimating tail probabilities, and they tend to be systematically underweighted, particularly in complex systems. This is the essence of the Black Swan thesis of energy transformation! But beyond anecdotal data (and I acknowledge that counter examples are easily found), one must look to statistical accuracy of expert forecasts in this class of projections into the far future.

It is not surprising then that when Professor Tetlock, in his book *Expert Political Judgment*, spent several years statistically analyzing expert political and economic judgment (over 80,000 forecasts from over 250 experts over twenty years), he came to the conclusion that the experts were not much better at forecasting, on average, than dart-throwing monkeys. Experts are subject to confirmation bias which sways their views by enticing them to focus on hypothesis confirming evidence and ignoring the rest. Tetlock asked several questions rhetorically, including "How many (experts) in 1945 would have predicted Japan and Germany would in 35 years be the 2nd and 3rd most powerful economies?" and "How many (experts would predict) that China in 1970 would be the 4th biggest economy in 2007 and moving up the rankings fast?" The resounding answer was "next to none." In another example, when

[21] http://blogs.cfr.org/geographics/2010/08/23/chinasoilconsumption/

given brain scans of a patient, clinical psychologists were not substantially better than their secretaries in determining an accurate diagnosis.[22]

Ray Kurzweil's comment as to why expert predictions are bad is worth noting:

> *"I have spent thirty years examining this issue. The problem with most futurism is that their assumptions are linear whereas the progress in information technology is exponential. They are not as stupid as their predictions would suggest. Their analyses are well thought out except for this one issue. But that, of course, makes all the difference in the world. Thirty steps linearly (1, 2, 3, 4, 5, ...) gets you to 30. Thirty steps exponentially (2, 4, 8, 16, ...) gets you to a billion. That's the progress we have actually seen in the price-performance of computing since I was an undergraduate.*
>
> *The reason for this is that our hard wired intuition about the future is linear. The reason we have intelligence is to predict the future, so that we can anticipate the future implications of our actions. That has value for survival. For example, our forebears are likely to have had the thought "if I continue on this path and that animal up ahead continues on its path, we'll intersect, so I better change my course." This linear approach to anticipating the future worked well enough that it became hard wired in our brains. It is such a strong aspect of our intuition that critics of my exponential perspective do not even bother to articulate the issue but just rather point to the incongruity of my predictions. Half way through the genome project (7 1/2 years into the 15 year project), only 1 percent had been collected which caused early critics to say "I knew this wasn't going to work. It's going to take 700 years to finish." My response was that the project was right on schedule and that 1 percent is only 7 doublings away from 100 percent and indeed the project continued to double each year and was done 7 years later."*

The vast majority of forecasts have been inaccurate because of this human tendency for linear thinking. Therefore, I encourage experts to change tone when it comes to predictions in markets, science and technological progress, and to think non-linearly. While the data might scream that there's nothing new to do, or economic clean energy solutions are not possible, always openly acknowledge there are possibilities nobody has thought of. Just because we don't know about a technology does not mean it is not possible. The impact of the highly improbable is assumed to be low, when in fact it can be very large if there are enough of these highly improbable possibilities.

My key message is that improbable is not unimportant. Incremental predictions are really the lowest of lowest bound of possibility, with nearly boundless upside. Case in point in the energy domain is the discovery of shale gas fracking technology, which has completely changed assumptions around natural gas prices and supply. Even these updated assumptions based on shale gas could be upended again by new "cleanest coal" technology that is being developed – biomethanation by microbes of coal in-situ by

[22] http://www.newyorker.com/archive/2005/12/05/051205crbo_books1

small startups like Ciris and Luca. This new pathway may yield natural gas at a fraction of the cost and environmental impact of shale gas!

And to budding entrepreneurs and investors: whenever an expert implies that something is impossible, take it as a challenge. Arthur C. Clarke famously said, “anytime a distinguished old scientist says something is impossible, he’s probably wrong.” This is particularly true for anything sensitive to non-linear effects and relationships or growing in complex ecosystems, notably climate, technology and social phenomena.

It is, however, important to recognize that experts aren’t bad at analyzing old data to gain an understanding of what has already happened: what caused the Cuban missile crisis, the theory of evolution, the links between human activities and climate change. All theories are evolving, and sometimes proven wrong with new data, but scientific method applied to the past is not the object of my attack. The issues begin when one takes all of that well-analyzed data and tries to assert that we know what will likely happen in the future.

The illusion of knowing is far more risky than simply admitting you don’t know. The future’s causality is often different than that of the past but cannot be reliably modeled in my view. My criticism is aimed mostly at social scientists, rather than at physical scientists, and at the econometric models and forecasts they offer so authoritatively with many embedded and unsound assumptions.

Part II: Energy Black Swans and the future of energy

There will be Black Swan technologies that completely change assumptions in the energy and technology sectors. Though mathematically not identical to Mr. Taleb's theory in terms of tail risk, there are similarities in the vast uncertainty and likely underestimation of the tail probability of unforeseen batteries, biofuels, carbon remediation and efficiency in every major category of energy use and production. By definition, we cannot predict what the technologies will be, but that is not "proof" that they do not exist and it makes it even more essential that we take as many shots on goal as possible. I think the Khosla Ventures "Clean Dozen" listed below are the kind of technologies that might constitute potential Black Swan candidate examples of "shots on goal," though some of them may not be radical enough and others may fail.

As venture investors, we are constrained to short-term fundable projects with milestones each year that are required to make next year's payroll! Venture startups are often funded for only a year at a time and must usually convince a new set of investors each year to co-invest with their previous investors. In the long term, the shots that emerge will be even more dramatic and disruptive and are hard to imagine today. Still, there is substantial value to short-term checkpoints: an advantage to annual funding is that it generally means annual testing of the idea's fundamentals; failing early and modifying trajectory often is a part of taking lots of shots on goal. On the other hand, there are many disadvantages to long-term projects like the multi-billion dollar international fusion project, the Tokomak, which in my view is unlikely to work, or many other government programs that are "specific" to a particular solution.

ARPA-E is, in my opinion, far more likely to produce results because it is not "specific" to solving one problem in a particular way. I believe the reinvention of energy infrastructure will be driven by a few large-impact but largely unpredictable technologies versus slow steady improvement in known technologies, regardless of whether we are talking about fossil energy technologies or green technologies. For example, I am not as optimistic toward traditional silicon solar cells or traditional liquid electrolyte lithium-ion batteries being that important even in a decade, despite the howls of protest I got when I suggested this recently at an energy storage conference. Likely, the most impactful ones will be low probability, extreme impact, and with only retrospective predictability. This is exactly the definition of Black Swan events that Nassim Taleb uses. Though Black Swans can be positive or negative in their impact, of course I target positive ones. Still, as a somewhat disheartening example, one negative Black Swan is "Jevons paradox;"[23] the observation that increased efficiency due to technology improvements often drives *increased* consumption of a resource, rather than a decrease.

It is important to note that how this innovation happens is also unpredictable. Sometimes disruptive innovation is a result of the combination of hundreds of incremental innovations in disparate fields, and other times it's a marrying of people of different backgrounds; for instance, having an aeronautical engineer look at cooling technology, or having a geologist look at electrochemistry. The key point is to make sure that all forms of innovation are encouraged, from kindergarten to our government policies

[23] Alcott, Blake (July 2005). "Jevons' paradox". *Ecological Economics* 54 (1): 9–21.

and regulations. I explore how innovation happens and the importance of a healthy innovation ecosystem in more detail in a companion document.

At Khosla Ventures, we expect to invest in maybe a hundred groundbreaking technologies between the past few years and into the next decade. Some will be shots at Black Swans, though we will continue to make good bets in select incremental technologies like better and cheaper thin film-solar cells. It is even possible that what seems incremental may turn out to be transformative. Much is unpredictable and my assertions are probabilistic. If there were a hundred such Black Swan venture funds, each with its own points of view, we would have 10,000 "technology" shots on goal over a decade, or at least more than 1,000 non-overlapping attempts. With that number of shots, or even just a thousand, I believe we would have a near certainty of at least ten assumption-shattering successes in major market segments.

A corollary to this **Black Swan thesis of energy and infrastructure transformation** is that many such efforts – maybe even most – may fail. The press will often focus on the most visible failures or naively assume every project at every stage has a high risk, but in my view the failures, especially if one fails early, barely matter, neither technically nor financially. If one can make a hundred times one's investment in one venture but lose all the money nine out of ten times, an investor will do just fine, assuming enough diversification. As Robert F. Kennedy said: "Only those who dare to fail greatly can ever achieve greatly."

I conservatively expect, for example, our biofuels portfolio to have at least one of ten ventures achieve a 50- to 100-times return, well over 50 to 60 percent of them to achieve good returns, and to lose money in 40 percent of the ventures. If I am right, we will do extremely well despite the few losers who will get a disproportionate amount of attention from journalists hungry for saucy stories that confirm the conventional wisdom that transforming the oil industry is not possible. Meanwhile, the successful ones will not only save consumers billions, but will vastly expand policy options for pollution, climate/carbon, national security and resource management.

To find and cultivate the green equivalent Black Swans to coal-based electricity, device and appliance efficiency, and oil production or consumption, one must search for technologies exhibiting potential Black Swan traits. After all, incremental improvements in existing technology, whether today's thin-film solar cells, wind turbines, or lithium-ion batteries, are simply not sufficient to fully, or even meaningfully, address our problems. They make interesting and sometimes large businesses, but will not impact the prevailing energy issues at scale. For that, we must look for and invest in quantum jumps in technology even with low probability of success if the impact of a successful venture is large; we must invest in potential Black Swan technologies.

We strive to find technologies over the next decade such as storage at $50 per kWh, wind and solar viable without subsidies (e.g., Solar with 30 percent efficiency at less than $0.50 per W), 100+ percent more efficient engines, 10 times cheaper and denser quantum-nano-thingamajigits to replace batteries, and in fact we have several low probability efforts in each of these areas. We need technologies that are disruptive, often 10 times better than today's conventional technologies.

There is a tendency to call every solar, wind or battery technology a Black Swan. Though Stion, Miasole and other thin-film solar cell investments may be good investments, I don't consider an 18 percent thin-film solar cell a Black Swan. Thirty percent PV at half the cost, on the other hand, may qualify if an economic electricity storage ecosystem also makes progress. We know of a few such shots on goal, within and outside our portfolio.   At Khosla Ventures, we often say we like technologies that may have up to a 90 percent probability of failure (though not to the exclusion of lower risk bets), because that is where the Black Swans are most likely hiding. Though nothing prevents Black Swans from hiding in low-risk technologies, it is less likely. I will highlight some examples of these high-risk "science experiments" later.

So what?

To the entrepreneur, I say "take expert pessimism as a challenge and an opportunity." It is unlikely that traditional big companies and most venture investors will fund outlandish ideas.   They are more likely to fund conventional wisdom - companies like Sunpower, which thinks silicon solar cells will be viable in five years, and Novozymes which uses enzymes for biofuels – seems like a losing idea to me, though of course differences of opinion are valuable. Corporate managers don't like to take on projects that are likely to fail. Too many careers would be at risk, so risk tolerance is low.

When you look at innovation over the last 15 years, radical innovation has come from research institutes, individuals and small companies, not large ones (e.g., Cree vs. GE in lighting, First Solar vs. BP or Shell in solar, and several others). In the last 15 to 20 years, big companies have mostly produced what I view as incremental innovations. There are exceptions for sure, Apple being a notable one. But what DuPont or BP considers innovation is mostly lower risk, incremental technology.

If you have a crazy idea, **pursue it any way you can,** and that likely means doing so outside of a big company. Make sure there's a probability the physics works, then don't worry about markets, or even a business plan, though thinking through all the likely issues in the future is important. **De-risk the technology as quickly as possible**, and if you need funding, get out there to **find an investor who is willing to patiently take the risk**. Then **try it** and if you fail, try again, and again, and again until your funding and options run out or you succeed.

Judging when to abandon a promising technology which keeps surfacing seemingly insurmountable problems is one of the toughest judgment calls to make and separates the best entrepreneurs from the rest. This is where larger corporations generally take the safer path and abandon it early or make it a long-term research project rather than a short-term market-disruptive goal. Good managers and scientists scurry away from probability failures towards safer career paths, instead of banging their heads against a seemingly insurmountable wall as an entrepreneur might do. Interestingly, this is at least partially because the entrepreneur may not have the option of a backup plan by pursuing another project or transferring departments within a large company.

For an investor, it's better to fail quickly on $2 million and two years, than on $200 million and six years. Still, there is the risk of missing out on a big breakthrough; to mitigate this risk, there are ways to shorten the technology innovation cycle and to increase by ten-fold the rate of experiments at relatively low cost. With particularly high-risk shots, this accelerated cycle rate is critical and key to successful exploration, and we have experimented with a bevy of techniques to optimize this. Occasionally, corporations try and cultivate an innovation culture so counter-examples to my general contention exist: Tata, in India, for example, annually rewards the "best failure."

To the prospective investor, I say, "we need more shots on goal." Applying rigorous financial tools to early-stage revolutionary startup opportunities is at best naïve and often absurd. By creating a lengthy process, you will be certain to weed out the most exciting and disruptive shots.[24] I encourage you to rely more on intuition and optimism, followed by paranoia. If you can convince yourself the physics are possible, and you can dream up big possible markets, then the technology deserves a shot. Your primary job is not to naysay, it is to help the founders assemble a world-class team with diverse skill sets and philosophies to create a cross-disciplinary "magic" soup of ideas and possibilities. This dynamic environment of creative contention, schizophrenic optimism and paranoia, auto-catalytic diversity and collective brilliance may yield innovative ideas from across disciplines to allow innovation to triumph. Technical and philosophical diversity in the gene pool of a company increases the probability of innovation and left-field solutions.

Rather than focus on what has worked in the past, allow yourself to ponder the improbable and back the people that can make it happen. Can biology help with coal gasification? Can air conditioning innovation come from supersonic flight without violating Carnot's theorem? Have new technologies and requirements made old architectures in engine current again? Can semiconductor fabrication techniques make better batteries? Cold fusion or artificial photosynthesis should not be an automatic no-no, though the timing may be premature for some futuristic technologies. An investor can create leverage for obscure but brilliant founders to hire the best team; this is one of our most important roles in an early startup. Again, judgment matters and I find investors often on the wrong side of optimism. The best financial returns lie in low-probability Black Swans, not in the next incrementally cheaper thin-film solar cell.

I firmly believe that even a 90 percent chance of failure for a new investment is ok, particularly when the 10 percent chance of success may return 100 times, and the investment completely changes assumptions about large markets. I'm not proposing everybody throw their money away at pie-in-the-sky technologies (and don't do it without great science and technology knowledge and a large dose of experience), but often a little investment is all it takes to take another shot and challenge assumptions. As an investor and advisor, it is our responsibility to encourage the entrepreneur to de-risk the technology as quickly and cost-effectively as possible.

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[24] Christensen, Clayton M., Stephen P. Kaufman, and Willy C. Shih. "Innovation Killers: How Financial Tools Destroy Your Capacity to Do New Things." Special Issue on HBS Centennial. *Harvard Business Review* 86, no. 1 (January 2008).

This is not about random gambles, but about betting on larger prizes with intelligent bets and constant focus on improving the probability of success. Still, this is an art form we are trying to develop at Khosla Ventures and we don't always seem to be very good at it. Having made over seventy five investments, I personally have never paid attention to an IRR calculation, because in this world, probability of success is more important than the illusion of calculating IRRs, and probability of disruption ("if your technology works") is more important than probability of technological success.

To be a successful Black Swan investor, judgment, skill, even experience in intelligent betting matters; for the layman investor, please don't try this at home. It is not easy and the science isn't generally what a lone inventor, like your neighbor, can figure out. For the layman technologist entrepreneur, try again and again and again, and get the input of the people around you, the more diverse the better. "Ideas are works of bricolage. They are, almost inevitably, networks of other ideas….The trick to having good ideas is not to sit around in glorious isolation and try to think big thoughts. The trick is to get more parts on the table."[25] But there are always exceptions in innovation, so the fewer the assumptions the better.

Energy isn't the only field with this sort of potential. Semiconductors have evolved several times since the 1950's, when a computer with the power of a solar calculator today took up a whole room then. Telecom experienced a revolution with the telegraph, and lately with optical fiber and IP protocol, where multiple Gigabits can be streamed a second, more data than was even imagined when the computer was invented.

Black Swan "shots on goal"

There are technologies already in development that have the potential to completely change assumptions. I don't mean technologies that will require massive Government incentives, or that consumers will have to be forced to adopt. When a Black Swan energy technology scales, people will pull it into the market, adopting it because it is the clear economic and behavioral choice.

A great Black Swan technology will create a wave of infectious adoption, completely reshaping or creating a market; think Google, Facebook, Twitter, and the iPhone, not solar cells with their many incentives, guilt trips and subsidies. Many people claim that a technology is economic with a 15- or 20-year payback, but if you want to create real pull in the marketplace, that simply won't fly. With respect to consumer products, such as lighting and HVAC, a truly powerful new replacement technology should pay for itself within 12 to 24 months, fast enough to be a no-brainer even at your credit card borrowing rates, and provide the same or better quality of life than the technology it replaces. In other categories, such as commercial and industrial technologies, the rules differ (e.g., high IRR hurdle rates), but in all cases, the lesson is the same.

[25] http://online.wsj.com/article/SB10001424052748703989304575503730101860838.html

The technology should sell itself – a technology that is pulled by the market instead of being pushed by legislation. Of course, in telecommunications, Wall Street eagerly provided hundreds of billions of dollars for fiber networks out of greed to try and profit from rebuilding our telecommunications infrastructure. They dug up most of the streets in America; an arresting display of the scale we can achieve when the motivation is there.

In our portfolio, we have a handful of technologies that have that potential, but only time will tell whether these or others result in true energy Black Swans. Still, technologies benefit from a bit of push (like subsidies or regulation) to get started or to go through enough iterations to get down the cost curve, particularly when up against entrenched incumbents with massive scale and years of cost reduction and political influence and un-leveling of the playing field behind them. That is when patience or public support matters but in my limited view it seems that 5 to 7 years is a good cap on that support after a technology starts scaling.[26]

Support for one technology can mean encouragement for it, but can also mean distorting the potential for a different, more competitive technology. I currently see this happening in the bias towards electric cars and away from internal combustion engines; our goals should simply be the lowest carbon emissions per mile driven. This is particularly important in energy, because incumbent technologies already operating at marginal cost generally need little additional capital investment, are fully amortized, and have scale.

As a result, these incumbents have a significant advantage over new entrants, especially in some of the higher fixed-cost commodity markets (e.g., biofuels, unconventional natural gas). Further, existing policies favor these incumbents, due to incumbency capitalism, where all the rules and regulations have been designed by the incumbents at the table lobbying for their point of view. In this case, the goal of government policy should be to create new competition and encourage disruption.

[26] http://www.greentechmedia.com/articles/read/corn-ethanol-time-to-move-on/

Black Swan-friendly policy

As I've mentioned previously,[27] Black Swan friendly policy is relatively simple. Don't pick winners (though this is hard and not always the most effective policy – compromises on this can sometimes help industries get started), instead create competitive markets focused on achieving the right goals. Encourage more long shots on goal. The US Department of Energy ARPA-E program is one example of such policy, though I suspect Black Swans will emerge even without ARPA- E. Still, the existence of ARPA-E may encourage more shots on goal and hence I suspect the probability of Black Swans will increase.

In his book *Adapt*, Tim Harford explores other programs, like NIH,[28] which help as well, but it isn't hard to see why a bureaucracy, entrusted with spending billions of taxpayer dollars, is more concerned with minimizing losses than maximizing gains. And the NIH approach does have its place. The Santa Fe complexity theorists Stuart Kaufman and John Holland have shown that the ideal way to discover paths through a shifting landscape of possibilities is to combine baby steps and speculative leaps. The NIH is funding the baby steps. Who is funding the speculative leaps? The Howard Hughes Medical Institute invests huge sums each year, but only about one-twentieth of 1 percent of the world's global R&D budget. There are a few organizations like the HHMI, but most R&D is either commercially-focused research, the opposite of blue-sky thinking, or target-driven grants typified by the NIH. The baby steps are there; however, the experimental leaps are missing.

Industrial policy does its best when it defines clear goals and rules of engagement, and its worst when it defines the steps to get there.[29] Policy should not exist to bias the outcome towards one technology or another. In the same way that experts are often terribly wrong, it is likely the government is even more wrong when it tries to prescribe the answer, or as is often the case, too slow to change direction when the world changes. In addition to being limited to incrementalism and old data much like experts, the Government has to deal with heavy lobbying by well-endowed existing interest groups and individuals, which impedes picking the right winners, and even more importantly prevents letting go of the losers. Not only that, it virtually assures that a new and unheard-of technology will not even be at the table. This may seem obvious, but for those at the US Department of Energy and in the halls of the US House and Senate, it is non-trivial to do this right. No matter what policy is adopted, it is hard to get it exactly right even in the absence of special interest lobbying. We must be patient and tolerant of some inefficiency and errors.

Doing nothing and letting the market handle it will not work nearly as quickly, and it may not even work at all, given the power of incumbents. Even though true Black Swan technologies will be competitive at scale with no subsidies, getting to scale will still cost money, and initial adoption is always tough and often slow. Most importantly, there are built-in incumbency capitalism biases already in the system. The fossil fuel industries are heavily subsidized worldwide to the tune of at least $550 billion in 2008,

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[27] http://www.washingtonpost.com/wp-dyn/content/article/2010/07/01/AR2010070104391.html; http://www.greentechmedia.com/articles/read/vinod-khosla-on-building-carbon-reduction-capacity/
[28] *http://www.slate.com/id/2293699; "Adapt: Why Success Always Starts with Failure" – Tim Harford, 2011.*
[29] http://www.businessweek.com/magazine/content/10_33/b4191028710037.htm

compared to $45 billion for renewables.[30] This doesn't count the estimated $7 trillion spent by the US keeping Strike Carrier groups protecting our oil interests in the Middle East over the last 30 years.[31]

Good policy can encourage more shots on goal, and short periods of protection allow competitive technologies to emerge and gain a little scale. Subsides have a place whenever there are new technologies that have a clear societal benefit, have a path to being market competitive, but aren't advanced enough or don't have the scale yet to be economically competitive versus alternatives. Not only that, simply leveling the cost of capital for incumbents and innovators can dramatically increase the number of innovations that develop market pull, and thereby greatly accelerate the entire innovation process. The very short pay-back periods and cheap capital which generation-side monopolies enjoy in electricity markets is a major drag on the ability of disrupters to reach customers – why not level the playing field?

Currently, policy is biased against innovation, and that bias is one of our biggest problems. The hardest part is in deciding whose judgment to use in these nuanced decisions. Add to this politics, lobbying and lack of sufficient appreciation among congressional staffers and the right decisions become extremely difficult to get even approximately right.

If we are to put subsidies in place, it is vital that the technology has a path to being market-competitive and scalable (no biodiesel from waste grease please). It's possible that many technologies will together reach scale, but I believe there will be a "winner take (almost) all" technology in each market segment. Of course, the number of market segments that will emerge is hard to predict today. For each industry, there is an incentive structure that will maximize new technology innovation and scale up speed, while assuring good return for the money spent.

A potential structure is to start ramping down direct subsidies when a class of technologies reaches a few percent of the existing market, though defining a market can be tricky. Should solar and wind be lumped together under "renewable electricity" when they started at such different times and scale? It is probably time to reduce subsidies for wind, but solar is still on a rapidly improving cost and new technology innovation curve. In the future, it will be a judgment call by the regulator to determine if these and other next-generation technologies merit their own "technology class" designation and a new round of subsidies or mandates, while letting the older ones expire.

The resources spent subsidizing wind could well be spent on subsidizing electrical storage for wind, which would substantially expand the market and quality of wind power. Subsidizing a mature technology like corn ethanol is completely unwarranted. As a technology matures, costs stop declining and sufficient scale is established, the new baby should learn to walk and live on its own without support.

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[30] http://www.bloomberg.com/news/2010-07-29/fossil-fuel-subsidies-are-12-times-support-for-renewables-study-shows.html

[31] http://www.foreignpolicy.com/articles/2010/08/05/the_ministry_of_oil_defense

The key is NOT to cherry pick the answers, such as in the electric vehicle deployment act, natural gas vehicle deployment act, and solar feed-in tariffs. Attempts to predetermine the right path, well before the market has decided which approaches are most economic, will further complicate the competitive landscape though some degree of guessing will be necessary. Neither complete market neutrality, nor picking specific winning technologies is the right answer.

Usually, as in most ideological disputes, the correct answer is often in the middle. When possible, specificity should be minimized, to cast the net for Black Swans as wide as possible. For example, instead of electric or natural gas vehicle mandates or subsidies we might specify "grams of carbon per mile driven" as the basis for mandates or subsidies as Europe has. Instead of solar or wind power we might specify a "low carbon electricity standard" as Ohio has,[32] so nuclear and carbon sequestered coal can compete with solar and wind to be the most economic low carbon solution. Instead of ethanol we could specify a "low carbon fuel standard" as California has.

Take transportation for example; right now, people are focused on batteries as a panacea to low emissions vehicles. Electric vehicles, plug-in hybrids and light electric hybrids (and very lately natural gas vehicles, NGVs) are in the limelight so often that it is hard to get anyone excited about alternative routes. This is no surprise, since the incentives aren't in place for alternatives. However, it may surprise many that hydraulic hybrids could deliver better efficiency than electric hybrids at a lower cost, and are compatible with large trucks, most of which happen to drive far more miles annually than a passenger vehicle. Combine that with ultra-efficient engines, lightweight vehicles and ultra-low carbon footprint bio-derived fuels, and you may create a vehicle fleet using existing infrastructure with at least 80 percent less carbon emissions. This ultra-clean fleet could be more cost effective than today's vehicles, even at consumer borrowing rates.

Given the prevalence of coal power plants, and the high cost of installing a national charging infrastructure, EVs can't promise anything close to that in the near future without the battery Black Swans and low carbon power generation we talked about earlier. Even with an economic battery technology, EVs will be coal-powered cars if we don't change the power generation sources too.

Meanwhile, some folks talk about natural gas as a replacement; not only will it require a new infrastructure, but it will never save more than 25 to 30 percent emissions compared to gasoline. Natural gas for transportation could be a dead-end street. Or of course somebody could invent a completely new approach to natural gas engines! Herein lies the complexity of the policy problem. In the end, I don't know and don't really care which technology triumphs, and the investments I have reflect that technology-neutral attitude. My point is that all of them should have similar access to the market and to the incentives that are jumpstarting that market.

Ultimately, good policy comes down to three principles:

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[32] http://www.pewclimate.org/node/5922

1) Structure policy to create a market around the specified goals (such as grams of carbon emitted/mile); allow for technologies or configurations that haven't yet been dreamed up and enable them all to compete on a level playing field by using phrases like "or equivalent" in policy making.

2) Create a mid-term (to 2020) dynamic framework, so there is predictability, while retaining the ability to adjust for Black Swans.

3) Evaluate technology trajectories such that the technologies must reach market competitiveness quickly, so that we focus on technologies that will be economic and will spread globally. The government policy should help create conditions that result in 100 private portfolios like ours though I doubt government money for such funds would be well directed. Further, it is important to realize that "been there done that" is actually a fallacy; in history, numerous inventions were before their time, they failed because technology had not caught up with the idea. Rather than discard these ideas and try to find new ones, there are plenty of "tried and failed" approaches that may return riches using tomorrow's technology or markets.

Caveats:

(a) Is disruptive change “knowable?” Is it possible to deliberately take economically viable shots at truly disruptive change? I don't believe so, but I do believe it is possible to dramatically change the probability that change will happen in any given area through the encouragement of appropriate culture, policy, cost structures, etc. The key to marginalizing Microsoft was not to build better software, but to build a better search for a connected world. The key to beat Google was not to focus on building a better solution to search, but to eliminate the need for search via social recommendations. Short of continuous experimentation and learning, is it possible to find the key to disruption? And is rapid evolutionary change, as is typical of Silicon Valley and the Internet ecosystem, the key to large steps forward? If so, is the energy system amenable to the same type of innovation or does its very nature doom us to slow innovation and slow progress? Personally I believe that even though the fundamental cycle time in energy is longer, we will see similar “unexpected evolution” but will substitute “months” with “quarters or years” depending upon the area of innovation. But it appears to me that many of our “current” assumptions about energy will be wrong in ten years and most will be wrong in twenty. Ten times change will more likely come from eliminating the current paradigms in their entirety. Similarly, food is a tool, the need is nutrition and taste for beef is a “gate.” Are we doomed to the negative environmental impact of the developing countries adopting a more “meats” oriented diet or will we grow these meats in the lab or is it more likely we will replicate the taste of beef with plant proteins and improve “efficiency of meat” by 5-10X, eliminating many of the concerns and reducing the need for corn production even below current levels? Even seemingly intractable areas like poverty are more likely to be impacted by innovation than all the policies and programs of government and the various non-profit organizations.

(b) Then there is “path dependence.” An incident like the Japanese tsunami or the revolution in Egypt, both in the first quarter of 2011, can completely change our priorities, our focus and the direction of our experimentation. And certain paths become a self-fulfilling prophecy or at least a “strong bias” on future outcomes. The “Arab Spring” may focus us on energy security and replacing oil, but will it be from renewable sources or from oil shale and tar sands? Or will it lead to increased focus on electric cars for transportation? The suitability of one path over another from a scientific and economic perspective is only one of many drivers, and often not the dominant driver. The answer is dependent on unpredictable dynamics based on politics, interest groups, and many other perturbations in an almost unknowable way. Will the tsunami kill nuclear energy, as it seems to be doing in Germany, Japan and much of the western world? Will that kill nuclear power in India and China or will it let these countries dominate the more open field? It is hard to predict what brings the attention of entrepreneurs, scientists and technologists to a particular task. A degree of randomness in this focus is unavoidable.

(c) We underestimate the unknowability of Black Swans. Human beings focus on what they know they don’t know, and spend no time searching for what they don’t even know they don’t know. The only answer is trial, error and failure. I often say that “my willingness to fail gives me the ability to succeed.” Add to this “diversity of thought and trial,” “imagining the possible (and maybe the impossible)," and "just do it" as critical factors in the rate of innovation for our energy problems. More "tail risk" would be a good thing. Given the probabilistic nature of innovation, at Khosla Ventures, we try and take "more shots on goal." We take shots where failure won't hurt us but "if we succeed it is worth succeeding." Not just shots, intelligent Shots: science (as we currently understand it, and modulated generally by our current biases) takes some things off the table (mostly), and thus we reduce ourselves to intelligent shots on goal, rather than random shots. In the clean energy regime, we see many proposals for perpetual motion machines, which ignore the laws of thermodynamics (which have been good to us). Likewise, we see horrendously complex and circuitous paths to reach amazing results, which we estimate (acknowledging our fallibility) will never see the light of day. We understand clearly that not every shot is worth taking, especially for us and given our set of experiences, capabilities and biases. Accordingly, this type of investing is not for the faint of heart, it requires the vision to imagine the possible, to embrace and nurture the improbable, but with the discrimination to eliminate the impossible, and to prioritize the improbables with the largest upside. It's ok to fail, as long as you fail at something worth succeeding and it is ok to realize that we will miss many shots we should have taken and others may succeed where we fail. Many of our decisions will seem foolish in retrospect and the shots taken by others will be "obvious" and "duh, how could I have thought otherwise." It is impossible to answer a priori the question, on the probability or economic viability scale, is it "intelligent shots on goal" or more like "shoot a rocket into space in enough directions to find life"? Being in a dealstream or rather an ideastream where we constantly see innovative ideas to conclude that it is the former and not the latter. But maybe to us with our "hammer" every problem appears to be a "nail."

(d) Attitude matters a lot in innovation. Larry Page, founder of Google, recently remarked "**Even if you fail at your ambitious thing, it's very hard to fail completely.**" To Page, the only true failure is not attempting the audacious. Equally eloquent, Nassim Taleb, in reviewing a draft of this document, commented to me: I would start looking at such ventures in terms of "optionality," option-like payoffs --the value of these options increases markedly with uncertainty, especially "tail" options. That is the essence of the investment strategy we are attempting. The future will be wild beyond our imagination and we will be wrong in many stark ways. But in order to get us there it will not take blind shots in the dark, but rather intelligent and open-minded shots; improbable but not impossible, bold but not pointless, and most importantly diverse shots on goal. But we feel confident that innovation and fearless risk taking will reinvent everything, and then reinvent it again every decade.

Imagine a series of "what if's" within a decade:

1. What if oil was 100 percent renewable and cheaper than fossil crude oil? What if we used 50 percent less of it?
2. What if coal based electricity could be 80 percent cleaner, nuclear could be proliferation resistant, safe, and waste free, and we used 80 percent less of it for lighting and cooling?
3. What if electricity storage was affordable for both stationary and mobile applications and we had a truly smart grid, well beyond today's "smart meters" that are little more than automated meter reading?
4. What if we applied unconventional technology to multiply resources for large global problems like steel, sugars and agriculture?

As improbable as some or all of these statements sound, we are working on all of them. KiOR, Ecomotors, Soraa, Caitin, Ciris, Calera, Terrapower, Lightsail, HCL Cleantech, and a few stealth efforts are all trying to make these "what if's" become reality. Our efforts may or may not succeed, but I believe that someone will make many of these improbable conjectures come true within the next 10 years. We are hoping to do all of them in the next five years. What makes the above interesting is that "improbable does not equal unimportant," and failure does not matter. One success would be worth all the rest failing, but I actually feel reasonably confident that many, if not most, of these efforts will succeed. And as investors, one success in the list may make for a good investment fund. We have our own "Clean Dozen" that address these questions. Though surely some, maybe even many will disappoint us, we have high hopes for these as "shots on goal."

The Khosla Ventures "Clean Dozen":

At Khosla Ventures, we have a few simple rules we use for investing:

1. Attack manageable but material problems
2. Technology that can achieve unsubsidized market competitiveness quickly
3. Technologies that scale – if it isn't cheaper, it doesn't scale
4. Technologies that have manageable start-up costs and short innovation cycles
5. Technologies that have declining cost with scale – trajectory matters

I realize that these rules leave out many reasonable technologies that don't fit the criteria that our constraints put on us. But I am also surprised how wide a range of possibilities this includes and definitely keeps us with plenty of experiments to try. The definition of Black Swan itself is subject to semantic debate, but I tend to simplify by adding "in my judgment" so I can include technologies that can have a 30-50% or more impact in the top ten areas of energy use, investment or carbon emissions. In many cases, as in Ecomotors or solar cells, the technology may need an "ecosystem assist" to get to materiality. I have excluded some of the usual technologies one might consider here, like solar cells, but 25-35% efficient solar cells at $0.50 per watt might qualify if electricity storage ecosystem also develops.

I acknowledge some of these classifications are arbitrary and I expect the list of qualifying technologies will change as more data comes in.

Oil Production

We can reduce the carbon intensity of fuels by 80 percent or more and make them 100 percent renewable. Things have changed quickly in the last few years; nearly everyone spoke only of ethanol, and now the sky's the limit. KiOR hopes to produce a drop-in crude oil or diesel and gasoline blendstock from wood chips, whole logs, grasses, agriculture waste (e.g., bagasse, corn stover) or even algae. When they first approached us, they criticized our strategy of pursuing only ethanol, claiming they could get straight to oil, though at the time they were far from it.

Over time, through multiple failures and iterations, the technology has become completely revolutionary. In seconds, they can generate crude oil, a transformation which takes millions of years in nature. All this using diverse feedstock that will create jobs in rural areas, putting the money we spend at the fuel station to work by pulling people out of poverty, not lining the pockets of petro-dictators. The best part is our hope that after some scaling, this technology will be economic at well below today's oil prices ($90 per barrel), unsubsidized, even with expensive US-based feedstock costs. Though many risks remain, it is exciting to see the potential change in assumptions such a technology could cause if successful. There are many other companies pursuing similar innovations in biofuels, several of which are in our portfolio. In the end, only one technology or company has to succeed to completely change what the word "oil" means, though I expect several to succeed.

Oil Consumption

What of oil consumption? The team at Ecomotors has reinvented the internal combustion engine. It seems like the obvious answer; after all, the fueling infrastructure is already in place (vs. electric or natural gas, which would require huge investments). Years ago, everyone discarded the 2-stroke cycle for internal combustion engines as too dirty; and though the opposing piston idea was discarded in the 1920's, Ecomotors is on a path to a low-emissions, ultra-lightweight, fuel-flexible 2-stroke, opposing piston engine that would improve efficiency by 50 percent or more in its most advanced configuration. Even 100 percent or more improvements are conceivable, even likely, if one stretches one's imagination. The Ecomotors engine is perfectly balanced by design, and can be easily "stacked" to increase flexibility and efficiency, improving efficiency by over 50 percent while reducing the cost and improving the reliability of the engine compared to hybrids.

They could, in a future generation, add fuel injectors that inject supercritical fuel into the engine from Transonic combustion, which could gain another 15 to 20 percent incrementally above and beyond the 50% Ecomotors hopes to achieve with their engine architecture alone, if Transonic technology succeeds. The Transonic injector completely rethinks how to put fuel into an engine; rather than a haphazard shot of air and fuel, it is a precisely modeled uniform injection of a supercritical fuel-air mix which creates excellent combustion conditions. Ecomotors also enables even more aerodynamic cars than the Prius because of its small size and much lower profile (roughly 50 percent smaller/lighter than current ICE at the same power) and at a far lower cost than a hybrid powertrain. Even larger improvements are possible if we include electric hybridization to the Ecomotors engine (their Tribrid design) or better still add a hydraulic hybrid to their drivetrain, like the one that NRG-Dynamix is working on.

Add vehicle light-weighting and transportation fuel consumption could take a serious hit. A 5 percent drop in demand from its July 2008 peak helped drive the price of oil from $140 per barrel to a dramatic low of $38 per barrel (demand was one of several factors) so imagine what a 50 percent drop in consumption could do to oil demand and carbon emissions! And we are evaluating even more radical ways to improve internal combustion efficiency; I consider Ecomotors more engineering than new science and in my view only at the margin of what I might call a Black Swan technology. It is mostly the large impact Ecomotors may have on the engine ecosystem that puts it in this category.

Electricity Production

What if we don't have to mine coal? Companies like Ciris aim to turn underground coal seams into long-term natural gas production wells, at or below the cost of conventional natural gas in the US, and with a small environmental footprint. If it works as envisioned, old-fashioned coal mining, with all of its financial and environmental costs could become obsolete and we would have a new definition of "clean coal," a term mired in conventional wisdom. Though natural gas conversion is a huge step in the right direction (50-60% less carbon dioxide than coal for power production), there are still carbon emissions.

By employing Calera technology on a Ciris-fed natural gas plant, even larger carbon footprint reductions are possible. On the list of greenhouse gas emission sources on the planet, electricity is #1 and cement is #3. Calera is developing a technology that not only reduces coal or natural gas plant carbon emissions, but produces building materials from the captured emissions. The key task is reaching economic viability in a world of low or no price for carbon emissions.

If the company can make the economics work, Calera can achieve a double whammy: power plants with lower emissions, and cement with nearly zero incremental emissions. We do expect that a decent carbon price will be essential to build Calera plants of significance. Or we might fail at the loftiest dreams, and still succeed in turning obsolete coal plants into "green" cement plants. Even this failure would be very innovative compared to what our current expectations are. Of course we could fail even more greatly! There are also bio-enzymatic approaches to carbon sequestration that are just beginning to be explored, maybe these will be the Black Swan? At this point, the carbon footprint behind Ciris' biomethanation is still unclear, as are the economics of the Calera process. But neither of these seems impossible.

What if nuclear energy were designed for passive safety, had virtually no proliferation risk, no radioactive waste to handle, and didn't require enriched fuel? Imagine every developing country getting access to energy sources with a lifetime of decades, requiring little to no maintenance. This is Terrapower's mission. The fuel could be nuclear waste or depleted uranium (which is a waste product from conventional nuclear fuel creation). By being able to skip the enrichment step, the amount of low-cost fuel available vastly increases. Not only that, Terrapower's traveling wave configuration literally consumes the fuel as it is created, making it difficult to weaponize. This alleviates the concern of sharing the technology with every country. This may face large regulatory and political obstacles, but if it works, it could usher in an era of cheap, clean, and safe electricity world-wide.

Electricity Consumption

We need disruptions to dramatically reduce energy consumption, yet ensure the same or better quality of life. Take lighting, for example. Soraa expects to be able to sell an LED bulb that will have less than a 12 month payback compared to an incandescent. They'll eventually fit any form factor, including standard home and business light fixtures (the marketing guys unfortunately but sensibly want to target the high value markets first, and hence may only get to the really mass markets later!); there'd be no reason not to change. These are better than CFLs, they are more efficient and have no compromise in performance compared to the best lighting out there. Others tout incremental LED solutions, but they require customer compromises: less light, limited bulb shapes, high cost with long payback, though I expect many technology providers will reach the ideal LED lamp goal sooner or later. The Soraa team is targeting no compromise high performance LEDs with less than 12 month payback based on a new approach to LED substrates. Not only would that drive adoption in existing form factors, they will catalyze whole new lighting designs. Hopefully the assumptions the team is making about cost and performance hold true.

In HVAC, most processes use the vapor compression cycle, heat pumps, evaporative chillers, or desiccant cooling systems. Caitin has discovered a whole new thermodynamic cycle; if proven and commercialized this may be the first practical new thermodynamic cycle in over 50 years. The existing cycles have been pushed to their limits in terms of performance and capability, are still expensive and most use nasty coolants. Caitin could potentially develop a system that is 2X more efficient though the system is far from practical today. Meanwhile, a number of other long shots have emerged: advanced high ZT thermoelectrics, thermoelastics, magneto-caloric materials, electro-caloric arrays, thermoacoustics, and several others. We can't be sure which will deliver results, but any one of them could change everything. Again a one or two year payback is critical for consumer adoption and Black Swan-level impact, and many technology risks still remain.

Electricity storage

In grid energy storage, the Lightsail team is exploring highly efficient and cost effective compressed air energy storage (CAES) technology. They believe they can get to costs of under $100 per kWh, without the need for, or location dependence of, underground caverns, and without the large energy losses, natural gas based energy input and huge footprints that experts assume for CAES. Most people tout grid storage because it will make renewables more viable by making their power output dispatchable. That's just the start. With cheap enough storage, transmission capacity is magically increased; the transmission grid is only 30 to 50 percent utilized except at peak times and utilities are clamoring to build more expensive transmission due to increased peak demand (those moments of the day and year that power demand spikes). Storage will obviate that to a large degree as power can be both generated and transmitted at off-peak times.

With storage, wind and solar farms can provide energy when consumers want it, not just when the wind is blowing or the sun is shining. Not only that, all of the effort being put into demand response in the home and office will become a lot less valuable, if the load control can be performed by storage. Meanwhile, we're working on storage devices using exotic physics, rather than electrochemistry, to reach affordable prices for transportation applications. Meanwhile, we have a few efforts looking at next generation power electronics and grid management technology; it will take a fundamental reinvention of power electronics in order to deliver the next generation smart grid. These efforts are very early, but if they're successful, they will upend conventional wisdom around how power is handled on the grid and in transport, creating dramatically more resilient and intelligent grid-tied systems, at a lower cost.

Many people assume electric vehicles will replace the internal combustion engine in a matter of a decade or two. Without some battery Black Swans, it seems unlikely, particularly given the Ecomotors/Transonic + biofuels approach to massive carbon reduction. Even at an aggressive price of $400-500/kWh at the pack level, an EV would take years to pay off for the consumer. We have invested in Sakti3 and Seeo, next generation Li-ion batteries that are substantially better than that (lower risk but not necessarily a 5-10X Black Swan) , but have also taken longer shots on goal at Pellion with attempts that don't even use lithium, and really long-shot nano-quantum-thingamajig-batteries that could be Black Swans but have very high probability of failure. Pellion is evaluating hundreds of thousands of material systems computationally, with few assumptions or antiquated rules of thumb about what will work best, while Recapping is looking at ceramics. So much of energy technology and the surrounding assumptions were developed and canonized before computers; I believe we have absurdly under-utilized computational methods in exploring the full realm of possibilities.

The long-term goal is for $50-100/kWh at the system or pack level; it could be that one or more of these delivers, and I hope it does. Again, failures don't matter because even one success makes the whole endeavor worthwhile to me personally and to society as a whole. Without such an innovation, electric cars will remain a 10% or so minority in the next decade. GM has announced they'll only build 10,000 Volts in 2011 since they'll be losing money on every sale despite huge subsidies, and even though the vehicle will be well over $10,000 more than a comparable gas vehicle. Several market studies from conventionally pessimistic to optimistic (these studies never assume game-changers, only varying "learning curves" and market acceptance), estimate a range of only 7% to 17% of new car sales by 2020. The key to keep in mind is if we make batteries better and truly economic, electric vehicles will still be coal-powered cars (coal is the source of most electricity in the US, Europe, India, China and many other places) until we get a low carbon electricity generation Black Swan.

Unconventional approaches to big problems

We're looking hard at technologies that could dramatically reduce the need for fertilizer and pesticide, while potentially reducing water needs as well. It is too early to talk about these technologies; they are "dreams with some experiments" more than they are complete technologies at this point. But first controlling the dosing of fertilizer and then reducing the need for nitrogen in agriculture and forestry are both worth exploring, and we are investigating both of them.

We're also looking at advanced materials modeling and design to maximize the physical properties of conventional bulk materials such as steel and aluminum. It seems feasible to reduce aluminum and steel use by 50% in many applications. This effort is also early and almost impossible to predict.

We have a company that is looking at changing where we get our sugars, for chemicals synthesis, biofuel fermentation feedstock and even food. HCL can take a wide variety of cellulosic biomass and convert it inexpensively to basic sugars. This has incredibly far reaching implications, particularly in the US where the dominant carbohydrate source is corn and high fructose corn sugars are our basic sugars. A change such as this, especially one that opens up perennials for food and fermentation sugars, instead of annual crops, could have huge implications for land use and environmental impact of crops and agriculture. Together with investigations around using plant proteins to replicate the taste, texture, smell and feel of meat, this may redefine the role of corn in the US, be applicable worldwide and could result in protein foods and sugars that could be five time more efficient!

The future

Visionaries invent the future. Far more is possible than pundits can imagine. Based on the acceleration of human progress, using a 2 percent rate of "innovation or change" (admittedly a murky metric) given the nature of the math, imagining 2040 today is like imagining today in the early 1920's! Can you imagine? 1925 was the year scotch tape was invented, and John Scopes was charged with the crime of teaching evolution in class. Commercial radio and commercial flights had just started.

There is always an underlying rate of innovation, and when it comes to commercialization of new technologies, we are accelerating. We're on the cusp of this re-invention; and the great talent of newly focused energy PhDs is still to come! That will only accelerate invention. The "shots on goal" I mentioned above feel mostly, with some exceptions, like engineering shots rather than fundamental science shots to me personally, and if we have successes it will only embolden us, and others who watch us. The science shots we have not started or barely started to take, such as artificial leaves, low energy nuclear reactions, anti-magnets, and nanostructured materials hold far more potential than the engineering shots we are taking now.

We can create a future where low carbon electricity is in abundance, low carbon fuel is cheaper than fossil electricity, electricity, fuel or other energy consumption is very efficient and carbon emissions and pollution are drastically lower than today. But we need patience. It'll take five years to invent a great new technology, at least five years to prove to skeptics and pundits that it can work and scale, and 10-20 years to have drastic market impact as it truly scales. We can hit 80 percent less carbon by 2050, or well before then while giving 5B+ people access to an energy rich lifestyle, but it will take an effort firing on all cylinders. We can re-invent the infrastructure of society, from cement to glass to engines to electricity and liquid fuel sources, and everything in between.

If there were 100 more portfolios like Khosla Ventures with 100 startups, we'd have 10,000 exciting ideas and maybe a 1000 fundamental new ideas. Even 10 of them succeeding can change all our basic assumptions about the future. The relationship between the number of companies and innovation isn't linear, it's more like a power law. The more shots on goal, the chance of long-tail Google-like impact goes up non-linearly because the innovation ecosystem gets richer and many more possible reactions (inventions) get autocatalyzed to success. In the end, I choose to be realistic about the challenges, but highly optimistic about our potential. Though I cannot prove this assertion, one of the unlikely shots is the most likely reality for tomorrow, not some incremental improvement. I simply don't know which "unlikely." Even some of the incremental improvements, over a long enough period of time will gain enough compliance with the fundamental laws of economic gravity or add enough to the ecosystem to be successful in unusual and unexpected ways.

Everyday I get up, I swing for the fences, and remind people that "unlikely is not unimportant." Incremental may be interesting but disruption truly invents the future. And the best way to predict the future is to invent it. And inventing the future we want is very possible. I'll be wrong more than I'm right, and for every wrong prediction there will be 2 other unexpected ideas for new leaps that will take its place. The only certainty is that if we all stay focused on the big problems, the world tomorrow can exceed our wildest dreams in ways we cannot imagine.

Appendix A: The KV "clean dozen" "shots on goal"

What if oil was renewable and cheaper than fossil crude oil and we used 50-65% less of it?

1. **KiOR** (www.kior.com): KiOR is a renewable fuels producer – taking wood chips, whole logs, agriculture waste (bagasse, corn stover) and other ligno-cellulosic material and converting it directly into a crude oil or gasoline and diesel blendstock that can be "dropped in" to the existing refinery or distribution infrastructure without significant modification. The company combines a proprietary catalyst system with an oil industry process called Fluid Catalytic Cracking (FCC) (a proven industry for 60 years). In essence, KiOR's technology simply reduces nature's process of creating oil from biomass by removing oxygen (deoxygenation of biomass) that usually takes millions of years to a matter of seconds (catalytic deoxygenation). Importantly, the plants can be small and still cashflow positive, and they're aiming for market competitive costs unsubsidized at $60-80 per barrel.

2. **Ecomotors** (www.ecomotors.com): Ecomotors is a company re-inventing the internal combustion engine, which is one of the relatively inefficient, yet most used devices in the world today. The company was founded by Dr. Peter Hofbauer, the former head of worldwide powertrain development for Volkswagen and designer of their first modern high speed TDI diesel engine. Instead of using the traditional 4-stroke engine, Ecomotors has designed and is developing a "direct gas exchange opposed piston-opposed cylinder engine" (OPOC). This unique configuration can yield up to 50 percent more efficient powertrains in dual module configurations at costs substantially lower than hybrid drive trains. The advantages of the OPOC design are in its relative simplicity (fewer parts), low cost, lighter weight, and higher power density. The OPOC's unique modular displacement configurations add substantial efficiency exceeding existing comparable engines by 50 percent in dual module and 60 percent in hybrid configurations. It is easy to imagine future enhancements over subsequent generations that push efficiency improvements to 100 percent to 150 percent higher than today's benchmark engines using technologies like supercritical fuel (Transonic) and hydraulic hybrid drive trains.

What if coal based electricity could be 75% cleaner and we used 75% less of it for lighting and cooling?

3. **Ciris** (www.cirisenergy.com): The world depends on coal for a substantial portion of its energy supply, something that will remain true for the foreseeable future, especially in "Chindia" and the US. While replacing coal is a legitimate long-term goal, what if we could clean up coal without the enormous costs associated with unproven IGCC? Ciris Energy is working on turning underground seams of coal into natural gas producing wells (30% reduction in emissions) without the financial costs and environmental degradation of traditional coal mining and burning. Ciris aims to render old-fashioned coal mining (from the belching emissions of coal power plants to the gigantic strip mines) obsolete.

4. **Calera** (www.calera.com): What if carbon dioxide wasn't an environmental problem, but rather a feedstock? Using carbon dioxide, waste alkalinity and brines, Calera's technology is attempting to produce cement and building materials from the captured emissions. The company has

developed new electrochemistry to enable the process and is attempting to overcome process cost – a task made more challenging in the absence of a material carbon price.

5. **Terrapower** (www.terrapower.com): TerraPower's traveling wave reactor (TWR) will offer a path to zero-emission, proliferation-resistant energy that produces significantly smaller amounts of nuclear waste than conventional nuclear reactors. After an initial start-up with a small amount of low-enriched material, this innovative reactor design can run for decades on depleted uranium – currently a waste byproduct of the enrichment process (or even spent fuel from other reactors). An established fleet of TWRs could operate without enrichment or reprocessing for millennia. TerraPower has explored the advanced physics of this concept in detail with 21st-century computational tools and is moving forward with the overall plant design. This would completely change the nuclear equation!

6. **Soraa** (www.soraa.com): Founded by three Professors from UCSB (including Shuji Nakamura, the inventor of the first practical blue LED), Soraa is developing high quality LED lighting at low cost – they expect to be able to sell an LED bulb with 80% less energy consumption than standard incandescent lamps with the same light output and with a 12 month payback. These lamps can be designed for any form factor – able to fit standard residential and business light fixtures while offering significant energy savings (the American Lighting Association estimates lighting is 17% of residential energy usage). These provide better light quality than CFLs with higher efficiency, no mercury, and have no compromise in performance compared to the best incandescent lighting. Other LED solutions exist, but all come with customer compromises be it less lighting, limited lamp shapes, high cost, or an uneconomic payback period.

7. **Caitin** (www.caitin.com): HVAC (heating, ventilating, and air conditioning) systems the world over generally use the same approaches – the vapor compression cycle, desiccant cooling systems, evaporative chillers or heat pumps. These existing cycles have been pushed to their limits in terms of performance and efficiency gains with little innovation to be had. Caitin is in the early stages of exploring a completely different approach - compressor-less cooling that exploits a whole new thermodynamic cycle (the first practical new thermodynamic cycle in over 50 years). If the system works as envisioned, they aim to provide very efficient cooling (coefficient of performance of 6-10), 2x better than state of the art compressors with an extremely short payback period and independent of local conditions like humidity.

What if electricity storage was affordable for both stationary and mobile applications and we had a truly smart grid, well beyond today's "smart meters" that are little more than automated meter reading?

8. **Lightsail** (www.lightsailenergy.com): Renewable power sources (solar, wind, geothermal, hydro) continue to grow as a percent of our energy supply, but there remains a catch – to be truly "dispatchable" and available to match demand, power generation needs the ability to have efficient and cheap energy storage. Lightsail is exploring highly efficient and cost effective compressed air energy storage (CAES) technology with return trip storage efficiencies upwards

of 75 percent. They believe they can get to power costs of less than $500 per KW and energy costs of below $100 per kWh, without the need for underground caverns (geographically constrained), without needing to use natural gas for power regeneration as is current practice, and without the large energy losses and huge footprints that experts assume for CAES. If there is low grade waste heat available, the effective efficiency will be even higher. Today, cheap grid-scale storage (with the exception of hydropower in specific geographies) simply does not exist – if Lightsail (or something like it) works, renewable power sources move from being a distributed, niche power source to potentially being a much larger base-load provider. Transmission capacity can increase substantially without additional transmission lines, the complexity of demand response eliminated and the grid made more stable.

9. **QuantumScape/ Ultra-advanced electrical energy storage:** Exotic physics instead of electrochemistry to provide inexpensive and very dense energy storage. Meanwhile revolutionary power electronics could help transform storage integration and the electric grid.

What if we applied unconventional technology to global problems like steel, sugars & agriculture?

10. **Advanced Agriculture:** Agriculture is ripe for innovation – we see significant potential to improve practices and technologies that have not changed much over time. We are looking at ways to improve on the large dependence of agriculture on nitrogen and the ancient Haber–Bosch process.

11. **Next Generation Materials (Steel, Aluminum):** Engineering metals like steel and aluminum to improve properties while dropping weight is theoretically possible. Steel can be stronger than steel. The question we are investigating is: can the potential be made practical and economic?

12. **HCL Cleantech (www.hclcleantech.com):** Biofuels, Chemicals, feed, and even food – all require sugars as part of their production process. HCL Cleantech uses concentrated HCL acid hydrolysis technology to convert a wide variety of cellulosic materials into high quality (food-grade) sugars, along with high value tall oils and lignin at a significantly reduced cost. Maybe we can move from annual row crops like corn to perennial, polyculture systems like sugar cane to produce our industrial, fuel and food sugar needs? Adding co-production of animal protein (which HCL is not doing) would be another great shot on goal!

Other interesting technologies:

Multiple other technologies are interesting as well, including Gen IV solar cells, small modular nuclear reactors, methane hydrates mining, high voltage DC transmission, electrochromic windows, new construction materials, thermoelectrics, bioplastics, waste utilization, solid oxide fuel cells, or other high efficiency distributed power generation and hundreds of other technologies that I consider important though not all are Black Swan "shots on goal." And there are technologies we desperately need like a Black Swan for water desalination.