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TerraPower

John Gilleland, CEO of TerraPower, returned to his office after a lengthy meeting with potential investors. It was October 2012, and TerraPower was in the process of raising a $200M Series D round to finance the ongoing development of its next-generation nuclear reactor.

TerraPower LLC was formally established in 2008 to develop a safe, cost-effective, environmentally friendly, and sustainable next generation nuclear reactor. The company was spun out of Intellectual Ventures, an "invention capital" business focused on buying, developing, and monetizing intellectual property. TerraPower had raised capital from Bill Gates (Founder and former CEO of Microsoft), Nathan Myhrvold (former CTO of Microsoft, Founder and CEO of Intellectual Ventures), Khosla Ventures, Charles River Ventures, and Reliance Industries.

The TerraPower reactor had the potential to provide massive amounts of clean, reliable electricity using a design that would be more efficient and safer than existing nuclear reactors. The design would use depleted uranium (the byproduct of existing uranium enrichment facilities) and/or spent uranium fuel rods (the radioactive byproduct of existing nuclear power plant facilities) as its input, turning the liability of existing byproduct stockpiles into enough electricity to provide every person on earth with U.S.-levels of per-capita energy consumption for centuries. Furthermore, improved passive (i.e., without human intervention) safety systems would shut the reactor down in the event of a power loss, dramatically reducing the odds of a reactor failure like the three that occurred at Fukushima, Japan, in March 2011. Finally, TerraPower's new design, with its much higher utilization of the fuel rods, meant that their reactor could burn for decades between refueling, reducing both the amount of uranium consumed and the nuclear materials proliferation risk as compared to existing nuclear power plant designs.

Though early in the fundraising process, Gilleland noted that this most recent conversation was similar to conversations with other interested cleantech growth equity investors. The conversations circled around a common theme: "This is the biggest idea that's ever been presented at our partners' meeting. We love what you're doing, but it's not right for us as an investment."

Reflecting on the disconnect inherent in the growth equity firm committee's decision not to make an investment despite the unanimous enthusiasm toward the venture, Gilleland knew that he had a disruptive investment opportunity. He would have to get creative in raising funding for the next few years of development.

Professors William A. Sahlman, Ramana Nanda, and Joseph B. Lassiter III and Research Associate James McQuade prepared this case. HBS cases are developed solely as the basis for class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective management.

Origins of TerraPower

The idea for TerraPower was born out of a brainstorming session led by Bill Gates, Nathan Myhrvold, and Lowell Wood.[a] The objective of the discussion was to identify a way to solve global poverty. The group rapidly came to the conclusion that access to affordable, clean, reliable energy would do the most good to the population of the world as a whole. TerraPower EVP Eben Frankenberg, who has been with the company since this very beginning, described the process:

> Energy is the single biggest lever in raising people out of poverty in the world. Access to efficient, affordable electricity is critical to powering everything from refrigerators to keep vaccines cold to light bulbs needed for reading and other educational activities. Looking to combat both poverty and global warming, Bill Gates said, "I would like to do something in energy. Can you put together a brief that lays out a few options?"
>
> We put together a brief based on that and held a large invention session. We looked at wind, solar, geothermal, tidal, and nuclear. The basic conclusion was that, in terms of the ability to supply abundant energy and make a substantial difference in carbon emissions, everything else is a rounding error when compared with nuclear. For example, we looked at the amount of ground needed to provide a gigawatt of power from solar or wind.[b] And only nuclear and geothermal were baseload power supplies; the rest were all intermittent.
>
> Granted, we had some bias, as Lowell Wood was an ex-nuclear guy, but we all quickly agreed that nuclear had the best potential to provide electricity and reduce carbon emissions on a truly global scale. We then asked ourselves, "what are better ways to do nuclear than what we are doing today?" Our biggest concerns were the waste produced by and the proliferation risks inherent in existing nuclear power plants. Bill spent a ton of time comparing waste production and proliferation risks to current industry benchmarks. We came across some academic papers on a traveling wave reactor design that could burn one fuel rod for decades. The more complete burn-up of the fuel rod meant less waste would be produced as fewer rods were needed, and the decades-long fuel cycle meant far fewer opportunities to access byproducts inside the reactor core that could be repurposed for nuclear weapons. Bill felt that this was a significant advantage over current technology, and with a handshake he said he'd fund it.[1]

Gates confirmed this rationale, noting, "If you want to improve the situation of the poorest two billion on the planet, having the price of energy go down substantially would be the best thing you could do for them. That, along with the carbon constraint, is hugely important, partly because global warming makes tropical agriculture virtually impossible."[2] Researchers have indeed found that per-capita consumption of electricity is highly correlated with standard of living (**Exhibit 1A**), and the National Academies named the "electrification of energy" the single greatest engineering achievement of the 20th century (**Exhibit 1B**).

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[a] Lowell Wood, Ph.D. is an internationally recognized scientist and technologist with research and development experience in controlled thermonuclear fusion, space-based ballistic missile defense systems, laser science and applications, very high-performance computing, and digital computer-based physical modeling.

[b]A one-gigawatt nuclear power plant would require approximately one square kilometer of real estate. A wind farm or solar panel installation with the same generating capacity would cover 100 km2 or 430 km2 of real estate, respectively.

Gilleland added, "A conclusion I came to independently was that there were areas for tremendous improvement [in nuclear power]. Modern plants are very safe, but things can be improved. It would be wonderful to have a system that didn’t in the long run require enrichment plants, reprocessing plants. When we talked to proliferation experts at various institutes, [they said] it would be an incredible reduction in the prospect of weapons."[3]

TerraPower started out as a small project, with six guys mostly doing computer modeling. The first step was to demonstrate the validity of these theoretical reactor designs using simulations. The company brought together a couple of nuclear experts from Lawrence Livermore national labs as well as some parallel processing experts from Microsoft to build not only a 3-D model to simulate the reactor design, but also a computer cluster powerful enough to run the simulations. The idea required building out one of the largest supercomputers in the world to construct a computer model that simulated the new reactor design at an atomic scale.

Tyler Ellis,[c] one of TerraPower's first hires, described why he was excited to join the company: "When I met with John and he described the vision for TerraPower, I asked him, 'Do you realize how long this will take and how much this will cost?' John responded, 'We're targeting a first reactor in 2020, and Bill Gates is our lead investor.' I thought those were good answers."[4]

TerraPower's vision was to develop innovative nuclear power technologies that would enable society to obtain sustainable, cost-competitive, proliferation-resistant, environmentally friendly electricity.[5] The go-to-market strategy was to become a nuclear technology design company. TerraPower EVP Eben Frankenberg explained, "We'd do design and develop our technology to demonstrate its potential, but we were never going to own or operate plants. There are roughly 3,000 man-years worth of engineering work on the first demo plant, but we planned to do only about 300 man-years of the highest-value work. Our business model was that we would eventually make money by licensing our reactor design. We'd own the intellectual property and the trade secrets. We'd do ongoing R&D to tweak and improve, but we didn't want the liability that comes with being owners/operators."[6]

The company was set up as an LLC, with Intellectual Ventures as the manager of the LLC. One benefit of that structure is that the tax offsets are a research tax credit for investors. "The LLC structure is great for the large expected operating losses, but it introduced all sorts of complications in terms of employee compensation," noted Frankenberg.[7] As a spin-out of Intellectual Ventures, TerraPower shared the parent company's emphasis on the value of intellectual property. Venture capitalist Izhar Armony (Charles River Ventures) acknowledged that this could have a polarizing effect in the investment community, as "many VCs have a somewhat negative perception of Intellectual Property. Their first experience with IP is often when they receive a Cease and Desist Infringement notice. But without IP, the small company will always be disadvantaged—we'd lose the protection of the invention and innovation effort by small firms and universities."[8]

Further complicating the intellectual property strategy, noted Greg Landis, TerraPower's IP Counsel, was "the fact that the timescale for developing nuclear technology is the same timescale as the duration of patents. As a result, we need to perpetually innovate to maintain our IP protection."[9] Armony added, "The clear analog that came to mind was the biotech industry. There, it takes 20 years to bring a new drug to market—which highlights why twenty year patent durations in those

[c] Ellis graduated from MIT in 2008 with a Bachelor's degree, a Master's degree, and a Ph.D. in nuclear engineering. He was also in the Harvard Business School Class of 2014.

fields might not be enough. We thought hard about what milestones would significantly de-risk the business and thus increase the valuation of the venture for us to create a return for our investors."[10]

In order to most effectively leverage the industry knowledge accumulated over the past half-century, TerraPower partnered with a large number of universities, national labs, and industry experts across all aspects of their research and development (**Exhibit 2**). Doug Adkisson, SVP of Operations, helped structure the various partnerships to ensure that TerraPower owned the intellectual property of anything developed. "Universities can be very challenging in the IP space," Adkisson explained, "in that they would like any new patents to be co-filed with shared licensing revenues. We've made clear that we are contracting them for a service, not for solutions, and are only paying for unanalyzed raw data."[11]

Given the many contracted services and strategic partnerships in play, Senior Engineering Manager Pat Schweiger emphasized that "TerraPower's strengths are (1) core physics and analysis, (2) fuel fabrication, (3) intellectual property and licensing, and (4) procurement capabilities." He noted that, "of the 600 people doing the design, we'll provide about 100 of them."[12]

TerraPower's Traveling Wave Reactor (TWR) Technology

The theoretical design for the TerraPower TWR called for a chain reaction to change the non-reactive uranium into more reactive plutonium as the reaction slowly propagated through the fuel rod, much like how the burning of a candle slowly melts wax up into the wick, which burns for quite a long time as the candle eventually burns all the way down. This "breed and burn" approach significantly streamlined the number of process steps as compared to those involved in generating electricity via traditional light water reactors (**Exhibit 3**). Bill Gates explained how this design differed from the design of existing reactors:

> The part of uranium that's fissile—when you hit it with a neutron, it splits in two—is about 0.7%. The reactors we have today are burning that 0.7%. The concept of the TerraPower reactor is that in the same reactor, you both burn and breed. Instead of making plutonium and then extracting it, we take uranium—the 99.3% that you normally don't do anything with—we convert that and we burn it. The 99.3% is cheap as heck, and there's a pile of it sitting in Paducah, Kentucky,[d] that's enough to power the United States for hundreds and hundreds of years.[13]

TerraPower later found that the theoretical projections of a 100% burn up for a traveling wave reactor (TWR),[e] weren't possible, but believed that they could achieve a ~30% burn rate of uranium in a fuel rod, as compared to 0.7% burn up in existing lightwater reactor designs. The TWR's more efficient use of uranium drove significant savings as compared to that of typical light water nuclear reactors (**Exhibit 4**).

Gilleland emphasized, "Higher burnup, burning what right now is waste—namely depleted uranium—yields this incredible production. We figured out that we could supply every person on

[d] The Paducah Gaseous Diffusion Plant in Paducah, Kentucky, is the only U.S.-owned uranium enrichment facility in the United States.

[e] "Standing wave reactors," in which fuel is moved with respect to a standing fission reaction zone, are recognized as a subset of TWRs.

earth with the U.S. level of per capita energy consumption for 1000 years if we can make the traveling-wave reactor go."[14]

The decreased risk of proliferation was largely derived from the long projected burn cycles for these power plants (operating for up to 60 years without needing to be refueled) and the elimination of the need for a nuclear fuel reprocessing plant. Fissile materials that presented proliferation risks were still present in the reactor, but they were not out where people could easily get to them.[15] Fuel reprocessing plants weren't necessary as the TWR would start with a small plutonium "match" at one end, but then spent fuel at the end of a first generation TWR reactor could be used to "prime" the reactors of up to six new second-gen TWRs.

The questions, skeptics said, were whether TerraPower's computer-simulated design could actually be made to work, and if so, how long it would take to do so. There was no physical precedent for TerraPower's design, and the project faced some major technical, business, and regulatory challenges.[16]

Financing TerraPower

Following seed financing in the "tens of millions of dollars" provided solely by Gates,[17] Gates was joined in TerraPower's Series A financing by Nathan Myhrvold and a few other individuals from Intellectual Ventures, as well as Izhar Armony from Charles River Ventures (CRV). Myhrvold reflected, "Why would any rational group of people create a nuclear power company?" Answering his own question, Myhrvold explained, "Part of the reason is that Bill and I have been primed to think long-term. We have the experience and resources to look for game-changing ideas—and the confidence to act when we think we've found one. Other technologists who fund ambitious projects have similar motivations. Elon Musk and Jeff Bezos are literally reaching for the stars because they believe NASA and its traditional suppliers can't innovate at the same rate they can."[18]

Izhar Armony noted that, "at the beginning, CRV was concerned about the investment, given how the long timeframes involved with nuclear technology development didn't line up well with the fund horizon expectations of our investors. But as individuals, we knew we had to do it. If it works, this would change the world." Armony added, "There are ten reasons that any startup could fail, but our job at CRV is to identify a path to success—no matter how hard that path may be—to help the company achieve a $1-billion-plus exit, and then consider ways and timeframes for our investors to realize value."[19]

In raising a Series B, Frankenberg described, "We knew we needed to find people who had an affinity for, and a successful track record investing with, Bill. They needed to be able to afford potentially losing $10 million. Most importantly, they had to be forward-looking visionaries and have a true passion for clean energy."[20]

TerraPower found that like-minded visionary in Vinod Khosla of Khosla Ventures. Frankenberg recalled the first meeting, "When we met with Vinod, you could tell he was interested right away. He was totally intrigued by the technology. When one of his colleagues asked, 'How are you going to make money?'… Vinod said, 'If this works, there are so many different ways to make so much money with it, why bother even talking about it?"[21] Khosla invested alongside re-ups from Gates and CRV to complete a $35 million Series B round in June 2010.[22]

The company's Series C investment round in late 2011 was a similar exercise. With many of the tech challenges solved, the company's focus had shifted largely towards commercialization. Given that India was projected to be the second largest market for new nuclear power plants (**Exhibit 5**), the TerraPower team reached out to Mukesh Ambani, Chairman of Reliance Industries[f] and, with a personal fortune approaching $20 billion as of October 2012, the richest person in India.[23] Reliance Industries joined the Series C financing in December 2011.[24]

Prospects of Nuclear Power

As the global population was projected to grow from 6.8 billion in 2010 to 9.1 billion in 2100,[25] an estimated 729 new large (1 gigawatt) power plants would be needed to provide that additional population with adequate per-capital consumption of electricity.[g] Should every country target a per capita consumption of electricity equal to that of the United States in 2010, 3,700 new large power plants would need to be added globally in the next nine decades. Izhar Armony noted that, "in China's recent 100-year-plan, the country projected that they will need 2000 gigawatts of power to supply China's population in 2100 with a per-capital-energy consumption rate of the U.S. in 2000. To meet this goal, China planned to commission 15 new 1GW power plants a year, with the aim to increase that rate to 50 new one-gigawatt plants per year in the near future."[26]

Given the increasing global appetite for electricity, it was important to minimize the impact that additional power plants would have on the environment. In 2010, 96% of U.S. GHG emissions were from fossil fuel combustion (**Exhibit 6A**), and electricity generation accounted for 42% of that total (**Exhibit 6B**). Although coal provided only 42% of U.S. electricity generated, it accounted for 79% of U.S. CO_2 emissions from electricity generation (**Exhibit 7A**). Though coal's percent share of global electricity generation was in decline, its absolute magnitude was projected to increase 10% by 2015 and 67% by 2035 (**Exhibit 7B**).

To reconcile the global society's increasing demands for electricity with the global need to reduce greenhouse gas emissions, less-GHG-intensive sources of electricity would need to be pursued, and the levelized cost of that new electricity generation would need to be economically competitive (**Exhibit 8**). Nuclear power was one such solution.

Proponents of nuclear power believe that greenhouse-gas-emission-free nuclear power plants would have to play a role in an environmentally sustainable society. In 2011 they noted that "if nuclear power were abolished today, to be replaced by other generating technologies in proportion to their current usage, the world would emit an extra 2 billion tons of CO2 every year."[27] Opponents of nuclear power cite safety and nuclear weapon proliferation risks as their main concerns, arguing that "atoms cannot be made to work for peace without making them available for war."[28]

Nuclear power also holds a significant advantage in resources consumed. Over 16,000 pounds of coal would be required to generate as much electricity as one pound of enriched uranium oxide—an amount of electricity that would cover the average American household's needs for over a year.[29]

Highlighting the nuclear industry's safety concerns following the Three Mile Island and Chernobyl disasters (1979 and 1986, respectively) was the Shoreham Nuclear Power Plant fiasco. Built 60 miles away from downtown Manhattan on Long Island, NY, between 1973 and 1984 for a total cost of $6 billion, the plant was held idle over concerns about how to safely evacuate residents in

[f] Reliance Industries is a petrochemicals, refining, and oil and gas conglomerate headquartered in Mumbai, India.

[g] Assumes 90% effective uptime per nuclear power plant historical average, and defines "adequate" as 2,500 kWh consumption per capita, per Exhibit 1.

the event of a disaster. The fully constructed plant was decommissioned in 1989 without ever going into commercial operation.[30]

With respect to the regulatory environment for nuclear power, one common joke among nuclear experts was that "a reactor vessel could not be shipped until the total weight of all required paperwork had equaled the weight of the reactor itself."[31]

In 2010, the prospects for nuclear power had been promising. In that year's State of the Union Address, President Obama called for building a new generation of safe, clean nuclear power plants in the United States.[32]

Public sentiment changed shortly after March 11th, 2011, when a 9.0-magnitude earthquake off the coast of Japan triggered a tsunami. A forty-foot-tall wall of water struck the Fukushima plant, knocking the power plant and its safety systems offline. With the critical cooling systems out of commission, heat and pressure built up, resulting in hydrogen explosions in two of the plant's six light water reactor units. The release of radioactivity from the plant was large and some workers received significant radiation doses but health risks for them and the general population were expected to be minimal. Industry experts noted that no loss of life had occurred or was expected as a result of the accident.[33] While radiation from the disaster spread for miles, the political and public-perception fallout from the disaster spread across the globe. In the weeks following the disaster, countries including Germany, Switzerland, and Italy stated their intentions to abandon the use of nuclear power in the near future.[34]

Shortly after the disaster at Fukashima, Myhrvold argued,

> The idea that this is a referendum on the use of nuclear energy is wrong. The issue is, a specific set of older plants designed with slide rules many, many years ago—were they up to the task? And I think the answer is that they were almost up to the task. It's actually remarkable that the plants survived as well as they did with respect to the earthquake. With all of the sensational coverage of what's going on in Japan, it's tempting for people to say, "Nuclear seems dangerous; let's turn away from it," when there's another whole set of scientists who have informed us that in fact the climate implications of continuing to not have nuclear are perhaps more dangerous. We can't afford to allow panic from a particular situation, no matter how tragic, to close our eyes to what could be superior technical solutions... Society has to draw conclusions based on engineering and science about what actually happened in Japan, what could have been done differently, how serious an issue this would be in other places, and make a rational decision on nuclear power. I am confident that a rational decision would say that nuclear power is a super-important part of our future.[35]

In 2011, global electricity production from nuclear power plants exceeded 2.5 trillion kilowatt-hours, representing over 13% of total electricity generated. As of October 2012, there were 256 new nuclear power plants projected to come on line before 2030 (**Exhibit 5**).

Innovation in Nuclear Power

Breakthrough innovations in the nuclear power industry have been few and far between, as the massive capital costs and long research, development, and construction timeframes represent the antithesis of the traditional rapid-cycle entrepreneurial mantra of "test and invest."

The first generation of nuclear reactors were designed in the 1950s and 1960s by engineers using comparatively primitive technology. Over a half-century later, significant advances in the understanding of particle physics and the introduction of computers allowed engineers to construct 3-D simulations of next generation reactor designs. By the end of 2011, 32% of the 435 nuclear power plants operating in the world were more than thirty years old.[36]

Innovation in the nuclear space for the past forty years has been incremental at best, focusing on marginal improvements to safety systems without making any significant modifications to reactor design. Some experts noted that nuclear innovation was still possible, but was severely constrained by public attitudes in different countries and the deliberate, cautious pace of national regulatory bodies such as the U.S.'s Nuclear Regulatory Commission and its equivalents around the world.

The two-plus decades following the accidents at Three Mile Island (1979) and Chernobyl (1986) left a generation-wide gap in the industry talent pool. The vast majority of nuclear experts who were available to comment on the happenings at Fukushima were over 60 years-old and until recently nuclear engineering programs at universities had attracted few students.

As world-wide concerns about climate change and energy security became more pressing after 2000, nuclear power re-emerged from its slumber. Talent began to re-enter the field and old ideas were re-examined by the field's committed practitioners. By 2012, there were a surprising number of privately funded new ventures with differing, quite novel designs looking to revitalize innovation in the nuclear industry. The technologies pursued by these new ventures ranged from small modular reactors (SMRs) to reactors that used alternative fuels (e.g., thorium instead of uranium) to nuclear fusion (see **Exhibit 9** for a partial list of nuclear industry new ventures). In support of this increase in new potential solutions, the United States Department of Energy began to study more expeditious permitting of new designs, partner with other countries to develop new designs, and provide support for export sales of nuclear plants (**Exhibit 10**). It was unclear how other countries would react to export sales, as national regulatory groups had to approve any installation and often favored plant design and construction by national suppliers.

The TerraPower Investment Opportunity

The benefits of nuclear power were clear; a greenhouse-gas-emissions-free energy source that was more abundant than hydro- and geothermal power, and more reliable than inherently intermittent supplies of solar and wind energy. But the challenges of massive capital costs and long construction timeframes associated with building nuclear power plants were exacerbated by significant technical, political, and regulatory risks (see **Exhibit 11** for a summary of typical nuclear power plant risks).

TerraPower projected that it would cost roughly $1 billion over the next four years to complete the detailed prototype plant design, followed by approximately $3 billion over six years to develop and qualify the critical fuel rods and construct the prototype plant.[h] Follow-on commercial plants could cost in excess of $4 billion each. To put these amounts in perspective, $4 billion represented 0.2% of an estimated $1.9 trillion spent globally on electricity in 2010.[i]

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[h] The minimum scale of the prototype plant was approximately 500 megawatts due to the minimum viable size of TerraPower's reactor core geometry.

[i] Based on 2010 estimated global electricity production of 19.0 trillion kWh. Assumes a global average price for electricity of 10 U.S. cents per kilowatt-hour. Actual electricity prices vary widely from country to country, depending largely on the type of power plants and fuels used.

Gates emphasized that, for TerraPower to make money, the economics of a commercial plant must be there; "The solution must be competitive economically. Even if it is a much lower proliferation risk, or there's fuel forever, if you can't afford it, it probably won't happen. The safest position is for it to be less expensive than any other nuclear process, and less than or equal to natural coal."[37]

(See **Exhibit 12** for a simplified financial model for a typical U.S. 1GW Gen III+ nuclear power plant.)

In addition to the direct financial returns of a commercial plant, TerraPower's technology had the potential to either significantly reduce or altogether eliminate the need for uranium mining, uranium enrichment facilities, spent fuel reprocessing plants,[j] and spent fuel rod storage facilities, resulting in significant cost savings and enhanced safety and environmental benefits.[38]

What Should Gilleland Do?

Gilleland's thoughts drifted through the many conversations with potential investors. All agreed that the vision of TerraPower was worth pursuing. The value of a reliable, proliferation-resistant, emissions-free source of electricity was unquestioned. However, the long timescale for the potentially great financial returns tended to exceed the time-horizon of most investors. Viewing the TerraPower venture as a series of staged experiments, the next experiment was to take the simulated reactor design and build a prototype plant.

Outside of raising money from typical growth equity and infrastructure funds, Gilleland could partner with a government and/or form a joint venture with an existing nuclear power player. Reliance Industries as an investor in TerraPower could provide an entry point into the fast growing Indian market. At the same time, Gilleland and Gates had talked with China National Nuclear Corp.[k] about a possible cooperation with TerraPower.[l, 39] One key consideration for valuation to any organization was the ability to export the technology to other markets. Because of the reduced-proliferation nature of the TerraPower design, it was arguably the best nuclear power technology to export.

In addition to the financial returns that an investor in TerraPower would want to see, Gilleland wondered how he could market the intangible value of reduced proliferation risk, eliminated GHG emissions, and energy independence. What would investors need to believe about wholesale industrial price of electricity that TerraPower would need to meet in the U.S., China, or India[m] to be cost competitive? How should investors value cost predictability in electricity generation? How would investors think about the costs avoided by halting the importation of energy from politically unstable regions of the world?

Whom should Gilleland call next?

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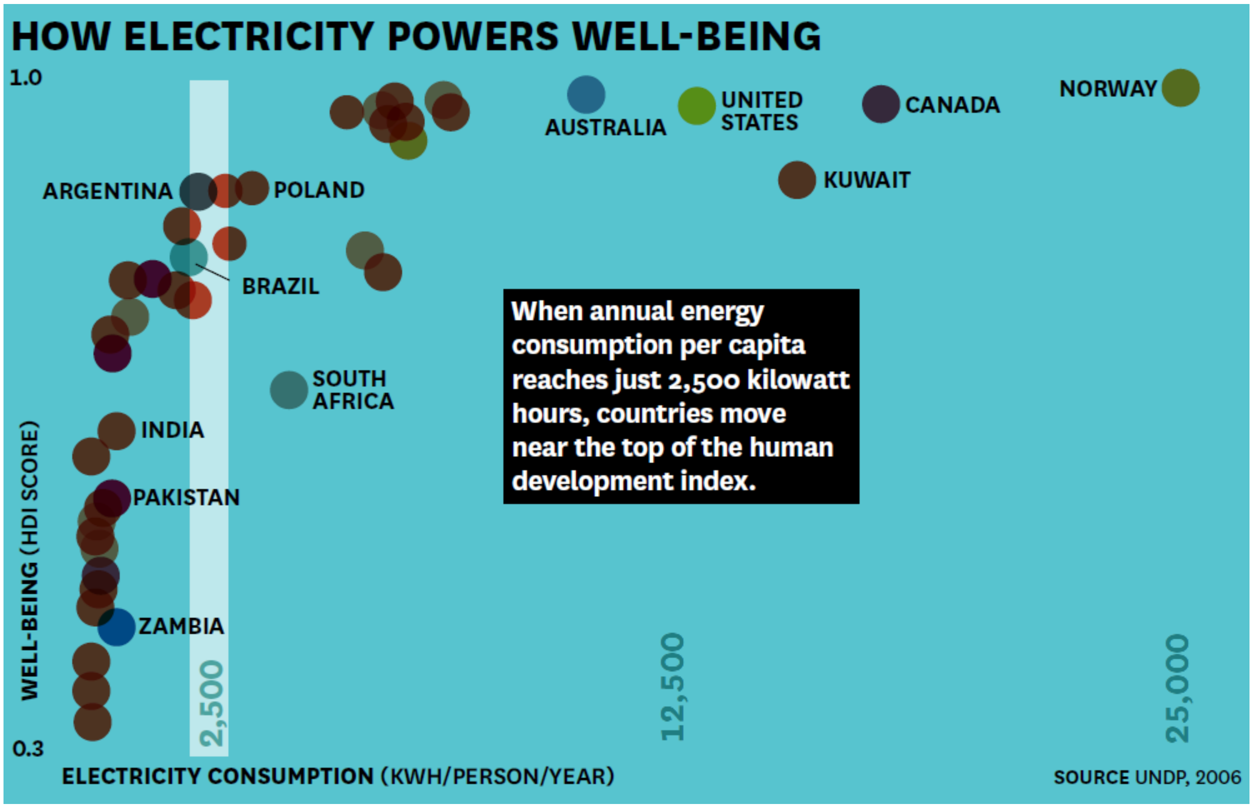
[j] The estimated cost for a spent nuclear fuel reprocessing plant was $40 billion.

[k] China National Nuclear Corp. had declared it would invest $120 billion in nuclear energy through 2020.

[l] As a 2012 benchmark, China had adopted the Westinghouse AP1000 design (owned by Toshiba) for inland power plants. The AP1000 was considered a Gen III+ class design. The construction timeline was approximately 50 months from first concrete to fuel loading, then six months to grid connection. The cost of the first few units was expected to be less than $2000/kW. Costs were expected to decrease to roughly $1600/kW for further units, with a significantly reduced construction timeframe.

[m] Though set to meet industrial policy objectives, the wholesale industrial prices of electricity in China and India were in the range of $40/MWh and $60/MWh.

Exhibit 1A Relationship between Per Capita Electricity Consumption and Well-Being (HDI Score)



Source: Majumdar, Arun, "Electrify the Bottom of the Pyramid: A little energy will spark a lot of growth," *Harvard Business Review*, HBR's List of Audacious Ideas for Solving the World's Problems, January-February 2012.

Exhibit 1B The Greatest Engineering Achievement of the 20th Century

The National Academies named the "electrification of energy" the single greatest engineering achievement of the 20th century:

> The wide distribution of electrical power in the 20th century brought light to the world and power to almost every pursuit and enterprise in modern society. Consider its impact on everyday life—lighting, heating and air conditioning, refrigeration, computers, transportation, communications, medical technologies, food production—the list is endless. Several key engineering innovations made this possible, including the turbine generator, the use of alternating current (AC), techniques to obtain electrical power from various resources (fossil fuels, water, sunlight, nuclear), and the construction and refinement of massive transmission systems. Electrification is responsible for innumerable developments that have made life safer, healthier, and more convenient; so much so that it is hard to imagine our lives without it. It runs the smallest electric appliances in homes and offices, the mammoth computers that control power grids and telecommunications systems, and the machinery that produces consumer goods. Its impact is vast, and it has touched the majority of people on the planet.

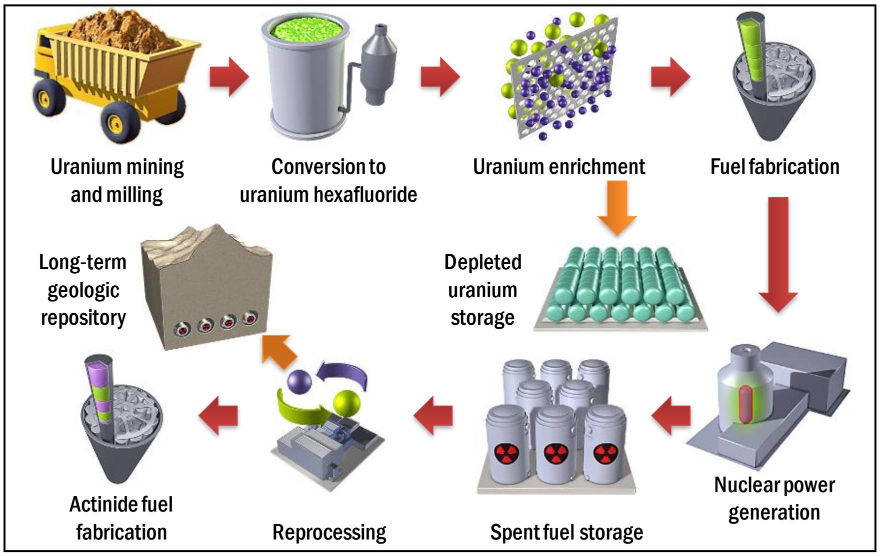
Source: http://www.nationalacademies.org/greatachievements/List.PDF, accessed April 2012.

Exhibit 2 The TerraPower Team: An Innovative Matrix Approach

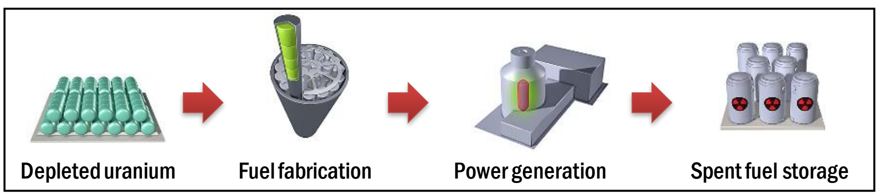
Source: Company documents.

Exhibit 3 How TerraPower's TWR System Compares to the Current Nuclear Reactor System

Current Nuclear Energy System



TerraPower's Traveling Wave Reactor (TWR) System

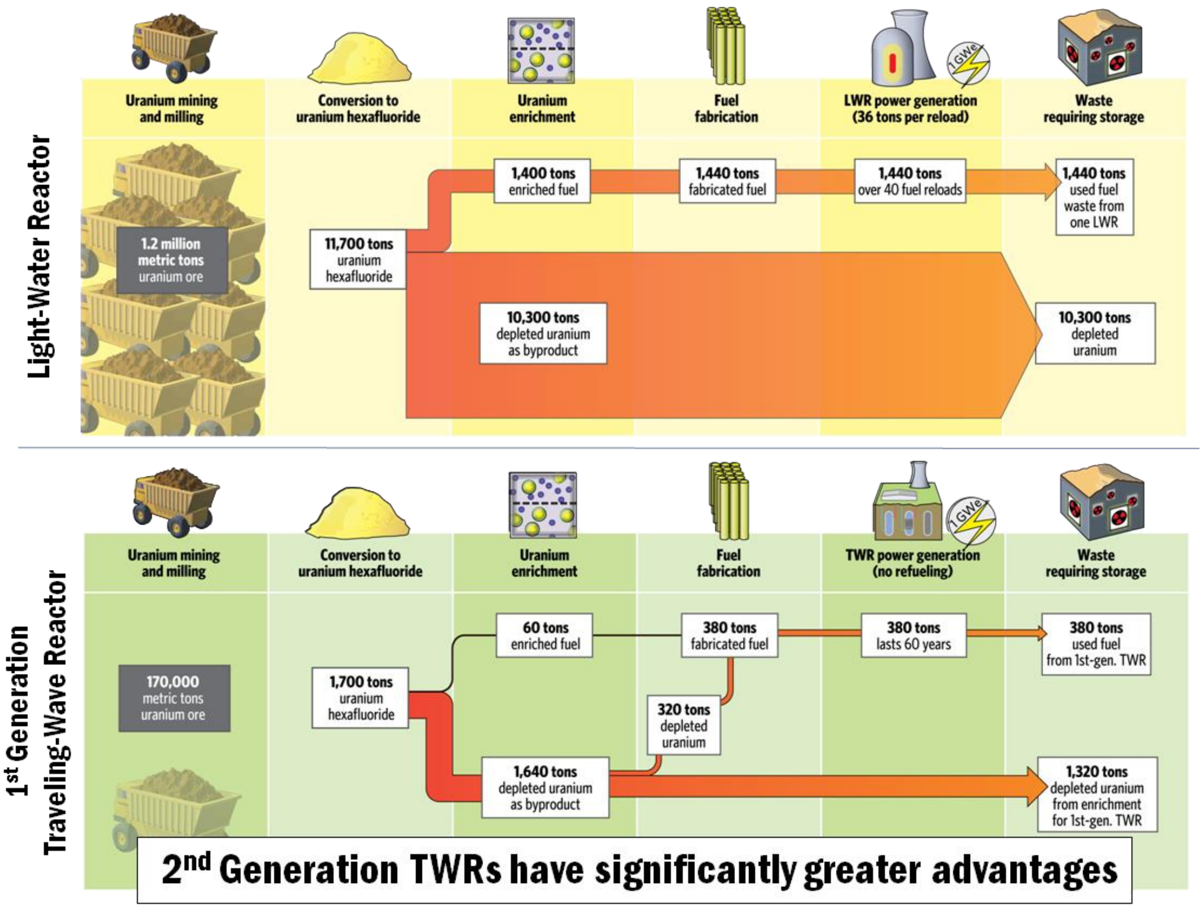


Benefits of the TWR

- Provide up to a 40-fold increase in fuel utilization efficiency when compared to conventional light water reactors (LWRs);
- Have significantly enhanced inherent safety features such as passive cooling in an event of an accident that requires no on-site emergency or offsite power like in current LWRs;
- Be the lowest complete fuel cycle cost alternative due to vastly improved fuel utilization, reduced uranium mining and fuel purchases, reduced need for enrichment facilities, elimination of costly reprocessing plants, and lower costs for waste transportation and storage;
- Be vastly more environmentally friendly by using waste (depleted uranium) as its main fuel, producing 8-40 times less waste than current reactors, and greatly reducing transportation and storage requirements;
- Be significantly more resistant to weapons proliferation since the nuclear vessel can remain closed and operate for 40-60 years without changing out fuel assemblies; the TWR minimizes and ultimately eliminates the need for uranium enrichment; and no chemical reprocessing is required; and
- Greatly enhance energy security since less uranium is required, making plant owners and countries far less vulnerable to uranium supply shortages or disruption, and commodity price increases.

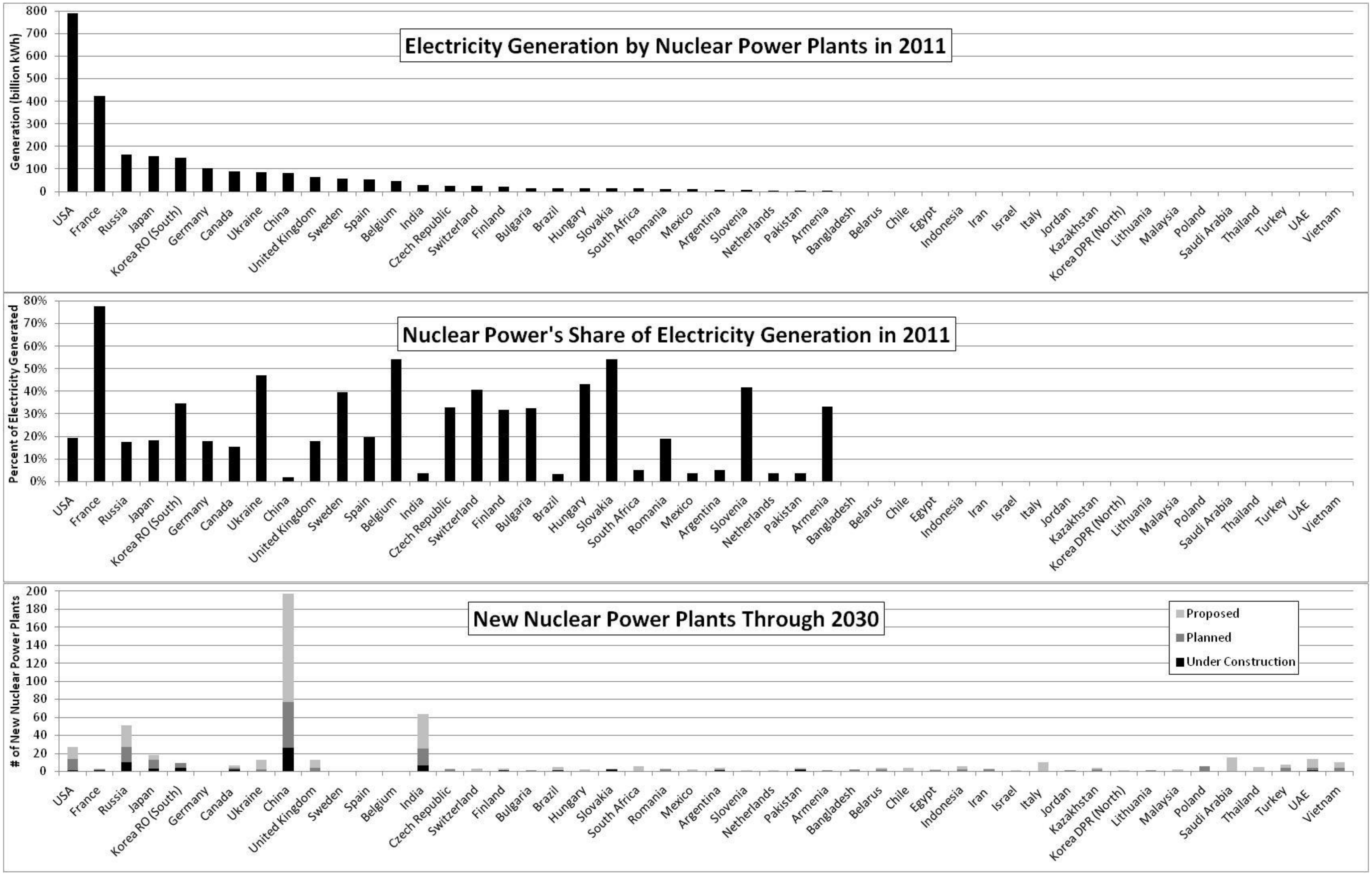
Source: Company documents.

Exhibit 4 Uranium Consumption in a Typical LWR vs. a TerraPower TWR



Source: Company documents.

Exhibit 5 Electricity Generation by Nuclear Power Plants in 2011, and Proposed New Nuclear Reactors Through 2030, by Country



Note: New plants coming on line are largely balanced by old plants being retired. Over 1996-2009, 43 reactors were retired as 49 started operation. There are no firm projections for retirements over the period covered by this Table, but WNA estimates that at least 60 of those now operating will close by 2030, most being small plants. The 2011 WNA Market Report reference case has 156 reactors closing by 2030, and 298 new ones coming on line. For Proposed New Plants: "Under Construction" = first concrete for reactor poured, or major refurbishment under way; "Planned" = Approvals, funding or major commitment in place, mostly expected in operation within 8-10 years; "Proposed" = Specific program or site proposals, expected operation mostly within 15 years.

Source: Compiled by case writer. Data from http://www.world-nuclear.org/info/reactors.html, accessed October 2012.

Exhibit 6A U.S. Greenhouse Gas Emissions by Source, 2010

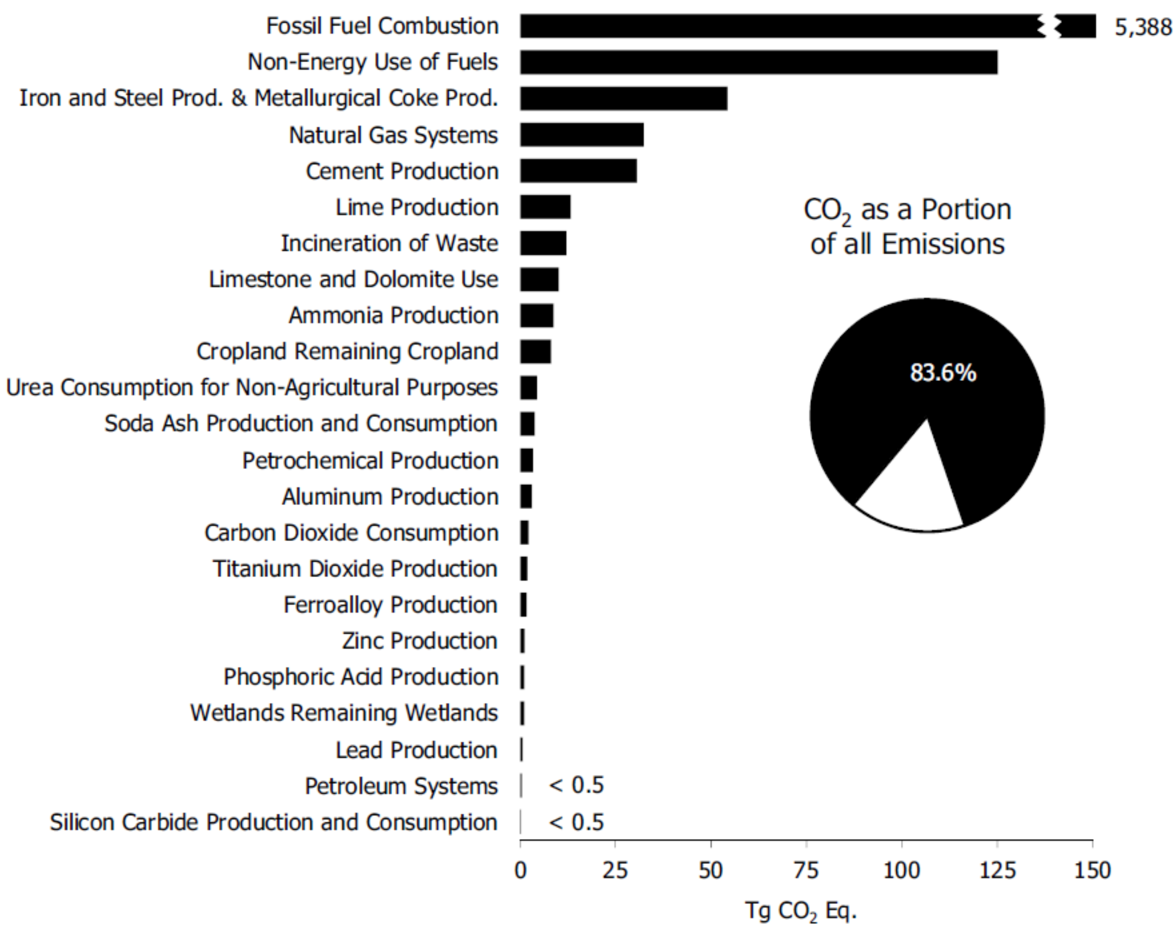
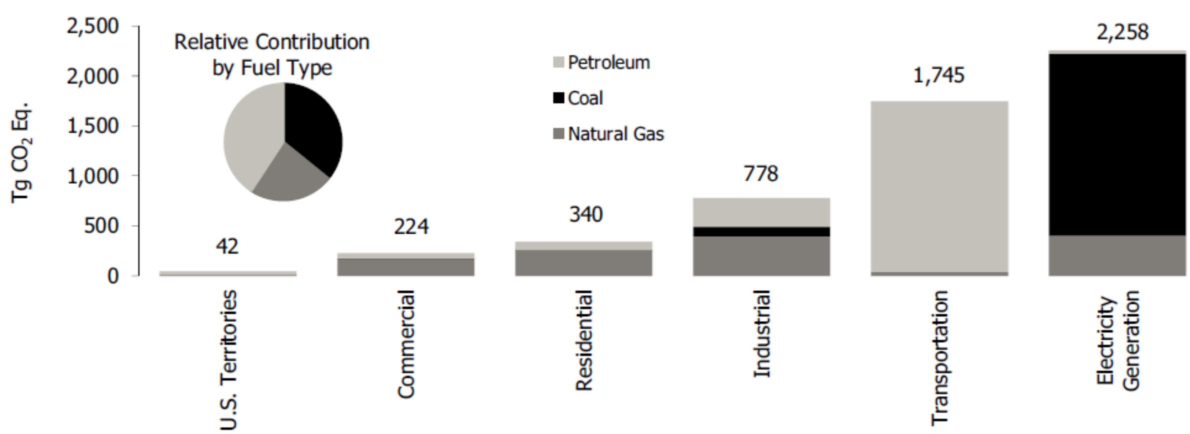


Exhibit 6B 2010 Greenhouse Gas Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Source: "Inventory of U.S. Greenhouse Gas Emissions and Sinks," U.S. Environmental Protection Agency, April 2012. (http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html)

Exhibit 7A U.S. Electricity Generation and CO2 Emissions by Fuel Source, 2010

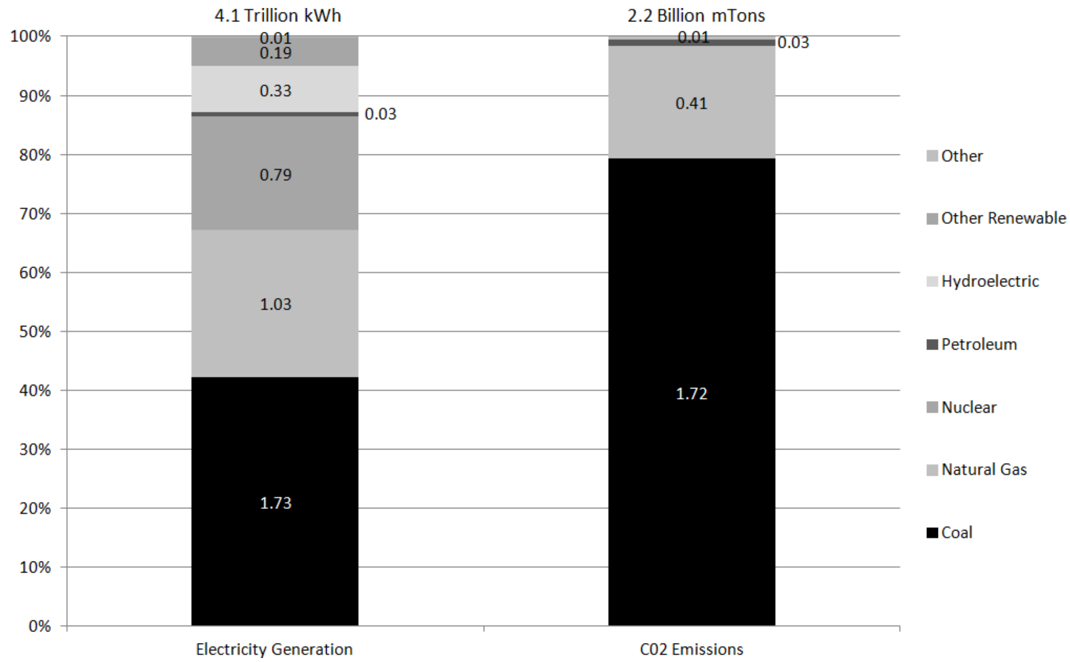
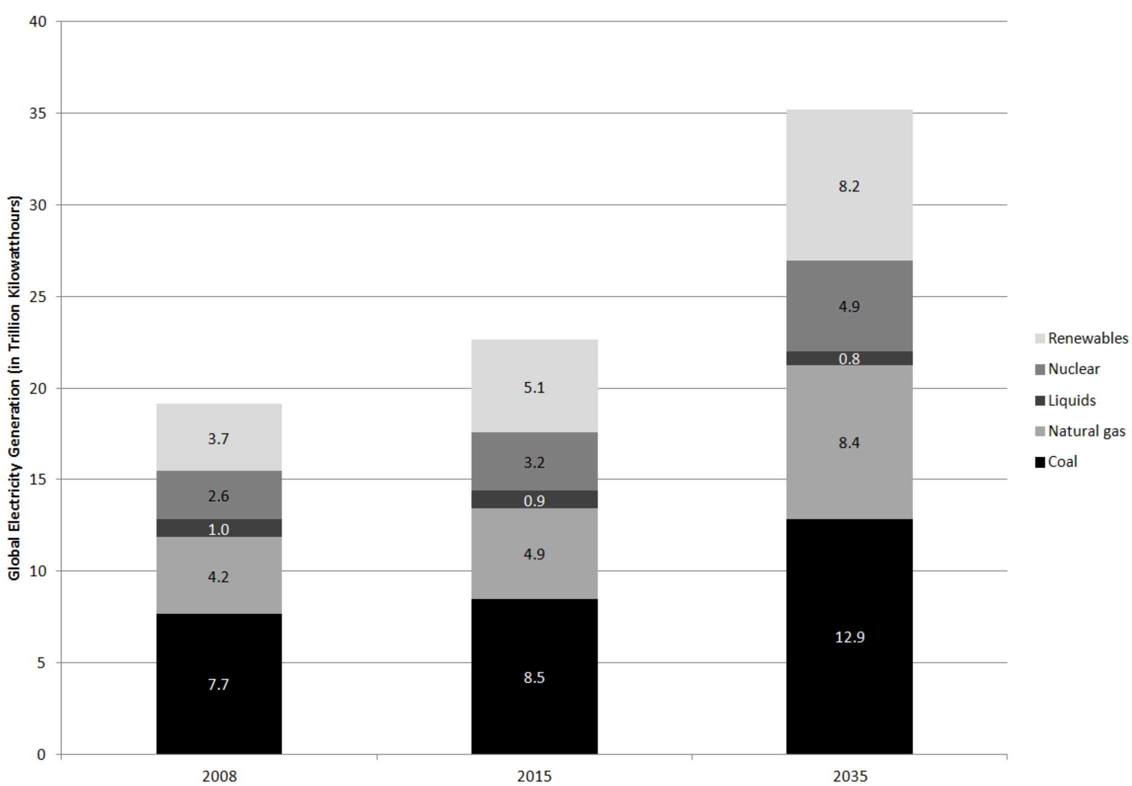


Exhibit 7B Global Electricity Generation by Fuel Type, 2008-2035E



Source: Compiled by case writer. Data from U.S. Energy Information Administration.

Exhibit 8 Estimated U.S. Avg. Levelized Costs (2010 USD/MWh) for Plants Entering Service in 2017

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System Levelized Cost
Dispatchable Technologies						
Conventional Coal	85	64.9	4.0	27.5	1.2	97.7
Advanced Coal	85	74.1	6.6	29.1	1.2	110.9
Advanced Coal with CCS	85	91.8	9.3	36.4	1.2	138.8
Natural Gas-fired						
Conventional Combined Cycle	87	17.2	1.9	45.8	1.2	66.1
Advanced Combined Cycle	87	17.5	1.9	42.4	1.2	63.1
Advanced CC with CCS	87	34.3	4.0	50.6	1.2	90.1
Conventional Combustion Turbine	30	45.3	2.7	76.4	3.6	127.9
Advanced Combustion Turbine	30	31.0	2.6	64.7	3.6	101.8
Advanced Nuclear	90	87.5	11.3	11.6	1.1	111.4
Geothermal	91	75.1	11.9	9.6	1.5	98.2
Biomass	83	56.0	13.8	44.3	1.3	115.4
Non-Dispatchable Technologies						
Wind	33	82.5	9.8	0.0	3.8	96.0
Solar PV[1]	25	140.7	7.7	0.0	4.3	152.7
Solar Thermal	20	195.6	40.1	0.0	6.3	242.0
Hydro[2]	53	76.9	4.0	6.0	2.1	88.9

[1]Costs are expressed in terms of net AC power available to the grid for the installed capacity.
[2]As modeled, hydro is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.

Note: Fuel costs accounted for substantially all of the variable O&M costs. Assumes natural gas price of $4.50 per mcf and coal price of $55 per short ton. These results do not include targeted tax credits such as the production or investment tax credit available for some technologies, which could significantly affect the levelized cost estimate.

Note: Potential cost of CO2 emissions are not included. Emissions (kg of CO_2e per MWh) for conventional coal and conventional combined cycle natural gas are 715 and 370, respectively. An assumed cost of $20 per mTon CO_2e would add $14.30 and $7.40 to the per MWh cost of conventional coal and conventional natural gas, respectively.

Source: U.S. Energy Information Admin, http://www.eia.gov/forecasts/aeo/electricity_generation.cfm, accessed October 2012.

Exhibit 9 List of Nuclear Power Generation New Ventures, as of 2012

Company Name	Year Founded	Overview	Investors	Website
Flibe Energy	2011	Flibe Energy seeks to develop modular nuclear reactors based on liquid-fluoride thorium reactor (LFTR) technology. LFTR, first conceived in the 1950s and 1960s at Oak Ridge National Labs (ORNL), is a form of advanced nuclear reactor design similar to other Generation IV reactor technologies. LFTR has several key advantages over existing light water reactors including: inherent passive safety; low operating pressure; very high temperatures; improved thermal efficiency; continuous fuel reprocessing; proliferation resistance; and the use of abundant 232Th as fuel.	[undisclosed]	http://flibe-energy.com/
Gen4 Energy	2007	Gen4 manufactures and commercializes nuclear power reactors. The company caters to mining and oil and gas production, island communities, and government facilities. The company was formerly known as Hyperion Power Generation and changed its name to Gen4 Energy in March, 2012.	Altira Group	http://www.hyperionpowergeneration.com
General Fusion	2002	General Fusion is developing technology for a nuclear Deuterium-Tritium fusion reactor that it claims can be cost-effective and see energy-producing results within the decade. It is focusing on a technique called magnetized target fusion, a hybrid between the two other common techniques in development: magnetic fusion and inertial confinement fusion.	Bezos Expeditions, Braemar Energy Ventures, Business Development Bank of Canada (BDC) Venture Capital, Cenovus Energy, Chrysalix Energy Venture Capital, Chrysalix SET, Entrepreneurs Fund Management, GrowthWorks Capital, Sustainable Development Technology Canada	http://www.generalfusion.com
Kurion	2009	Kurion develops and provides proprietary technologies and solutions that isolate waste from the environment to help enable clean and safe nuclear power. The company claims that the solutions are modular, are quickly deployable, are able to work with existing systems, and substantially reduce customers' total lifecycle costs.	Firelake Capital Management, Lux Capital	http://www.kurion.com/
Martingale, Inc.	1982	Focused on low-cost electricity and the use of no new technology, Martingale is designing a "radically" simple liquid thorium fuel molten salt reactor. Employing advanced shipbuilding techniques, the 250MW design uses sodium fluoride salts, and denatures the converted U-233, promising natural coal-equivalent costs with proliferation risks lower than Gen III+ LWRs.	[undisclosed]	[n/a]
NuScale Power	2007	NuScale Power plans to commercialize a small scale (45MW) light water reactor able to produce heat and electricity for government buildings, district housing communities, and large corporate buildings.	CMEA Capital, The Michael Kenwood Group	http://www.nuscalepower.com
TerraPower	2008	TerraPower has developed an economic nuclear energy system while greatly reducing proliferation risks and creating new options for converting low-level waste into vast energy resources.	Charles River Ventures, Intellectual Ventures, Khosla Ventures, Reliance Industries	http://www.terrapower.com/home.aspx
Tokamak Solutions	2009	Tokamak Solutions is developing technology for a fusion neutron source to transmute nuclear waste and produce medical isotopes and new materials. It is currently developing its compact design and investigating new potential markets.	Rainbow Seed Fund	http://www.tokamaksolutions.co.uk/
Transatomic Power	2011	Transatomic Power is a nuclear reactor design company that has developed the WAMSR -- a Waste-Annihilating Molten Salt Reactor. WAMSR is a 200 MW molten salt reactor that converts high-level nuclear waste into electric power.	Angel Investors	http://transatomicpower.com/index.php
Tri-Alpha	1998	Tri-Alpha is a developer of nuclear fusion technology. The company was in "stealth mode" as of October 2012, but an Aug. 2011 technical presentation by the company claimed they had sustained a fusion reaction for a record breaking duration, exceeding two milliseconds.[40]	Enel, Goldman Sachs, PIZ Signal, Venrock Associates, Vulcan Capital	[n/a]
Universal Fusion	2011	Universal Fusion is developing a compact inertial electrostatic confinement fusion reactor for distributed power generation. The reactor used carbon nano tube grids and pulsed power to produce a periodically oscillating plasma sphere electrostatically in plasma. The company claims the reactors can be produced at a cost of $1000/kW and operated at less than $0.01/kWh. The company is looking to carry out a demonstration project.	[undisclosed]	[n/a]

Source: Compiled by case writer. Data from news articles, research.cleantech.com, and company websites, accessed October 2012.

Exhibit 10 Excerpt from U.S. DOE Small Modular Reactor (SMR) Subcommittee Charge Memo

The Secretary of Energy
Washington, DC 20585

April 3, 2012

MEMORANDUM FOR WILLIAM J. PERRY
CHAIRMAN
SECRETARY OF ENERGY ADVISORY BOARD

FROM: STEVEN CHU Steven Chu

SUBJECT: Charge to the Secretary of Energy Advisory Board Small Modular Reactors (SMRs) Subcommittee

Purpose of the Subcommittee

Nuclear power is the United States' largest source of emission-free base load electricity, providing 20 percent of the Nation's supply from 104 operating reactors and is an integral element of the Obama Administration's Clean Energy Initiative. These reactors have become reliable and safe, providing affordable electricity to consumers and good financial returns to their owners. This has led to interest in new nuclear construction by the utilities and several types of modern large (>1000 MW (e)) reactors are engaged in the licensing process before the Nuclear Regulatory Commission (NRC). However, several factors, including the economic slowdown, the lack of a price on carbon, the tragic accident at Fukushima, and the potential for new domestic supplies of unconventional natural gas, have slowed the drive toward building new large reactors in the U.S. Leadership in commercial nuclear technology could further shift to foreign suppliers. The Department of Energy's (DOE) Small Modular Reactor (SMR) program could define a new path forward for domestic advanced manufacturing as well as energy security, on a technology platform that is both safer and more financially viable.

The SMRs under consideration are much smaller (<300 MW(e)) than conventional commercial reactors. They would be built in a factory as a complete steam supply module and then transported by rail or truck to a utility generating site where they would be connected to conventional steam turbines and electric generating equipment. Factory fabrication opens the prospect of reducing costs by working in a controlled environment with a dedicated workforce that enables improvement through learning. The number of modules at each reactor site could be sized to the meet the anticipated utility demand. Further advances in safety and security would result from simplicity in design, robustness to seismic events, much greater coolant to thermal power ratios, and

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below ground emplacement. These methods are also expected to significantly reduce manufacturing and deployment costs. Further, the smaller size and modular construction represent a promising match with the financial structure of privately owned utilities that represent a large fraction of U.S. electricity supply. An additional attribute of the SMRs being developed is that the entire nuclear system could be designed, licensed, built, and operated by U.S. companies and institutions.

DOE has recognized the potential of these SMRs and has initiated a program to accelerate their commercialization. The vision is to have a fleet of SMRs built in the U.S. of sufficient size to make a significant contribution to the Nation's clean energy goals. As a first step in this process, the Office of Nuclear Energy has issued a Funding Opportunity Announcement (FOA) to share the costs of finalizing the designs, and completing the certification and licensing requirements of the NRC. A complete strategy to achieve the goal of an operating fleet will need to address the challenges of first-movers and the prospects of learning in factory-based manufacturing. The DOE SMR program, as envisioned, could provide the impetus to restore the U.S. into a global leadership position for commercial nuclear power and clean energy supply and to maintain global leadership in the non-proliferation and nuclear security arenas.

The broad purpose of the SEAB Subcommittee on SMRs is to advise the Secretary on ways to advance this technology to achieve a global leadership role in civil nuclear technology for the United States, and ways for DOE to accelerate that role.

Tasks

Looking beyond the current DOE program authorized by Congress and begun by the FOA, this SEAB Subcommittee will:

(1) Identify areas in which standards for safety, security, and nonproliferation should be developed for SMRs to enhance U.S. leadership in civil nuclear energy.
(2) Identify challenges, uncertainties and risks to commercialization and provide advice on policies and other approaches that may be appropriate to manage these risks and accelerate deployment in support of national goals.

Subcommittee Membership

Existing SEAB members: Nicholas Donofrio (Chair), Norm Augustine, Frances Beinecke, and John Deutch.

External members: D. James Baker, Al Carnesale, Admiral (ret) Bruce DeMars, Andrew Kadak, William Madia, Richard Meserve, Burton Richter.

Source: U.S. DOE. http://www.ne.doe.gov/smrsubcommittee/documents/Charge%20memo%20to%20the%20SMR%20Subcommittee.pdf, accessed October 2012.

Exhibit 11 Types of Risk Inherent in Nuclear Power Plant Projects

Risk Type	Description of Principal Risks	Primary Risk Taker(s) and possible mitigation
Design risks	Misspecification of design, or design does not meet specification, possibly requiring re-design during construction, licensing amendments, additional work and replacement equipment.	Owners and/or vendor, according to fault. Avoid first-of-a-kind risks by using established design, use experienced project managers.
Construction and supply chain risks	Delays by contractors or sub-contractors in completing on-site work or in supplying equipment; sub-standard work or equipment, requiring replacement; costs of work or equipment greater than expected; delays in commissioning of plant; etc.	Vendor and/or other contractors, also owners. Use appropriate contractual arrangements, with experienced contractors and established design.
Regulatory and licensing risks	Unexpected delays in obtaining construction and operating licenses and permits from national and local agencies; unreasonable failure or delay in renewing operating or other permits during plant operating life.	Owners and government. Need to establish an efficient and predictable regulatory system; risks will be reduced once system is fully demonstrated.
Political risks	Change of government and/or policy towards nuclear: could result in impaired fiscal, financial or contractual; arrangements; additional regulatory requirements; forced abandonment of construction or premature closure of operating plant.	Owners and government. Establish a broad political consensus on the role of nuclear power, with clear legal and contractual cover for political risks.
Financial risks	Changes in interest rates and taxes; inability to re-finance loans on favorable terms; foreign exchange risks; costs and availability of nuclear liability and other insurance.	Owners. Risk reduction through use of financial instruments; need for government to establish legal framework for nuclear liability.
Natural disasters, force majeure	Earthquakes and other natural disasters (according to region), which could cause damage to plant and forced outages; security risks and threats of terrorism, which could add to costs.	Owners. Licensing and design requirements for seismicity, etc.; insurance; avoid politically
Operating risks	Equipment failures and incidents during operation, leading to reduced electrical output, unplanned outages, additional repairs and maintenance, etc.; delays and incidents during planned maintenance and refueling.	Owners, also vendor and/or other contractors (including warranties). Use experienced contractors, skilled operators, proven equipment design.
Fuel supply risks	Delays in the supply of fabricated fuel elements, resulting in reduced electrical output or even closure; fuel quality issues, resulting in handling difficulties; unexpected large increases in fuel cycle costs.	Owners. Long-term fuel cycle contracts; use competing suppliers; government may need to establish nuclear agreements with supplier countries.
Electricity market and carbon-trading risks	Failure to be dispatched by system operator; unexpectedly low electricity prices in market; failure of customer for power purchase or off-take contract(s); unfavorable changes in electricity market regulation or carbon trading regime.	Owners. Electricity market with suitable provisions for long-term contracts, price setting, dispatch, etc.; stable system for carbon trading or pricing.
Waste management and decommissioning risks	Failure to establish national facilities in expected time frame, with inability to move spent fuel and waste off-site; higher than expected costs due to policy uncertainty and delays; increased requirements for decommissioning cost provisions.	Owners and/or government. Need for government to establish clear and consistent policies, and suitable measures to implement them.
Nuclear proliferation risks	Enriched uranium and spent fuel rods used/stored on site could be repurposed to make nuclear weapons.	Owners and/or government. Maintain a high security facility with appropriate level of personnel at all times.

Source: OECD/NEA (2009) Facts and opinions, NEA News 2009–No. 27.2 http://www.oecd-nea.org/pub/newsletter/2009/27-2/1-The%20financing.pdf

Exhibit 12 Simplified Financial Model of a Typical Gen III+ Nuclear Power Plant in the United States

Macro Assumptions		
Plant Size	1,000	MW
Tax Rate	35.0%	

Setup Assumptions		
Total Planning Cost	$1,000	million
Total Construction Cost	$4,000	million
Planning Duration	3	years
Construction Duration	4	years
Implied Total Overnight Cost	$5,000	million

Capital Assumptions		
Assumed WACC	5.0%	

Operational Assumptions		
Wholesale Electricity Price	$80.00	USD per MWh
Percent Uptime	90.0%	
Fuel Costs	$7.70	USD per MWh
Ops & Maintenance	$11.00	USD per MWh
Useful Life	60	years
Plant Decommissioning	$350	million

Plant Decom. in year
67

Year:	0	1	2	3	4	5	6	7	8	9	10	20	30	40	50	60	67
Setup & Decommissioning Costs																	
Planning ($M)		($333)	($333)	($333)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Construction ($M)		$0	$0	$0	($1,000)	($1,000)	($1,000)	($1,000)	$0	$0	$0	$0	$0	$0	$0	$0	$0
Decommissioning		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	($350)
Total Setup & Decom. Costs		**($333)**	**($333)**	**($333)**	**($1,000)**	**($1,000)**	**($1,000)**	**($1,000)**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**($350)**
Operations																	
Million MWh Produced		0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.889	7.889	7.889	7.889	7.889	7.889	7.889	7.889	7.889
Revenue ($M)		$0	$0	$0	$0	$0	$0	$0	$631	$631	$631	$631	$631	$631	$631	$631	$631
Fuel Costs ($M)		$0	$0	$0	$0	$0	$0	$0	($61)	($61)	($61)	($61)	($61)	($61)	($61)	($61)	($61)
Ops & Maint. ($M)		$0	$0	$0	$0	$0	$0	$0	($87)	($87)	($87)	($87)	($87)	($87)	($87)	($87)	($87)
Depreciation ($M)		$0	$0	$0	$0	$0	$0	$0	($333)	($333)	($333)	($333)	$0	$0	$0	$0	$0
Operating Income ($M)		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$150**	**$150**	**$150**	**$150**	**$484**	**$484**	**$484**	**$484**	**$484**
Tax Shield/(Expense) ($M)		$0	$0	$0	$0	$0	$0	$0	($53)	($53)	($53)	($53)	($169)	($169)	($169)	($169)	($169)
Net Income ($M)		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$98**	**$98**	**$98**	**$98**	**$314**	**$314**	**$314**	**$314**	**$314**
Add Back Depreciation ($M)		$0	$0	$0	$0	$0	$0	$0	$333	$333	$333	$333	$0	$0	$0	$0	$0
Operating Cash Flows ($M)		**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$431**	**$431**	**$431**	**$431**	**$314**	**$314**	**$314**	**$314**	**$314**
Cash Flow from Setup & Decom ($M)		($333)	($333)	($333)	($1,000)	($1,000)	($1,000)	($1,000)	$0	$0	$0	$0	$0	$0	$0	$0	($350)
Cash Flow from Operations ($M)		$0	$0	$0	$0	$0	$0	$0	$431	$431	$431	$431	$314	$314	$314	$314	$314
Net Cash Flow ($M)		**($333)**	**($333)**	**($333)**	**($1,000)**	**($1,000)**	**($1,000)**	**($1,000)**	**$431**	**$431**	**$431**	**$431**	**$314**	**$314**	**$314**	**$314**	**($36)**

Plant NPV	
NPV of Setup/Decom ($M)	($3,984.2)
NPV of Operations ($M)	$5,089.5
Total Plant NPV ($M)	**$1,105.3**

WACC	5.0%
Project IRR	6.5%

Note: The depreciation period for nuclear plants is 15 years.
Simplifying assumptions:
- Straight-line depreciation method
- Zero net working capital

Note: Assumes no construction delays. Operating and Maintenance costs ("Ops. & Maint.") includes used fuel storage. Raw materials (e.g. steel and concrete) account for majority of plant construction cost. Assumes that the tax shield is used by operator and/or investors to offset other income.

Source: Case writer analysis. Data from www.world-nuclear.org, www.nrel.gov, and www.nrc.gov accessed October 2012.

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