21st Century Civilian Nuclear Power and the Role of Small Modular Reactors

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Firas Eugen Taso

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Advisers:
Professor Bruce Everett
Professor Ann Rappaport

Abstract

Nuclear power provides benefits, such as reduced carbon emissions, low operating costs, baseload power, and energy independence. It also raises significant concerns regarding capital cost, safety, regulation, waste, public perception and proliferation. Recently there has been renewed interest in nuclear power due to small modular reactors (SMRs), that some argue could bring a "renaissance" of the industry. This thesis first presents an analysis of large-scale nuclear power focusing on benefits and concerns, and then examines the new SMR trend. It assesses whether SMRs are a game-changer for the industry towards nuclear resurgence by analyzing promising models and perceived benefits and costs of SMRs. Based on extensive literature review, 22 expert interviews and economic modeling, the conclusion is that nuclear power as an energy source should be pursued as part of a larger energy portfolio with specific government intervention, while SMRs, although likely not game-changers per se, can play a complementary role in re-inventing the industry without significant support from policy-makers.

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List of Abbreviations

ABWR – Advanced Boiling Water Reactor

AEA – Atomic Energy Act of 1953

AP 1000 – Westinghouse's Gen III+ reactor (pressurized water reactor)

APWR – Advanced Pressurized Water Reactor

BTU – British Thermal Unit (1 BTU = 1 055.05585 Joules)

CCS – Carbon Capture and Storage

DoD – Department of Defense (United States)

DoE – Department of Energy (United States)

EIA – Energy Information Administration (United States)

EPR – European Pressurized Reactor, AREVA design

EPRI – Electric Power Research Institute

FAS – Federation of American Scientists

GE – General Electric

GWe – Gigawatt, electric

GWt – Gigawatt, thermal

HEU – Highly Enriched Uranium

IAEA – International Atomic Energy Agency

IGCC – Integrated Gasification Combined Cycle

IPCC – Intergovernmental Panel on Climate Change

LCOE – Levelized Cost of Electricity

LWR – Light Water Reactor

MW – Megawatt

MWe – Megawatt, electric

MWt – Megawatt, thermal

NIMBY – "Not In My Back Yard"

NPT – Non-Proliferation Treaty

NRC – Nuclear Regulatory Commission (United States)

NEI – Nuclear Energy Institute (United States)

PBMR – Pebble Bed Modular Reactor

PWR – Pressurized Water Reactor

SMR – Small Modular Reactor

Note on Recent Events in Japan, March 2011

At the time this thesis was being written, a major event occurred in the nuclear industry that may have consequences going beyond the analysis and recommendations of this paper. According to the United States Geological Survey, on March 11, 2011, at 5:46 UTC, 9.0 Richter scale magnitude earthquake hit the Eastern coast of Japan 80 miles at sea East of Sendai, Honshu. This was the largest earthquake recorded in Japan's history and one of the strongest ever recorded in the world, and it resulted in large damages to infrastructure and significant loss of life, estimated by some up to 20,000 people.[1] The earthquake was followed by over 100 aftershocks, many of them the magnitude of large earthquakes, and in particular by a devastating Tsunami which caused significantly more damage than originally predicted.

Of particular concern is the damage that occurred at Fukushima Daiichi Nuclear Power Station. Following the massive earthquake, the power plant shut down when its safety systems were activated, as designed.[2] However, the Tsunami was larger than the engineers had predicted in the 1971 designs, and the water disabled the cooling units, as well as the mobile diesel generators brought on-site to replace them. The natural disaster caused explosions and alleged leaks of radioactive gas in three reactors, resulting in partial meltdowns, while spent fuel rods at another reactor overheated and caught fire, releasing radioactive material directly into the atmosphere.[3] The situation is developing as the paper is being finalized, and reports in the media, as well as by official agencies such as IAEA, NRC and Japanese authorities are conflicting as to the extent of the damage and the effects of the accident. It is therefore currently hard, if not impossible to know the true facts beyond speculation as to the outcome of the crisis, as well as

[1] United States Geological Survey Website. "Magnitude 9.0 - Near the East coast of Honshu Japan". Retrieved on March 24, 2011 from: http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/

[2] Barry Brook. "Fukushima Nuclear Accident – a simple and accurate explanation". Brave New Climate Website, March 13, 2011. Retrieved on March 15, 2011 from: http://bravenewclimate.com/2011/03/13/fukushima-simple-explanation/

[3] New York Tomes Online, March 24, 2011. "Japan — Earthquake, Tsunami and Nuclear Crisis (2011)". Retrieved on March 24, 2011 from: http://topics.nytimes.com/top/news/international/countriesandterritories/japan/index.html

the effect this incident will have on the nuclear industry in the United States and abroad (so far Germany and Russia have suspended the extension of operation licenses for their nuclear power plants until an investigation into their safety and emergency preparedness is completed.[4])

Therefore, while an acknowledgement of the events was necessary in the context of the topic for the thesis, the author did not wish to speculate on the outcome of the crisis, nor on the potential impact on the nuclear industry or the development of small modular reactors. It is clear that this is a major event in nuclear history (compared by some to Three Mile Island and Chernobyl), but it remains unclear at this point in time, and likely for the foreseeable future, what the extent of the damage is and how this will impact public opinion, regulator's and legislator's action and the utilities' and industry's response.

[4] Energy Tribune Website, March 14, 2011. "Germany to Suspend Nuclear Power Extension". Retrieved on March 24, 2011 from: http://www.energytribune.com/articles.cfm/6834/Germany-to-Suspend-Nuclear-Power-Extension

Executive Summary

Civilian nuclear power has had a tumultuous history. It has experienced an uphill battle due to public perception, waste management, security and safety, proliferation concerns and, above all, economics. Despite its advantages of being a zero-carbon energy source, operating on really high density fuel at over 90 percent capacity and having low operating costs, nuclear power is today not materializing its “renaissance”, as was predicted at the beginning of the 21st century. However, a new technological approach is currently being promoted in the nuclear industry – small modular reactors (SMRs) – perceived as an innovation allowing the industry to rebound and expand beyond its current capacity, and to areas that were not possible before.

This paper first explores large-reactor civilian nuclear power, presenting the history of the technology and industry, the current situation worldwide, and the future outlook. It analyzes the benefits and full costs of nuclear power in order to present the reader with a full picture of the industry and the dilemma policy-makers have to face. Then the paper introduces SMRs, the concept, definition and promising models being discussed by industry and regulators currently. Their benefits, such as modularity, reduced initial capital cost, versatility for remote areas and applications, and simplified designs, and their costs, including overruns, safety and proliferation, as well as waste management are discussed. The analysis is conducted based on an extensive literature review, the opinions of 22 experts in the nuclear industry and economic modeling.

This leads to policy recommendations for large and small reactors. In case of the large plants, the government should remain involved with the industry and provide assistance necessary to maintain the civilian nuclear power industry. Existing plants should be maintained, while new projects should be carefully analyzed economically before being approved and subsidized by taxpayers. SMRs should receive little government assistance, and only when they are ready to be deployed, as a first-to-market incentive. R&D should remain in government hands, as well as researching a solution for waste and reprocessing. Overall, nuclear is a fiercely contended topic, but it is also an opportunity to bridge to the future until new, renewable ways of producing energy become viable.

Introduction

"The stars do not seem to be aligning for large reactors. But they are no longer the only game in town"

The Economist, December 2010[1]

Nuclear power was introduced as a civilian energy source in 1954, after having been initially used by the US as a destructive weapon against Japan at Hiroshima and Nagasaki in 1945.[2] The product of Admiral Rickover's dream of seeing nuclear power produce energy for peaceful purposes, this new energy source was quickly adopted in the United States and soon after around the world.[3] Deemed a feasible and long lasting source of energy worldwide due to the high energy content of Uranium, the main fuel used in the fission process, nuclear power has the potential to replace conventional energy generating facilities using fossil fuels, eliminate dependence on foreign imports of fossil fuels in resource-poor countries (i.e. oil, gas, coal) for energy production as well as to curtail global warming by eliminating CO_2 and other greenhouse gases emissions into the atmosphere.[4] Despite dire opposition by environmentalists and public citizen groups, especially after accidents at Three Mile Island in the US and Chernobyl in the Ukraine, nuclear energy has continued to grow since its inception, albeit inconsistently over the decades, demonstrating increased performance and efficiency. Today it is a major source of energy, supplying 20 percent of US' and 14 percent of the world's electricity in 2009[5].

However, nuclear energy is a complex issue for policymakers. The economic, technological, social and political implications of nuclear power make any decision a complicated one. Despite its maturity, widespread usage and steady progress, compared with other energy sources nuclear power has a level of government intervention and public concern that makes it a contentious topic of debate. Although proponents of nuclear power argue it is a clean, efficient, and increasingly safe way of producing energy, issues such as technical complexity, large capital investments, operational costs such as insurance and maintenance, long-term implications of waste management, and the perception of consequences associated with potential accidents, security and proliferation make nuclear power less compelling.

Though recently there has been talk in the US and around the world of an imminent resurgence of nuclear power, a "nuclear renaissance" of sorts, it has thus far failed to materialize. In recent years, an increased interest in Small Modular Reactors (SMRs) emerged. Defined by the International Atomic Energy Agency as reactors producing less than 300MWe, SMRs have captured the public eye and the scientific, economic and policy debate. They are not a new technology, nor are they making their appearance for the first time in the nuclear debate. They have been in operation, somewhat modified, for over 50 years in the US and other navies. The basic models up for regulatory review in the near future are light water reactors (LWRs), in effect miniatures of the large plants in operation today. Other "exotic" concepts such as the pebble bed reactor, fast breeder reactors or traveling wave reactors exist, and may play a significant role in the future. SMRs present significant advantages, such as lower capital cost, assembly-line manufacturing offsite and modularity allowing for fast scale-up, simplified safety systems due to size and, in some cases, turn-key solutions with limited or no need to refuel for the operating lifetime. Nonetheless, concerns about proliferation, safety, escalating costs, competitiveness and waste also plague SMRs, making them the hot debate topic today.

Given the complex nature of nuclear power, the purpose of this thesis is two-fold:

First, it presents the reader with a general perspective on nuclear power benefits and costs and explores the claim that nuclear power is a feasible energy production alternative. Concretely, the paper will argue that if all economic costs, safety, legal and liability issues are taken into consideration, nuclear power today may be more expensive and less compelling as an energy source than currently recognized, making a “renaissance” an uncertain goal. The paper will argue, however, that despite these drawbacks, nuclear power should be included in the world’s energy portfolio, and policymakers should continue to push for maintaining or expanding the industry and nuclear’s share of power generation worldwide.

Second, the thesis analyzes SMRs and determines whether they constitute a viable solution that can help a faster resurgence for nuclear power in the United States and abroad. Based on the conclusions drawn from literature review and interviews with nuclear experts such as nuclear engineers and physicists, think tank specialists, academic experts, regulators, environmentalists, industry experts and nuclear consultants, the paper will argue that, in order for SMRs to make an impact in the current US and world context, several technical, regulatory and public perceptions conditions must be met. Since the jury is still out on SMRs and the situation will likely remain unclear until test models are built and proven viable, the industry should continue to pursue the technologies and push towards adoption of the most promising model as a complement to large plants. To this end, policy recommendations follow and next steps are suggested in order to promote SMRs and nuclear power, concluding the analysis.

The first part of the paper will present an analysis of civilian nuclear power in several steps. First, a historical and technical look at nuclear power, since it is important to understand what nuclear power is, how the fission process works, and how it came to be an integral part of the energy mix in the US and several other nations. Next follows the current situation of nuclear power and a projected outlook for the future, both in the US and worldwide. The analysis will then focus nuclear power’s benefits in order to establish its legitimacy and impact as an energy producing solution, as well as the full array of costs involved with nuclear power production in order to show why nuclear power is less compelling overall from some observers’ point of view, basing the analysis on an economic model and expert interviews.

The second part of the paper is the analysis of SMRs. The thesis will offer a brief definition, and look into their history to date. It will then look at the most promising models, offering a matrix with all the current SMRs being proposed, in the US and abroad. Once the background is presented, the paper will analyze the benefits of SMRs, and why proponents of nuclear power are enthusiastic about these reactors. It will then also look at the forecasted costs and concerns over SMRs, and how they are perceived by skeptics and opponents.

The third part contains policy recommendations if nuclear power is to be pursued as part of the energy portfolio of the US and the world. There is a significant emphasis on SMRs and how to achieve widespread deployment, ramp up production capacity and stay competitive in the world market with the new technology. It also recommends policies on necessary subsidies and support, as well as the proposed level of government involvement

Finally, the conclusion provides a summary of all the arguments for and against nuclear, suggests the best course of action and explores next steps.

Research and Thesis Methodology

The analysis and conclusions of this project are built on three research methods:

1. Literature review, primarily books, articles, official publications and opinions published by think-tanks, regulatory agencies, industry groups and manufacturers. While there is no dedicated section in the thesis for the literature review, the analysis draws on these sources significantly. A list of these materials is included in the bibliography, and detailed citations are provided throughout the paper, where appropriate.

2. A series of 22 interviews with nuclear experts which include nuclear engineers and physicists, think tank professionals, academic experts, nuclear regulators, environmentalists, industry experts and nuclear consultants. They were selected based on their expertise, as well as their affiliation to organizations with different opinions on nuclear power and SMRs. The author attempted to select as broad a group as possible to include pro-nuclear and anti-nuclear experts, proponents as well as skeptics, in order to gain a complete picture of the nuclear field and the arguments about the topic. The aim has been to select a diverse group based on expertise in engineering, regulation, policy-making and academia, as well as broad knowledge on issues like waste, proliferation, safety and economics, as well as a mix of experts on large reactors and SMRs. While access to some experts was not possible due to time or availability constraints, the selected group provided a great base for research. The table below presents the interviewees, with their affiliation.

Figure 1- List of Interviewed Experts

No.	Last Name	First Name	Company	Position
1	Banks	John	Brookings Institution	Non-resident fellow
2	Bunn	Matthew	Harvard Kennedy School	Professor
3	Chiesa	Luisa	Tufts Engineering Department	Professor
4	Corradini	Michael	University of Wisconsin	Professor
5	Ferguson	Charles	Federation of American Scientists	President
6	Ferroni	Paolo	Westinghouse	Nuclear Engineer
7	Gallagher	Kelly	Fletcher School	Professor
8	Genoa	Paul	Nuclear Energy Institute	Director, Policy Development
9	Hamilton	Bruce	Fuelco	Director
10	Howsley	Roger	World Institute of Nuclear Security	Director
11	Ingersoll	Daniel	Oak Ridge National Laboratory	Senior Program Manager
12	Joosten	James	U.S. Energy Information Administration	Senior Energy Analyst
13	Kirshe	Mark	M4Services	President
14	Koplow	Doug	Earth Track	Founder
15	Lester	Richard	MIT Nuclear Engineering Department	Professor
16	Maloney	Stephen	Accenture	Management Consultant
17	Moomaw	William	Professor	Fletcher School of Law and Diplomacy, Tufts University
18	Peters	Mark	Argonne National Lab	Deputy Director for Programs
19	Petroski	Rob	Terra Power	Nuclear Engineer
20	Snodderly	Michael	Nuclear Regulatory Commission	Technical Assistant for Reactors to Commissoner Apostolakis
21	Sokolski	Henry	Nonproliferation Policy Education Center	Executive Director
22	Squassoni	Sharon	Center for Strategic and International Studies	Director and Senior Fellow, Proliferation Prevention Program

While there is no dedicated section summarizing each interview separately, the expert opinions are interspersed in the paper where appropriate and inform the conclusions and recommendations in great part. Biographies of the experts are presented in the Appendix, and a list of the interviews with dates is presented in the bibliography. Please note exact citations are not presented every time an expert opinion is mentioned due to space and page layout considerations, but for the convenience of the reader, the name of the interviewee is mentioned every time an opinion is utilized, and the list of interviews with dates and names is presented in the References section on page 111.

3. A financial model built by the author that attempts to assess the economic viability of large nuclear power as compared to coal (both with and without a carbon tax, as well as with and without Carbon Capture and Storage technology), natural gas (with and without a carbon tax, as well as with and without Carbon Capture and Storage technology), wind (onshore and offshore installation), and solar (small photovoltaic and large photovoltaic) based on data collected from the EIA and assumptions about capacity factors, cost of capital and financing,

operational costs, fuel costs, time to build a plant, length of financing, inflation, etc. for a 40-year operating life. The model is used as a method to assess the true financial costs of nuclear and to make recommendations about its adoption and feasibility, alongside literature and expert opinion. The model assumptions are contained in the figure below:

Figure 2 - Economic Model Assumptions

	Per Year
Inflation	2%
Bank Loan Rate	10%
Discount Rate	12%
Carbon Tax ($/ton CO2)	$25

	Coal	Natural Gas (CC)	Solar**	Wind**	Nuclear
Capacity Factors*	74%	42%	18%	30%	91%

	PC Coal	PC Coal w/CCS	Adv Nat Gas CC	Adv Nat Gas CC CCS	Large Solar	Small Solar	Offshore Wind	OnShore Wind	Nuclear
Time to Build (years)	2	4	2	4	3	2	3	3	8
Financing Time (Years)	20	20	20	20	20	20	20	20	30

* Rounded, source: EIA, 2010
** Represents an average of large and small (onshore and offshore)

Leverage Ratio	70%

	Coal	Natural Gas	Uranium
Fuel Cost (per MM BTU)	$ 2.26	$ 5.08	$ -
Fuel Cost (per pound)			$ 46.26

The model was designed to compare different generating sources of electricity in order to provide quantitative backing for the statements and conclusions reached, as well as to verify expert claims by changing assumptions; for example, how would a different cost of capital, or different fuel costs affect the overall price of electricity and the competitive advantage for some of the current technologies. The model assumes a 12 percent rate of return across all electricity generation alternatives to allow for a fair comparison. It also assumes a 40-year operation period, a leverage ratio of 70 percent and cost of bank financing of 10%, higher than regularly estimated by current research. It compiles these costs for coal, natural gas, wind and solar in order to compare the alternatives from a utility's business decision-making perspective. The different outputs from the model based on the several scenarios are presented in the appendix, with a discussion of the results in the body of the paper.

Part One – Civilian Nuclear Power Analysis

Nuclear power has been around for over half a century, and is ever present in our everyday lives in the Western world, and increasingly in China, India and other developing countries.[6] In policy analyses, environmental arguments, including the climate change debate, nuclear power is often mentioned. There are pro-arguments to why nuclear power should be used, and counter-arguments on why it is too risky or costly for us to consider an expansion of the industry. Though the US Navy and others, including the Russians, the French, the British and the Chinese, have been using nuclear power for decades in their submarines, aircraft carriers, ice breakers, etc., the large boom expected for nuclear power after its introduction in the 1950s and initial excitement of the 1960s and 1970s did not fully materialize.[7] Today, our societies argue incessantly about the benefits and costs of nuclear, with no consensus in sight. This negatively affects the nuclear industry, as no new reactors have been built in the US in the past 30 years, and only a few were built or are under construction around the world in recent years.

This section analyzes the civilian nuclear power sector in detail in order to give the reader a solid background on the history and policy context in which nuclear power has operated in the past, and its current state in the world, as well as experts' opinions for its future development. It will address the controversial issues of benefits and costs of nuclear power, including the policy debates, the waste management problem and public perception concerns the industry is facing. Nuclear power is a contested issue, and, if one is to discuss its future, then a solid background and understanding of the technology and industry in the US and worldwide are necessary.

I. What Is Nuclear Power?

In order to understand the policy implications of nuclear power, it is useful to first understand the physics behind the nuclear reaction (fission process), the components of a nuclear reactor, types of reactors in use, next generation reactors, as well as waste management issues.

a. The Nuclear Fission Process

The reaction by which nuclear energy is achieved is called nuclear fission. Certain natural chemical elements, such as uranium, are relatively unstable. When the nucleus of such an element is impacted by a neutron which it absorbs, it can split into two fragments, releasing at the same time two or three neutrons and energy.[8] When there is enough fuel in the reaction to create enough free neutrons to balance the number which is lost by leakage and capture by other atoms (known as critical mass), the system becomes self-sustaining. The isotope Uranium-235 is one of the few elements found in nature that can undergo fission and is therefore frequently used as fuel in nuclear reactors.[9] Some man-made elements, such as plutonium (which is formed when a uranium atom absorbs a neutron but does not split), are also used in the fission process due to their ability to split and release energy and neutrons. At the impact, the U-235 nucleus splits, and the mass lost is converted to energy following Einstein's $E=mc^2$ formula[10]. The following reaction explains the fission process (though others reaction products are possible):

$$235U + n \longrightarrow 143Xe + 90Sr + 2n + 200MeV$$ [11]

An atom of Uranium 235 (enriched Uranium) is bombarded with a neutron. The impact causes the atom to split (in this case into an atom of xenon and an atom of strontium), and releases two additional neutrons and significant heat (energy). The reaction is repeated until most atoms of Uranium are gone and the fission cannot sustain itself any longer.

b. The Nuclear Reactor and Types of Nuclear Reactors

A nuclear reactor is a way of generating heat to boil water, thereby producing steam and driving turbine generators for electricity production. In effect, it is not much different than the concept for a coal or gas-powered power plant. The major distinction is given by the way in which the steam is produced. The uranium acts as an extremely high-energy source of heat. It heats water and turns it to steam. The steam drives a steam turbine, which spins a generator to produce power. Fission reactors usually consist of several parts: a reactor core that houses the reaction itself; a working fluid (usually water) to remove heat from the reactor core; a reactor vessel to prevent the reactor from emitting ionizing radiation and neutrons; and a containment vessel (steel and concrete) to prevent leakage of radioactive isotopes[12].

The reactor core contains nuclear fuel in the form of mildly enriched U-235 (uranium U-235 found in nature does not have the needed concentration of atoms for the fission process in some reactors and requires addition of two to five percent of uranium-235). A critical mass of two pounds is necessary to maintain the fission process in the reactor.[13] The fuel is formed into pellets half an inch in diameter and an inch in length. The pellets are arranged into long rods, and the rods are collected together into bundles. Next, the reactor core contains a neutron moderator which aids the formation of a chain reaction by slowing down fast neutrons, a working fluid which absorbs the heat of the nuclear reaction, a mechanism (such as control rods) that regulates and controls the chain reaction by absorbing free neutrons, and a neutron reflector which aids the reaction by keeping neutrons from escaping the core.[14]

Most reactors are controlled by means of control rods that are made of a strongly neutron-absorbent material such as boron or cadmium. Inserting a control rod into the reactor core has the effect of absorbing all neutrons that would otherwise have passed through the space occupied by the rod; when the reactor is shut down, the control rods make the reaction subcritical, so that the chain reaction is not self-sustaining. Pulling a control rod partway out of the core reduces the neutron absorbent effect by permitting neutrons to survive (and impact fuel) where otherwise they would have been absorbed. When the rod is pulled sufficiently far from the core, the core becomes a critical assembly and the nuclear reaction is governed by the physics of the chain reaction rather than the usual laws of radioactive decay.[15]

All nuclear reactors are built with at least one rapid-shutdown control, traditionally called SCRAM, that inserts all or a large number of control rods into the core simultaneously. In many reactors, the rods are mounted vertically and suspended by electromagnets, so that interrupting the power to the electromagnets causes the reactor to fail safely by dropping all rods into the core. Because most reactors use water as a working fluid, many facilities can, as a last resort, insert borax, a readily soluble boron compound that absorbs neutrons, into the core water.[16]

A number of reactor technologies have been developed since the inception of nuclear power plants, demonstrating the importance given to nuclear power and the research that went into developing this form of energy. Fission reactors can be divided roughly into two classes, depending on the energy of the neutrons that are used to sustain the fission chain reaction. Thus, reactors can be thermal reactors or fast reactors.[17] Thermal reactors use slow (thermal) neutrons and moderating materials intended to slow the neutrons until they approach the average kinetic energy of the surrounding particles. Thermal neutrons have a far higher probability of fissioning U-235 than the faster neutrons which result from the fission process.

Fast reactors use fast neutrons to sustain the fission chain reaction, and are characterized by the lack of moderating material. They require highly enriched fuel (sometimes weapons-grade uranium or plutonium) in order to reduce the amount of U-238 that would otherwise capture fast neutrons. Some are capable of producing more fuel than they consume, usually by converting U-238 to Pu-239. Some early power stations were fast reactors, and were mainly used to produce weapons-grade fuel (as enrichment plants) for the atomic arms race of the Cold War, but overall the class has not achieved the success of thermal reactors in any application due to its operating cost and inefficiency.[18] An example of this type of reactor is the Fast Breeder Reactor (FBR), currently in use only in France, Russia, Japan and India (see Appendix, Figure 3).

Most reactors in use today are thermal reactors. These can be of several kinds. The most common ones use light water (LWRs) and the pressurized water reactor or PWR (and its Russian equivalent VVER) and the boiling water reactor or BWR. At the beginning of 2008 there were 212 PWRs worldwide, 150 of which were located in France, Japan and the US, as well as 92 BWRs and 51 VVERs (see Appendix, Figure 4).[19] The PWR uses ordinary water both as a coolant and moderator. The water is kept at high pressures to remain in liquid form and a steam generator transforms it into steam as it leaves the core (see Appendix, Figure 5). The BWR operates on the same principle, only the pressure for the water is lower and the steam goes directly into electricity generation (see Appendix, Figure 6).[20] For example, in the Russian RBMK (the Chernobyl reactor type, 17 still in operation), water is used as a coolant and graphite is used as a moderator, leading to a faster reaction, with the steam passed directly to the power generator. Some thermal power reactors are more "thermalised" than others, which leads to use of un-enriched uranium for the fission process The heavy water reactor, the Canadian CANDU (34 operating) uses heavy water (D_2O, formed with Deuterium, the heavier isotope of hydrogen) both as a coolant and as a moderator. CANDU use heavy water because it is a good coolant, but a poor moderator, allowing the neutron flow from un-enriched uranium to proceed without inhibition.[21]

The design and license life for a nuclear power reactor is initially 40 years, a period after which it is required to cease its activity or apply for re-licensing due to safety and efficiency reasons. This is a precautionary measure, as equipment could malfunction and radioactive fuel or products of the fission reaction could escape into the environment, causing serious damage. However studies based on operating and material experience have revealed no major technological issues inhibiting longer use. As a result, in 2003 the US granted extensions to allow 10 reactors to operate for 60 years, and authorities in Russia, the UK, France and Germany are looking into extending licenses for some of their plants in the near future.[22]

New generation reactors have already been built and are operational, while others are being presented to policymakers for approval. Some new reactors are evolutionary from the PWR, BWR and CANDU such as the advanced Boiling Water Reactor (ABWB) and rely on standardization for increased construction efficiency (lower construction and maintenance costs) and on passive safety control for better safety and accident management.[23] The ABWB includes recirculation pumps and piping contained inside the pressure vessel for increased safety as well as fully automated response in case of emergency. Three of these new generation reactors are already operating in Japan, two are being built in Taiwan and one is planned for construction in the US, under the “Nuclear Power 2010 Program”, a national plan to re-launch the nuclear program in the US.[24]

In addition to these improved reactor models, also known as Gen III, scientists are designing generation IV reactors, even more advanced, more cost efficient and safe alternatives to today’s power plants. These include a Gas-Cooled Fast Reactor, a Lead-Cooled Fast Reactor, a Molten-Salt Reactor, a Supercritical Water Cooled Reactor, or the Traveling Wave Reactor, among others.[25] While discussing these new concepts in detail requires further technical explanation and is beyond the scope of this paper, it is important to note that new designs are available as scientists are working towards new ways of creating nuclear energy. These developments could help ensure its future in a way not envisioned after the nuclear disasters and the political and social opposition of the past decades.

c. Waste Management

Fissionable elements such as uranium and plutonium are radioactive. This means that they decay slowly over a long period of time, measured by half-life (i.e. the time needed for half of any given number of atoms in an isotope to decay) by emitting radiation. Because of their abundance and radioactivity, these resulting products form a significant part of nuclear waste and require isolation for a long period of time.[26]

Radioactive waste results from any activity than makes use of nuclear materials (that is nuclear power plants, medical or industrial uses). It has to be managed safely and economically, as well as in an environmentally and publicly accepted manner. Based on the concentration of radioactive material, nuclear waste is divided into low-level waste or LLW (including overalls, syringes, containers that have been in short contact with radioactivity), intermediate-level waste or ILW (industrial equipment used in the nuclear process that emits radiation), high-level waste or HLW consisting of the remnants of the fission process and spent-nuclear duel or SNF that will not be reprocessed.[27] For handling and transport the important factor is the radioactivity level, but for storage and disposal what matters is the half-lives of the radioactive isotopes it contains.

Even though nuclear waste constitutes only a small percentage of the yearly waste produced by industrial facilities, it needs to be disposed of properly. To date, U.S. nuclear power plants have produced over 50,000 tons of high-level spent nuclear fuel.[28] The spent fuel consists of 95.6 percent uranium, 3.0 percent stable or short-lived fission products, 0.9 percent plutonium, 0.3 percent cesium and strontium, 0.1 percent minor actinides (neptunium, americium, and curium), and 0.1 percent long-lived fission products in the form of isotopes of iodine and technetium.[29]

Regulations imposed by IAEA require minimization of amounts of waste produced, conditioning and packaging to permit safe handling and protection during transport, interim storage and final disposal procedures. Safe transport of nuclear waste is common, and special shockproof containers designed of steel are being used routinely. While procedures and solutions for LLW and

ILW permanent disposal are readily available (such as near-surface facilities of enforced concrete and low permeability), a long term solution for HLW of SNF has not yet been found. However, experiments are being done with geological disposal, long-term storage and reversibility, and the nuclear industry and regulators are working on ways to safely handle and dispose of waste. [30]

One solution to waste is reprocessing. Currently, Russia, Japan and France are reprocessing some of the spent fuel, but the process is not economically viable given the low cost of Uranium for a once-through cycle, according to Michael Corradini. In the US, reprocessing was prohibited by Executive Order by President Carter in the late 1970s, as concerns over proliferation and the arms race at the time were high.[31] However, experts Mike Peters, Daniel Ingersoll, Michael Corradini and Rob Petroski, who have worked in nuclear power and have experience in waste management, agree that reprocessing is a solution that needs to be considered.[32] William Tucker and Gwyneth Cravens, as well as Robert Bryce in their books on nuclear power downplay the problem of waste as something that could be addressed if political will existed.[33,34,35] If the economics become viable (i.e. uranium for a once-through cycle becomes expensive), then reprocessing will likely be more appealing. One advantage of reprocessing is that it reduces the amount of waste. However, there remains a portion of the fuel that cannot be reclaimed, and a permanent repository for that waste is necessary. Work on those repositories has commenced and stopped in several locations in Europe and in the US, and currently there is no repository in operation, making waste a serious issue for nuclear power.[36]

Another suggestion would be to expand the research to include thorium. A ton of thorium (the slow-decaying, slightly radioactive metal) produces as much energy as 200 tons of uranium, or 3,500,000 tons of coal. It is much cheaper and three times more abundant than uranium, a nuisance to miners that dig up rare earths metals. Unlike uranium, thorium is not fissionable, but it can be used as a nuclear fuel through breeding to fissile uranium-233 (U-233)[37]. Thorium decays its own hazardous waste and can expel the plutonium left by uranium reactors. It cannot melt down and does not produce reliable fuel for bombs. Research for this is in the incipient phases, but the US, China and India have plans to develop the technology in 20 years-time. The US, Australia and India have large deposits of thorium, and an energy program based on thorium technology is not inconceivable.[38]

II. History, Background and Policy Context

Nuclear science emerged with the discovery of the neutron by Sir James Chadwick in 1932. In 1939 Enrico Fermi discovered that when atoms fission energy is released. [39] Accelerated by the urgency of World War II, nuclear science developed rapidly. The first controlled chain reaction was achieved in 1943, the first atomic weapon was tested successfully and used in 1945 and the production of electricity using nuclear energy occurred for the first time in 1951.[40] The United States began producing energy with nuclear power for the grid in 1953 and the UK, Russia, France and Germany followed within the decade.[41] Admiral Hyman Rickover was in charge of the nuclear Navy, and a proponent of using the technology for civilian generation.[42] Ten more countries began nuclear-based generation of electricity in the 1960s and another 10 followed in the 1970s.[43] The oil crisis of the 1970s caused a surge in nuclear power demand and construction of nuclear power plants.[44] Despite nuclear accidents at Three Mile Island in the US in 1979 and Chernobyl in the Ukraine in 1986, and despite strong international political and social opposition, many countries continued to pursue reactor construction throughout the 1980s and 1990s. The development curve was impressive from the 1960s to the 1980s: in 1965 there were 45 reactors worldwide; by 1985 there were 365. After that, growth slowed considerably, but the industry grew in the 1990s and 2000s, and by 2002 there were 441 reactors in operation.

Capacity also increased from 45 GW installed to 360 GW in 2002[45] (see Appendix, Figure 7).

In the US by the 1980s there were over 100 reactors in operation, and currently there are 104 commercial nuclear reactors located at 64 sites in 31 states and providing approximately 20 percent of the nation's electricity each year.[46] In 2009, U.S. nuclear plants generated a record 806.2 billion kWh of electricity, or 20 percent of the national energy production.[47] According to the World Nuclear Association, during the 1980s, one new nuclear reactor started up every 17 days on average, a situation that is no longer occurring today.[48] Watts Bar 1, a TVA project in Spring City, TN, which came on-line on February 7, 1996, was the last U.S. commercial nuclear reactor to be put in service.[49] This is quoted by certain advocacy groups as evidence of an increasingly successful worldwide campaign for nuclear power phase-out in the late 20th century. Political resistance to nuclear power has been successful so far in New Zealand, Italy and partially Germany and the UK, though the Germans and the British are reconsidering plans to phase out nuclear power in recent years, The Philippines have also committed to phase out nuclear power[50].

World's policymakers continue to pay close attention to the development of nuclear power given its importance as well as its risks. The International Atomic Energy Agency, the United Nations' body which coordinates nuclear power management, was founded in 1957 and works for the safe, secure and peaceful uses of nuclear science and technology. Its key role is to contribute to international peace and security, and to the World's Millennium Goals for social, economic and environmental development.[51] Under its auspices, signatory countries involved in nuclear power production have adopted treaties and conventions regulating and ensuring the safety of nuclear power use. Additionally, bodies such as the European Union's Nuclear Energy Agency[52] or the US Nuclear Regulatory Commission[53] oversee the application and implementation of safety guidelines. In addition, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) came into force in 1970 and has 189 signatory countries committing to non-proliferation, disarmament and the right to peaceful use of nuclear energy.[54]

The US Congress, as well as European nations and others have additional legislation regulating nuclear power. After the Manhattan Project in the 1940s, the Atomic Energy Commission was created in the US to maintain civilian government control over the field of atomic research and development.[55] The US Nuclear Energy Act was modified in 1953 to allow private ownership of nuclear power plants, in effect declassifying the technology for the private sector and encouraging utilities to build nuclear power plants. In 1957, the Price-Anderson Nuclear Industries Indemnity Act was passed in Congress guaranteeing limits on liabilities for utilities operating nuclear power plants. In response to changing needs in the mid 1970's, the Atomic Energy Commission was abolished and the Energy Reorganization Act of 1974 created two new agencies: the Nuclear Regulatory Commission to regulate the nuclear power industry and the Energy Research and Development Administration to manage the nuclear weapon, naval reactor, and energy development programs. The Department of Energy was created in 1977 as a descendant of ERDA, and has since been a supporter of nuclear power offering research facilities at the national laboratories for development of nuclear technology, guaranteeing waste disposal for nuclear power plants and offering loan guarantees and financing for utilities wishing to build new plants.[56] Similar supports are in place in Sweden, France, Russia and recently, India and China, where the nuclear industry is heavily regulated, and subject to government policies.

III. Current Situation and Future Outlook

In the U.S. and the European Union, as well as in China, India and Russia, the Middle East and other parts of the world investment in research and in the nuclear fuel cycle has continued. Some experts predict that electricity shortages, fossil fuel price increases, global warming and heavy metal emissions from fossil fuel use, new technology such as passively safe plants, and national energy security will renew the demand for nuclear power plants.[57] Many countries remain active in developing nuclear power. Japan has an active nuclear construction program with new units brought on-line in 2005, and is working on developing both fast breeder reactors and thermal reactor technology, alongside China and India.[58] South Korea and the US are working on developing advanced thermal technology reactors; while South Africa and China are also currently developing versions of Gen III reactors.[59] Several EU member states (France, Slovakia, and Romania, among others) actively pursue nuclear programs, while other member states continue to have a ban on nuclear energy use (Denmark, Italy), yet use imported nuclear from member states which produce nuclear power[60] (see Appendix, Figure 8).

The UK in particular recognized that a likely future energy supply shortfall could be filled by either new nuclear plant construction or maintaining existing plants beyond their programmed lifetime in the context of the international climate change debate and the dependence on foreign imports.[61] Additionally, in late 20th, early 21st century, nuclear power is of particular interest to China and India as they experience rapid economic growth and a rising need for energy.[62] In the U.S., three consortia responded in 2004 to the U.S. Department of Energy's solicitation under the Nuclear Power 2010 Program and were all awarded matching funds for nuclear power development. The Bush Administration’s Energy Policy Act of 2005 awarded loan guarantees for up to six new reactors, and authorized the Department of Energy to build a reactor based on the Generation IV (Very-High-Temperature Reactor) concept to produce both electricity and hydrogen.[63] The Obama administration also seems committed to advance nuclear power in the United States thorough loan guarantees and continues support for first-movers in the space.[64]

A 2007 status report from the anti-nuclear European Greens claimed that, even if Finland

and France build a European Pressurized water Reactor (EPR), China started an additional 21 plants and Japan, Korea, Eastern Europe or the Middle East added more plants, the overall global trend for nuclear power capacity will most likely be downwards over the next two or three decades.[65] With long lead times of 10 years or more, it would be hard to increase or even maintain the number of operating nuclear power plants over the next 20 years, unless operating lifetimes are substantially increased beyond 40 years.[66] This point is supported by Charles Ferguson who, in a 2007 special report, points out the difficulty of ramping up nuclear power construction, given constraints for materials, qualified construction labor, manufacturing facilities and trained operators.[67] However, China plans to build more than 100 plants,[68] while in the US the licenses of almost half its reactors have already been extended to 60 years and plans to build more than 30 new ones are under consideration, as of 2010. [69] In a 2008 report, the International Atomic Energy Agency predicted nuclear power capacity could double by 2030, though that might not be enough to increase its share of electricity generation given the increasing world demand.[70]

As of January 2011, 31 countries were operating 442 nuclear power plants for power generation, representing an installed capacity of 375 Giga Watts and supplying about 15 percent of the world's total energy and about 19 percent of the world's electricity.[71] Sixty-five new power reactors were under construction in 11 countries at the beginning of 2011, amounting to 63 GW (see Appendix, Figure 13, 14 and 15 for current status and location of worldwide reactors).[72] New countries, traditional non-nuclear power users are adding capacity. Egypt, the United Arab Emirates and others are contracting with the US and South Korea for large and small plants. [73] At the same time, existing plants are expanding output. In the US, licenses to modify plants are being granted. By 2009 there were 5.8 GWe added, and under the new scenarios, if approved, by 2014 the US could have an additional 3.5 GW from upgrades to existing plants, the equivalent of 9-10 new large reactors cumulative, according to Paul Genoa (see Appendix, Figure 10).

However, nuclear has had a modest expansion track record in recent years. In 2008 there were no new reactors brought online worldwide, while in 2009 only two were added to the grid. 58 reactors are under construction worldwide (some with little activity), but only two reactors in Western Europe and one in the U.S. Currently, even solar and wind capacity are being added faster.[74] The world's largest nuclear construction program is in China, which might be a few percent of electricity supply by 2030 if targets for construction and deployment are met. However, the International Energy Agency World Energy Outlook 2010 "Current Policies" scenario projects no growth in nuclear share of electricity to 2035.[75] In fact, an Oxford Economics study on nuclear power released in 2008 claims that, without a substantial program of new investment, the capacity of the US nuclear energy industry will dwindle to zero by 2050. The specific jobs and associated value-added and tax benefits that industry would support would consequently likely also be lost, creating short and medium-term economic problems.[76] According to Paul Genoa at NEI, with no new plants built and the existing ones approaching retirement, there is a questionable future for nuclear power in the United States, but also abroad, where, besides China, there is not much push for new plants recently. According to a study by NEI, if no new plants are built and licenses are not extended on existing plants, the nuclear industry will scale back and the last plants' licenses will expire and be decommissioned by 2055[77] (see Appendix, Figures 11 and 12). This creates a problem if the industry is to survive.

The future is therefore uncertain for nuclear power. Demand for electricity demand has decreased in recent year (mainly due to the economic downturn of 2008), and, according to Stephen Maloney, capacity in the US right now is above demand (approx 89% of installed capacity), and is likely to remain that way for the next five years as economic growth is expected to remain sluggish around 1% per year. The slowdown is due to the economic crisis, but also to increases in energy efficiency. This means utilities will be less likely to invest in new plants in the near future, and, given the expensive capital costs of nuclear power today, even less likely to consider nuclear plants. This sentiment is shared by Henry Sokolski and Doug Koplow, who also do not see the economics of nuclear power adding up. In their opinion, there will be no new reactors built in the US in the next ten years, and, without government support, very few built internationally, halting nuclear expansion for the time being and likely in the future. In a 2008 Carnegie report, Sharon Squassoni also voices these concerns, stating that without government support nuclear does not have a "renaissance" in store, and it is questionable whether it even should, given safety, economic, waste and proliferation concerns.[78]

Even nuclear experts who believe nuclear is a good technology and should be part of the energy mix in the US and the world see nuclear power as growing modestly over the next few decades. Matthew Bunn acknowledges that the nuclear industry in its current format is unlikely to grow significantly to make an impact in the world's energy mix. He points to the need for institutional changes in policy. He also points out the need to make the industry safer, adopting measures to identify and remove unsafe reactors, decommission old reactors and design new regulations for safety approaches in newcomer states. However, with conditions changing, he anticipates anywhere from 25 to 40 or 50 new plants by 2050 being built. Mark Peters estimates five to 10 new large reactors being built in the US in the next decade, while Daniel Ingersoll, Rob Petroski and Charles Ferguson predict five to six. Michael Corradini estimates six to eight large reactors in the near future, while Richard Lester also sees a limited and modest future for nuclear power in the US and the world given the current market conditions. To further reinforce these views, Exelon, the largest utility operating nuclear power plants in the country indefinitely delayed plans to build a new nuclear reactor in Texas. [79] NRG Energy and UniStar have also delayed plans for new power plants in Texas and Maryland, respectively, despite loan guarantees from the federal government.[80] According to Bruce Hamilton, Richard Lester and Matthew Bunn, if the price of gas doesn't increase from $4-$5/million BTUs and the regulatory hurdles do not ease, nuclear will not have a significant expansion in the next few years.

The economic model tested this: at the current price for natural gas of $5.08/million BTUs[81], the price of gas-generated electricity should be 7.3 cents/kWh, while nuclear is 12.4 cents. However, if the price of natural gas were to go up to $8/million BTUs, the price of natural gas-produced electricity would be 9.8 cents, closer to the price of nuclear (see Appendix, Figure 16). Natural gas prices have been extremely volatile in the past four decades, with wellhead prices as low as $1.50 and as high as $14 / million BTUs[82] (see Appendix, Figure 18). Therefore at high prices, natural gas plants are less attractive, given the high cost of fuel. However, at a lower cost they become the first choice. The reason natural gas is so cheap today is the discoveries of shale gas in the Marcellus reservoir in the Northeast, and in other parts of the country (see Appendix, Figure 19). This leads experts like Bruce Hamilton and Henry Sokolski, as well as Stephen Maloney to assert that nuclear will be less competitive given these new discoveries and the resulting low price of natural gas.

Enforcing this point, the CEO of Exelon, John Rowe, has stated repeatedly, as recently as March, 2011, that if natural gas continues to be priced low, and in the absence of a carbon tax, despite past volatility in natural gas prices new nuclear will remain economically unfeasible due to its prohibitive capital costs, and natural gas plants will be built instead to meet growing electricity demand in Exelon areas.[83] The economic model also demonstrates this point. While nuclear has a cheap cost of production at around $0.059, and natural gas is higher, when a 12% return on investment requirement as added, natural gas at current operating prices would require 7.3 cents/kWh, while nuclear increases to 12.4 cents/kWh (see Appendix, Figure 20.) With a carbon tax of \$25/ton CO_2, the price of coal increases from 7.9 to 9.7 cents, while natural gas goes from 7.3 to 8 cents per kWh (see Appendix, Figure 20). However, with a carbon tax of \$200/ton CO_2, natural gas increases to 12.9 cents, while coal goes up to 21.5 cents, making nuclear, at 12.4 cents much more attractive and certainly more competitive (see Appendix, Figure 17).

From a regulatory standpoint, efforts are being made to streamline the licensing process and procedures, in order to encourage utilities to look at nuclear power. In the US, for example, according to Mike Snodderly, the combined licensing 10CFR52 provision, a 2002 initiative for one-step licensing in an effort to remove regulatory risk and better define the rules and processes needed to obtain a license for a nuclear power plant in the United States should simplify things. In addition, re-licensing, or extension of current licenses can take anywhere from two to three years, while license amendments could take up to one year. As Michael Snodderly indicates, license renewals are a safe way to prolong operation for safe nuclear power plants, based on identifying long-lived components, analyzing the pressure vessels, and only then allowing for continued operation. If power plants were not safe by NRC standards, they would be shut down. Incentives therefore exist from a regulatory perspective, but since the new regulatory procedure is relatively new, it remains untested and therefore regulatory risk remains high, according to James Joosten.

It is therefore apparent that nuclear energy constitutes an important source of energy and extensive attention is given to this issue by policymakers around the globe. Even though currently relatively small compared to conventional energy production, nuclear energy nonetheless plays an important role in electricity production throughout the world and has the potential to meet a larger portion of the world's energy demand.[84] According to the Energy Information Administration, by

2030 nuclear power could supply almost 20% of the world's energy, with continued support from the international community.[85] Similar predictions come from BP's World Energy Outlook 2030[86] and Exxon's 2011 Global Energy Analysis[87], and, though the energy giants' analyses put less emphasis on nuclear (around 16 – 18 percent of total production capacity), they do see a significant role for the technology in the next two decades. What appears to be generally agreed is that a "renaissance" in the current status quo is unlikely at the scale that nuclear proponents would like to suggest. Scenarios like Robert Bryce's N2N (natural gas to nuclear) solution, which assumes that the US and the world should continue on a path of expanding its natural gas capacity while transitioning to nuclear for the remainder for the world are unlikely to materialize unless major development occurs in the near future.[88]

IV. Advantages and Benefits of Nuclear Power

Based on the process of fission in a nuclear reactor, nuclear power has a very high energy density making it a very attractive source of energy. The decay of one Uranium-235 atom releases 200 MeV[89]. Compared to combustion of fossil fuels, fission requires a much smaller volume of fuel to produce the equivalent amount of energy. The energy released by the fission of 2 lbs. of uranium in a typical reactor is equivalent to that released by about 90,000 lbs. of wood, 44,000 lbs. of coal, 30,000 lbs. of oil and 28,000 lbs. of liquid natural gas.[90] Alternatively, powering a 100-Watt light bulb running continuously for a year (roughly 876 kWh) would require 876 lbs. of coal, 377 lbs. of natural gas, 508 lbs. of oil, but only 0.0007 lbs. of uranium.[91]

Additionally, in the past few decades, nuclear power plants have developed great reliability. Power plant reliability is measured by capacity factor—the percentage of electricity actually produced, compared to the total potential electricity that the plant is capable of producing. For example, Bruce Hamilton points out that the average capacity factor for U.S. nuclear plants was 91.8 percent in 2007, compared to coal at 71.8 percent, natural gas at a range of 16.6 to 43.3 percent depending on the type of plant, heavy oil steam turbine at 19.6 percent, hydro at 27.8 percent, wind at 30.4 percent, solar at 19.8 percent, and geothermal at 73.4 percent.[92] To be sure, Doug Koplow mentions that the measuring of capacity factor should occur from the moment the plant was supposed to be operational, which more often than not is not the actual time it opens (delays are common), but even with that capacity factor would be over 75%. Thus, using these measures, nuclear power plants are performing better than most of their fossil fuels and renewable energy counterparts and are an efficient and effective alternative energy source.

Capacity factors can be somewhat misleading because, while renewable sources are currently at maximum generating capacity due to constraints on availability of “fuel” (sun or wind), fossil fuel plants may sometimes be used in intermediate or peak load, which means that they are shut down deliberately for some of the time when there is no demand, in effect reducing their capacity factor. Since nuclear is expensive to build, it usually remains on unless it needs to be taken offline for refueling or maintenance.[93] However, even with that in mind, nuclear capacity factor is higher than its competitors, on average, giving it an advantage.

Since there is no long-term large storage ability for electricity, there has to be an instantaneous demand response. There are of course large differences on hourly bases (peak usage hours) and seasonally (summer vs. winter). Hence there is a need for base load (electricity generation capacity that is always on, feeding the grid), intermediate load (capacity that is brought on in higher demand times) and peak load capacity, which is only needed during the highest periods of demand (i.e. summer afternoons, etc.)[94] Nuclear power provides that base load electricity. This is why it does not, or should not compete with renewable sources like solar and wind. While Amory Lovins, the director of the Rocky Mountain Institute claims that nuclear does not have a future due to solar and wind. Robert Bryce disagrees. He claims that solar and wind, while worth pursuing, cannot provide baseload power and only generate peak power sporadically.[95] He points to the case of Denmark, which, despite having 20% of its installed electricity capacity in wind generation, is forced to sell wind off peak at under-cost rates, and import nuclear and hydropower from Sweden at higher prices when the 30% capacity factor wind is not producing needed baseload electricity.[96] This means nuclear is a constant source of electricity, and its competitors are coal and gas, not renewables. Experts also agree. Mark Peters, Daniel Ingersoll and Rob Petroski agree that the US should pursue a portfolio with nuclear and renewables concomitantly. Doug Koplow concurs, adding that subsidies for renewable are almost as high as for nuclear, making them also problematic and less desirable.

Most importantly, especially in today's climate change context, nuclear energy is attractive due to its environmental benefits of zero emissions during operation and lower emissions during its entire life cycle (see Appendix, Figure 24). Waste management and safety concerns set aside, nuclear power is more desirable, from an environmental point of view, than conventional energy production methods or even alternative energy forms such as hydroelectric, wind or solar power, including the manufacturing process.[97] Nuclear energy is the world's largest source of emission-free energy, since it produces no controlled air pollutants, such as sulfur and particulates, or greenhouse gases, preventing ground-level ozone formation and acid rain.[98] For example, coal emits 1041 tons of CO_2 per GWh produced, natural gas emits 622 tons, solar 39 tons, hydro 18 tons, nuclear 17 tons and wind 14 tons of CO_2 (see Appendix, Figure 22). In fact, Pacala and Socolow, in their influential work on reducing carbon emissions published in 2004, in which they argue that reduction and stabilization of CO_2 in the atmosphere to 450 parts per million can only be achieved by a combination of measures (wedges), include nuclear as one of the options for wedges.[99] Matthew Bunn however claims that nuclear power should expand by more than 40 or 50 plants by 2050 in order to be a credible wedge in the Pacala and Socolow solution.

In addition to CO_2, nuclear plants prevent other kinds of dangerous emissions from fossil fuels. Coal-fired power plants produce 13 pounds of sulfur dioxide and six pounds of nitrogen oxide per MWh, oil emits four and 12 pounds respectively, natural gas puts out 1.7 and 0.1 pounds and nuclear has zero emissions of both[100] (see Appendix, Figure 23). James Joosten points to several studies by the US Geological Survey and Alex Gabbard that draw attention to the dangerous emissions of coal plants. For example, in 2006, U.S. nuclear power plants prevented 3.43 million tons of sulfur dioxide, 1.11 million tons of nitrogen oxide, and 696.6 million metric tons of carbon dioxide from entering the earth's atmosphere. [101, 102] Additionally, the NO_x emissions avoided by U.S. nuclear power plants are equivalent to the NO_x emissions from approximately 58 million passenger cars (43 percent of the U.S. total). The carbon dioxide emissions avoided by U.S. nuclear power plants are equivalent to the carbon dioxide emissions from approximately 134 million passenger cars. Nuclear power plants accounted for more than a third of the total voluntary reductions in greenhouse gas emissions reported by U.S. companies in 2003, according to the Energy Information Administration (EIA).[103] Emissions reductions from nuclear energy usage amounted to122 million metric tons of CO_2, 37 percent of the 332 million metric tons of total CO_2 reductions reported.[104]

Nuclear power plants offer a compelling safety record to date. Public radiation exposure, dangerous to humans due to its carcinogenic and genetic malformations results (the largest reason for concern regarding nuclear power generation), is minimal for nuclear power plants. In fact, a coal-fired power plant releases more radiation into the atmosphere than a properly functioning nuclear power plant due to the radioactive materials contained in the coal. This material is burned and released in the atmosphere, whereas a nuclear plant exchanges no radioactive material with the outside environment in normal operation conditions.[105] In a study from the early 1990s, Peter Hogson showed that nuclear power is second lowest only to natural gas in average number of deaths per 1000MW of energy produced, well below coal, oil, wood, wind or hydroelectric alternatives.[106] In a recent NPR talk show on November 9, 2010, Diane Rehm discussed nuclear safety and public perception following of the temporary closure of the Vermont Power and Indian Point Unit 2 plants. Both experts present on the show and the public calling in were optimistic that the safety of power plants is not a major concern.[107]

In her book *Power to Save the* World, Gwyneth Cravens talks about “Fencepost Man”, an individual who lives, eats, breathes, and does not go outside an operating area of a nuclear power plant under normal operating conditions. Even in that situation, the radiation that he/she would receive (measured exposure in milirems) is insignificant compared to background levels. Radiation is one of the phenomena less understood in everyday life, and nuclear plants, in normal operating conditions, are not more dangerous than an X-Ray machine, or even natural sources.[108]

Robert Bryce, in *Power Hungry*, and William Tucker, in *Terrestrial Power* also mention that argument.[109,110] A normal functioning nuclear power plant is not a threat, in terms of radiation or safety concerns for the surrounding public. Mark Peters also mentions that the safety record is excellent for nuclear plants in the US and that a lot of improvements have been made by industry, researchers and regulators in recent decades; if the record is maintained, the industry is on the right track. Daniel Ingersoll and Michael Corradini support that point, adding that safety has been improved over the years; nuclear might have other problems, political or economic, but safety of operation is not one of them. Nuclear power is safer than a coal power plant with regards to radiation emitted yearly.[111] The industry should continue to improve safety, but according to nuclear experts interviewed, they are in a good place. It is also worth noting, as Paolo Ferroni and Matthew Bunn mention, that a nuclear accident anywhere would be devastating for the industry, and so there is a concerted effort to improve and maintain safety, particularly after Fukushima.

Public acceptance also appears to be growing in recent years. This is indicated by Cravens and Bryce, but also by market research studies.[112] People living around nuclear power plants tend to support the industry and new reactors more than those who do not. According to a March 2009 study by Bisconti Research commissioned by the Nuclear Energy Institute, from a sample of 1000 participants, 70% favor nuclear energy; a follow-up survey of 1,152 people living within a 10 mile radius of an existing reactor found that 84% favor nuclear energy, 90% have a favorable impression of the nearby plant and 76% would find a new reactor acceptable at the nearby plant.[113] While this study fails to assess the NIMBY attitude and opinions of people not living near a power plants, and therefore public acceptance of nuclear power at large, it is a strong indication that people living near power plants accept them and in fact increasingly view them favorably.

From a manufacturing and operating perspective, if compared directly to the production costs of other forms of energy, nuclear power is relatively inexpensive to produce and therefore attractive to utilities once the capital costs are laid in for the operating life of 40-60 years (see Appendix, Figure 21). According to the model, nuclear production costs are 5.9 cents/kWh, while for coal they are 7.4 cents, for gas they are 9.2 cents, and wind comes to 13 cents, while solar is at 15 cents per kWh (see Appendix, Figure 21).

According to the model, fixed and variable O&M costs, including fuel, are 1.2 cents/kWh, while for coal they are 2.2 cents and gas is 2.8 cents per kWh. For solar, those costs are 1.7 cents, while for wind they are 2 cents (see Appendix, Figure 20). Therefore operating costs for nuclear are about 15% of total cost, including operating and support staff, training, security, health, safety and management. They also include conversion, enrichment, fuel fabrication and back-end activities costs.[114] Uranium fuel costs are under 2% of total operating costs, as uranium reserves are abundant around the globe[115], though environmental and health concerns associated with extracting and processing uranium remain. Thus, nuclear power has potential to compete with conventional power sources, as well as with renewable alternatives, on an operation, management and fuel production basis.[116]

Most other experts interviewed also agree with the benefits of nuclear power. Mark Peters, Daniel Ingersoll, Bruce Hamilton, Michael Corradini and James Joosten support the industry and its future expansion. Rob Petroski and Paolo Ferroni also believe nuclear is safe and can address the climate change concern, albeit at the higher cost. Stephen Maloney indicates that nuclear is a mature technology that engineers and utilities know how to operate (especially the LWR reactors, which the US has operated without incident on nuclear Navy ships for 50 years). Even skeptics, like Doug Koplow admit there are benefits from using nuclear power over fossil fueled generating plants, though the economics do not play out in nuclear's favor. Currently, according to the model, the cost per kWh for nuclear required to provide a 12% IRR is 12.4 cents while coal is around 7.9 cents and natural gas is at 7.3 cents (see Appendix, Figure 20).

A resurgence of nuclear power in the US and worldwide could also carry socio-economic benefits. A ramp-up in production would mean the addition of jobs, manufacturing facilities, training and education, security services, and would create small economies around power plants. In a study in the *Energy Law Journal*, Roland Frye mentions the "renaissance" of nuclear power (large scale plants) could add jobs and manufacturing facilities boosting the economy.[117] The American Council on Global Nuclear Competitiveness issued a report in 2008 predicting that new U.S. reactor construction could create 350,000 jobs in the next twenty years. The report assumes that construction will begin on 33 reactors by 2021, and another 20 by 2025, and also assumes the construction of four uranium enrichment plants and a reprocessing plant. [118] A 2008 Oxford Economics study reinforces those findings, and adds that value-added of nuclear power expansion would amount to $45 billion.[119] In addition, Jim Snyder speaks about the creation of permanent and temporary jobs. Permanent jobs would be in the thousands after training and qualifications, and would be high paying. In an economy that is struggling to rebound after the worst financial crisis since the Great Depression, nuclear poses a significant economic benefit.

While these arguments are attractive, one has to also keep in mind there is an opportunity cost of creating jobs in the nuclear industry, as the capital invested in nuclear expansion could produce greater economic benefits someplace else.[120] The job argument could stand on its own only if there were no government subsidies involved (of which there are many, discussed in the next section). Since there is no concrete way to examine that alternative, the economic argument should not be strongly relied upon, but should nonetheless be mentioned for consideration.

V. Costs and Concerns with Nuclear Power

Nuclear power also has significant costs and concerns that may offset its numerous benefits. Doug Koplow mentions the subsidies that are hidden in nuclear power generation; Henry Sokolski points out, beyond economics concerns, to the proliferation dangers, as does Sharon Squassoni; John Banks mentions the security aspects of nuclear power. Even supporters like James Joosten, Steve Maloney, Paul Genoa or Mark Peters acknowledge the high costs of nuclear as being a major concern. Nuclear power has open and hidden costs associated with its production. These costs must also be taken into account as they may outweigh benefits and prevent its widespread implementation as the alternative source of energy.

Economics is the first hurdle for nuclear expansion. Stephen Maloney asserts nuclear is just too expensive. He compares it with a Lamborghini – a marvel of technology with a price tag to match. And while everybody wants one, few can afford it. When utilities make a decision to build a new plant, there are several options available, and nuclear is currently not one of them. It costs between four and six billion dollars to build a new reactor, while the capital costs of coal or gas are much lower, even though operating costs are higher. According to the model, nuclear capital costs are 11 billion for a two-reactor Gen III plant generating 2.2GW, at a cost of $5,300/kW. To compare, coal stands at $2,800 per kW and natural gas comes to $1000 per kW. When accounting for the fact that most utilities in the US do not have the capitalization necessary to support one of these projects, much less several, the balance tips significantly against nuclear power. The initial capital investment requires land, planning, construction and licensing fees, and amounts to about 80% of all costs.[121] For a cost of financing of 10%, nuclear capital cost per year are around 87%, while for natural gas and coal they are 48%. Renewables come in closer, with solar at 85% and wind at 87%, but nuclear is still the largest expense capital-wise.

Rob Petroski, Paolo Ferroni and Mark Kirshe all point to the expensive capital costs, while Mark Peters and Daniel Ingersoll, together with Kelly Sims Gallagher, Richard Lester, Matthew Bunn and Michael Corradini see the high capital costs of nuclear as a serious impediment to its development and resurgence in coming years. According to James Joosten and John Banks, due to the large capital costs of large nuclear plants, utilities in deregulated markets (where cost of capital build-up cannot be charged to the consumer until the unit comes online) will never invest in nuclear at the current cost, while utilities in regulated markets might consider it. This may perhaps be an unintended consequence of deregulating electricity markets, taking away any incentive to invest in nuclear. The current track record however demonstrates that even utilities in regulated markets are reluctant to invest in nuclear. Mark Kirshe takes this point further. He indicates that the large investor-owned utilities are the likely candidates to invest in nuclear, but at the current cost and with other alternatives available, this will likely not happen.

The 2009 MIT study on the costs of nuclear power supports these empirical findings. The study, which updated the figures released in 2003, finds that if in 2003 base overnight cost was $2,000/kW, denominated in 2002 dollars, today overnight costs are around $4,500/kW, denominated in 2007 dollars. And while the overnight cost of building coal- and gas-fired plants has also increased, the raise is not as dramatic as nuclear. In 2003 overnight cost for a coal-fired plant was $1,300/kW, denominated in 2002 dollars, while today it is around $2,300/kW. For gas, it increased from $500/kW, denominated in 2002 dollars to $850/kW.[122]

James Joosten also points out that other plants capital cost have increased, but nuclear comes at a premium (see Appendix, Figure 25).This means that nuclear has gone up in cost in recent years by almost 100%, while gas and coal, the main competitors, have only increased by 77% and 70% respectively. Incorporating all cost elements, the levelized cost of electricity (the dollar cost per kilowatt-hour that must be charged over time in order to pay for the total cost) from nuclear power is 8.4¢/kWh, denominated in 2007 dollars. The levelized cost of electricity from coal at a cost of capital of 5% is 6.2¢/kWh, denominated in 2007 dollars, while gas is 6.5¢/kWh.[123] It is worth noting that in the MIT study, adding a $25/tCO_2$ charge to coal and gas-fired power raises the levelized cost of electricity from coal to 8.3¢/kWh and the levelized cost of electricity from gas to 7.4¢/kWh.[124]

The assumption here is that the cost of capital is 5%, but this is rarely the case.[125] According to the model, the levelized cost of electricity at 10% cost of financing required to cover an investment rate of return of 12% is 7.9 cents for coal, 7.3 cents for natural gas and 12.4 cents for nuclear. This means that nuclear is not competitive with conventional sources without support.

While it is more appealing than renewables (wind is 26 cents while solar is 33 cents before any subsidies), it still is not justified from a business perspective.

This happens mainly because, since investments must be financed and incur significant interest charges, debt service becomes part of the cost of electricity generation and is passed to the consumer (see Appendix, Figure 26) [126]. The model assumed 70% leverage and a cost of borrowing of 10%. While for coal and natural gas the time to complete a power plant is 2-3 years, for nuclear it is around 7-8 years, making it more expensive with each year it requires more financing without producing any electricity. And while the repayment period was levelized at 20 years for all generating sources, the fact that nuclear does not produce anything until year eight makes the economic case a tough one to make for any utility.

When adding that NRC licensing, according to Mike Snodderly, can take anywhere from two to three years for a new reactor, and there are usually delays in the project, building a new plant can take up to seven or eight years, which increases financing costs. According to the model, as the borrowing rate is 10%, if the plant was built in 4 years the cost would be 9 cents, but with eight years (assuming regulatory delays), the cost increases to 12.4 cents/kWh. In the additional scenario of overruns and delays, this becomes even more problematic. A Congressional Budget Office 2008 study on the role of nuclear power in generating electricity compared US utilities' projections of average overnight costs with actual overnight costs of 75 reactors built between 1966 and 1977. The average overrun was 207 percent, and in some cases exceeded 250 percent.[127] This does not create a good economic argument for a utility considering nuclear.

Furthermore, nuclear power plants are required to set aside provisions for decommissioning, involving shutdown of the plant, management of radioactive waste until disposal and disassembly of the plant. According to a 2003 study by the Nuclear Energy Agency

(NEA) in Europe and the US, the cost of decommissioning a light water reactor is about US$500/kWe and significantly higher, US$2500/kWe, for gas-cooled reactors.[128] While the costs associated with decommissioning are not extreme, they are a major component of the cost of nuclear energy. As Daniel Ingersoll points out, however, the costs of decommissioning are set aside in a trust by the operators, so no additional subsidies or tax dollars are used in the process. Stephen Maloney, who has experience in plant acquisitions, mentions that decommissioning trusts are in fact some of the selling points for nuclear plants. Since decommissioning costs may be lower than the amount in the trust, utilities may benefit from the amount in the trust when purchasing existing plants. Stephen Maloney indicated that recently there has been consolidation in the industry, with large utilities like Exelon buying plants, in part due to the trusts available.

This large initial investment has an amortization period of 25-30 years, according to Stephen Maloney. Given the average 40 year lifetime of a nuclear plant, this expense significantly reduces the advantage given by the low costs of operation, maintenance and fuel. Extended operating lives for power plants can allow for increased returns toward the end of the lifetime, but overall it is obvious why the prospect of large nuclear is unattractive. A case can be made for utilities in regulated markets, which are able to charge customers while the plant is being built in order to recover costs faster, something that is not available to utilities in deregulated markets, according to John Banks, Paul Genoa and Charles Ferguson.

If considering the full array of economic costs involved in building, operating and decommissioning a nuclear power plant described above, it can be argued that nuclear power plants today are prohibitive to build. Bruce Hamilton states that, because of the NRC's and public concern with nuclear power, additional safety systems that are redundant and likely not needed are built into a nuclear power plant. Consequently, even if nuclear power today is safe, given the NRC requirements, a utility can either have compliant nuclear power or cheap nuclear power, but it would be hard to achieve both. There are many regulatory guidelines in place requiring many redundant safety systems taking the cost of nuclear power higher that it should be, and therefore making it prohibitive. While R&D costs are also significant and will need to be amortized in the cost of nuclear energy, simplifying designs might help in the near to medium future at reducing construction costs, making nuclear power plants economically attractive. According to the model, if overnight costs were reduced from $5,300/kW to $3,000 per kW, the levelized cost of electricity would decrease to 7.6 cents per kWh, which would make nuclear more attractive.

Another set of costs often overlooked by nuclear energy advocates is that of regulation, liability and subsidies. While some of these costs are not incurred by the power plant directly, they are somehow passed on to the consumer or the taxpayer, thus increasing the cost of nuclear energy. Doug Koplow and Henry Sokolski emphasize this point, affirming that, if nuclear was to be stripped of all the subsidies and loan guarantees, it could not compete in the energy market. This is an argument that Amory Lovins, director of the Rocky Mountain Institute makes often in his anti-nuclear campaign. If nuclear could compete from an economic standpoint with the other sources of energy (conventional and renewable) without subsidies, then its adoption would be easier.[129] As the model shows, currently that is not the case, meaning that there are significant subsidies involved in nuclear power allowing it to stay competitive (for existing plants at least).

From a regulation and licensing perspective, obtaining the permit to build and operate a nuclear power plant can be a lengthy, complicated and costly process. In the US for example (and the rest of the world has similar requirements) a utility wishing to build and operate a nuclear power plant has to apply to the Nuclear Regulatory Commission (NRC) in several stages. First they need to obtain a construction permit and safety permit, then they need to obtain an operating license and after the facility is built and functional, they need to agree to constant monitoring, testing and scrutiny from the NRC.[130] This process, while useful from a safety perspective, can take up to several years, and can cost a significant amount, since the NRC is a fee-based organization, with estimates of around $200 per hour for staff time, according to Charles Ferguson. Currently, in the US there are 30 outstanding applications for new reactors, awaiting review by the NRC.[131] Beginning in 2002, the process was streamlined and all the licenses can be obtained in one application.[132] However, as Stephen Maloney and Bruce Hamilton point out, the pre-approval process is not going to change things dramatically; until the design is proven and functioning, the regulatory process is still a lengthy and burdensome cost to the industry. Mark Kirshe additionally points to the fact that in the US only 35 utilities are licensed to run nuclear plants, and they fund 90% of the NRC budget. Additional utilities may come into play, but the field is rather limited and the process unlikely to change in the near future.

Bruce Hamilton also indicates another cost of the regulatory process. In the US, the NRC is a somewhat independent body, whose charter is safety, but who does not take into account the balance between safety and risk. In fact, this is a political view of safety, without consideration for cost and risk assessment. This means safety needs to be achieved at all costs, without an acceptable risk level (similar to the auto industry, the airline industry, etc.) The only way power plants can operate is if they fulfill the requirements of the NRC, which leads to over-engineering and overly redundant systems, making nuclear more expensive than it should be, if an acceptable risk level was factored in. In other countries, including France, China and Russia, the government controls the regulators, which leads to fewer burdens on the industry.

Insurance and liability also affect the costs of nuclear power making it almost prohibitive for operators. Given the perceived hazardous nature of the nuclear process, nuclear power plants are required to insure against nuclear accidents. Under IAEA provisions, the operator of a nuclear power plant is both strictly and exclusively liable for nuclear damages suffered by third parties as a result of nuclear accident.[133] No private insurance company can afford to completely insure a nuclear power plant. This is why a “pool” of private companies guarantees insurance in some cases, charging a large premium that is passed to consumers through energy prices. This premium does not apply to conventional energy sources. However, even insurance companies pools cannot always provide the necessary funds to insure nuclear power plants.[134] As a result, in many countries (especially those that rely on electricity production from nuclear power for more than a quarter of their total) governments limit the liability of operators by providing public insurance that would otherwise be unavailable or too expensive to purchase. This is a direct cost to taxpayers meant to sustain the operation of a nuclear power plant despite insurance requirement. While the risk of an accident is low, it is certainly not zero, and policymakers have to assess the viability of providing public insurance to nuclear companies, funded by taxpayers.

In the US for example, the Price-Anderson Act of 1957 provides for payment of public liability in the event of a nuclear incident from government funds, in the amount of $9.5 billion of coverage.[135] The act requires nuclear power plant operators to buy all the nuclear liability insurance that is available from private companies or provide an equal amount of financial protection (currently $200 million). For the rest, the power plant operators are assessed up to $88 million for each incident that exceeds private insurance.[136] Hence, while allowing nuclear power plants to operate, the Price-Anderson Act provides public funds for their insurance, thus making taxpayers liable in case of a nuclear disaster.[137] As part of the Energy Policy Act signed by President Bush on August 8th, 2005, Congress extended the Price-Anderson Act to cover private and DOE operated plants and activities (i.e. transport of nuclear waste) until 2025.[138] However, these recent developments in nuclear power legislation are a two-edged sword. On the one hand, without the act nuclear power plants would be unable to insure against disaster and would not be able to operate and produce energy at an acceptable price for consumers. On the other hand, with its provisions, taxpayers are held liable for potential accidents and must pay a premium.[139]

Nuclear power also holds hidden costs to taxpayers and consumers in the form of government subsidies. In order to encourage nuclear power production and make it competitive with conventional energy sources, governments give production tax credits to utilities and cover some licensing costs. According to the model, the current levelized cost of nuclear is 14.9 cents per kWh, while the rate in the market is on average, for all sectors, 9.51 cents per kWh.[140] This indicates that there is some subsidy to keep nuclear at an acceptable level. As in the case of government-provided insurance, this is a significant cost, because even if the price of nuclear power is lower due to the subsidy, as taxpayers, customers do not gain much from the price competitiveness of nuclear power. A good example is again the US Energy Policy Act of 2005. According to its provisions, a production tax credit of 1.8 cents per kilowatt-hour is given for the first 6,000 megawatt-hours from new nuclear power plants for the first eight years of their operation, subject to a $125 million annual limit.[141] Additionally, according to the legislation, the government covers cost overruns due to delays caused by regulations (which as discussed above are primary causes of the high cost of some plants) up to $500 million each for the first two new nuclear reactors, and half of the overruns due to delays (up to $250 million each) for the next four reactors.[142] Hence, while lowering the cost of nuclear power, legislation creates a vicious circle where citizens benefit as customers but incur costs as taxpayers, causing equity issues.

Nuclear power also imposes a significant potential social cost on the world. The only two nuclear accidents that occurred in the history of civilian nuclear power generation have demonstrated the possible devastating consequences of nuclear power and have negatively shaped public perception. The Three Mile Island is the first noteworthy accident. On March 28th 1979, Reactor Two from the Three Mile Island nuclear power plant in Pennsylvania leaked radioactive material into the environment over a radius of 30 miles following a malfunction in the feed-water system.[143] Although no explosion occurred, the reactor core melted and the environmental impact due to radiation leakage was measurable, as was the damage to the reactor itself, though some experts and review after 30 years point to the fact that the impact was perhaps smaller than initially believed.[144] So far approximately $70 million have been paid in claims and legal transaction costs while $1.5 billion constituted the investment loss from the accident.[145]

The Chernobyl disaster, synonymous with nuclear power catastrophe, was the second nuclear incident to date and has created large public opposition to nuclear power, causing countries like Italy, Austria and Switzerland to cease their nuclear programs.[146] The accident occurred at the Ukrainian nuclear facility of Chernobyl in 1986 on a Russian RBMK gas-cooled reactor and was caused by poor reactor design and human error. The reactor exploded, releasing nuclear waste and fission products into the atmosphere. The result was catastrophic, as wind patterns carried the radioactive waste thousands of miles away, affecting countries in Europe and Asia. Thousands were exposed to radiation, which resulted in cancer, malformations and deaths. Scientists claim that the radiation released at Chernobyl was 200 times more than was released at Hiroshima and Nagasaki together.[147] Even though the explosion was caused by poor safety features that have since been corrected, Chernobyl confirmed just how devastating a civil nuclear disaster can be.

Nuclear power is also problematic due to the radioactive waste it creates in the fission process. The clean operation of nuclear power plants in energy production is partially offset by the potential environmental costs of radioactive waste. Aside from the economic costs (transport and storage of used radioactive fuel and fission products) nuclear power operators have to ensure long term storage for nuclear waste in a way that does not affect the environment or society.[148] In the past two decades the U.S. government has spent over $6 billion to develop an underground storage repository at Yucca Mountain, about 100 miles from Las Vegas. The project was recently canceled by the Obama administration due to concerns over whether the mountain is dry enough to prevent waste containers from eroding. [149] Mark Peters, who has worked on Yucca Mountain, believes the repository would work well, as does Michael Corradini, who claims the project was not a technological, but rather a political issue, especially given that the current Senate Majority Leader, Harry Reid, is from Nevada, where his constituents oppose the project. Robert Bryce, William Tucker and Gwyneth Cravens also elaborate that point in their books. From their conversations with experts and visits to Yucca Mountain, the process was likely abandoned for political, rather than technical reasons.[150] Currently, there is a Blue Ribbon Commission, whose report is due in spring 2011, to identify potential other sites for a US repository.[151]

In the US, an additional subsidy and cost to taxpayer is the DOE's commitment to take the waste from commercial operators for permanent storage. While currently waste is stored in pools on site, and the issue is not pressing, according to Mark Peters and Daniel Ingersoll, a permanent solution needs to be reached in the medium future. Utilities are suing the federal government over its failure to handle and dispose of the waste, a guarantee that is costing taxpayers more money. It must be noted that recent technological advances in Gen III and IV reactors, as well as dismantling nuclear warheads for energy production through the Megatons for Megawatts program, which has already eliminated the equivalent of 13,000 warheads, may solve part of the radioactive waste problems.[152] Concretely, more and more of the 30 new nuclear power plants in the US (and worldwide) are Gen III, passive systems that reuse the waste.[153] France and other countries are already exploring the opportunity of reusing radioactive waste and depositing the products of the nuclear reaction in accessible places for potential future reuse.[154]

Lastly, nuclear power poses a large national security threat, as well as significant foreign policy complications. From a security and safety perspective, nuclear power is a concern, especially in the wake of 9/11 and increased terrorist threats. According to Roger Howsley, security at power plants in the US is adequate and the construction and safeguards in place at US reactors are fail-safe. In *Power to Save the World*, Gwyneth Cravens describes her visit to the McGuire nuclear plant in North Carolina, and notes that it is one of the most secure facilities imaginable. Attacks by air, bombs (short of a hydrogen bomb), truck or armed assaults would not be able to destabilize or penetrate the concrete structure or containment vessel of a power plant.[155] The situation is more problematic in the rest of the world. In some European countries there are no armed guards, and a 2007 event in South Africa, where hostile forces penetrated the defenses and reached the control room of a nuclear plant in Pelindaba raised awareness of those vulnerabilities.[156] Roger Howsley maintains that security at power plants is something that should not be of concern, but the issue remains.

Nuclear power can be a powerful weapon in the hands of terrorist groups, and the adoption of nuclear power worldwide could provide them with more opportunities to obtain the fuel needed for weapons creation. Roger Howsley mentions that a nuclear rod is heavy and could not easily be transported out of a power plant. He claims IAEA regulations and inspectors could not miss such a diversion of material. However, as new states gear up for nuclear power, especially in the Middle East (UAE), those concerns are legitimate and serious. Charles Ferguson, in a report while with the Council of Foreign Relations points out this threat and the necessity of better controls and safeguards against non-proliferation.[157] In addition, countries with nuclear aspirations, like North

Korea and Iran, among others, could protest the expansion of nuclear power without their participation and may demand assistance with development of power plants, which would cause significant foreign policy and diplomatic complications. Sharon Squassoni is also cautioning against which states receive nuclear power plants and technology, pointing to the recent unrest in the Middle East, as well as safety and security concerns at home, where some of the older reactors may be more vulnerable from a security standpoint.

To conclude, civilian nuclear power has been around for over 50 years, but despite significant growth in the 1960s and 1970s, it is currently slow and sluggish, and plagued with issues that appear to hold it in a status quo situation. The benefits are clear, but the costs, as indicated by the model, by literature and by the experts appear to be higher and pose a great level of uncertainty. While nuclear can compete with renewable energy sources like wind and solar (almost half the price for electricity required to reach a 12% return on 10% financing costs), it cannot currently, in the absence of a carbon tax or higher prices for natural gas, with conventional plants. Therefore, the case for nuclear is more difficult to make than proponents would indicate.

Part Two – Small Modular Reactors

In recent years there has been a renewed interest, both private and public according to Matthew Bunn, in Small Modular Reactors (SMRs). Some of them are new concepts and technologies, like the Hyperion or Toshiba 4S reactors, or existing technologies scaled down from large PWR or LWR reactors, like the NuScale or mPower. In the eyes of some experts and proponents of nuclear power, these new designs and new approach from the industry could change the playing field and help promote a resurgence of nuclear power not just in the United States, but worldwide, opening the field to countries that were thus far not considering nuclear for economic or capacity reasons. SMRs could, in theory, help promote nuclear power and give it the jump start that has been talked about for decades in the US and other nuclear states. In order to understand SMRs, and arguments for and against them, this section will describe the technology, look at current models and regulatory and political environment on SMRs and analyze them from benefits and costs perspectives.

I. History, Background and Current Situation

Since the 1950s, the size of reactor units has grown from a few MWe to more than 1600 MWe, with corresponding economies of scale in operation.[158] At the same time there have been many smaller power reactors built both for naval use (up to 190 MWt) and as neutron sources, yielding expertise in the engineering of small units. The International Atomic Energy Agency (IAEA) defines "small" as under 300 MWe.[159] However, there is another characteristic for small modular reactors: they are modular, meaning that they can work individually, or as part of an array, as modules of a larger unit producing larger amounts of power. There is an inherent advantage in this system as the initial capital cost required for a power plant changes, based on the size of the reactors, and utilities could add new capacity when and if they feel it necessary, not having to commit funds for a large reactor like they have to do today (incremental cost).[160]

SMRs can be built in factories offsite and shipped to their destination via truck or boat.[161] For some of the proposed models, they can be buried underground and not accessed again until the fuel cycle has ended, some claim between 30-50 years. Others have longer cycles between refueling (18-36 months) than large water reactors.[162] Being smaller, these units would have fewer redundant systems, and their operation and components would be simplified leading to lower costs for operation and deployment. Some may need to use higher enriched fuel, while others would operate like normal reactors on a smaller scale, according to Sharon Squassoni.

There are currently of two types of SMRs: first-to market LWR reactors with a timeframe of coming online of five to 10 years, or advanced, non-LWR designs which have a longer timeframe of coming to market of 10-25+ years.[163] None are currently licensed, though applications are currently being discussed and, in the case of some reactors, are close to being filed with the NRC, as Mike Snodderly mentions. Others are looking at SMRs as well. Russia, for example, has explored SMRs on ice-breakers in the Baltic for decades, and has a unit, the Akademik Lomonosov which has already been launched in 2010 with anticipated deployment after commissioning by 2012, and others in the works.[164] China, India and South Korea are also looking at the technology not only for domestic use, but for international exports and building a new industry market.[165] For example, China has already exported small and medium power reactors. In 1991, China began building a reactor in Pakistan and started constructing a second reactor there in 2005.[166] While the French and the Japanese are still not committed to SMRs, the interest in SMRs is growing around the world, some of the technology is rather familiar and some argue trusted, and the future of the nuclear industry may be influenced by these reactors.[167]

SMRs are not a new concept, at least not for the scaled-down version of the LWR and

PWR reactors, according to Daniel Ingersoll and Stephen Maloney. They have been in operation, with some modifications, in the nuclear navy for half a century, starting with Admiral Rickover, and continuing today in the nuclear navy of several states, and on ice-breakers and small remote sites in Siberia in Russia.[168] Interest in SMRs was relatively high in the 1950s, when the industry was in its incipient phases, but when larger plants were designed and the technology demonstrated for civilian use, they were abandoned and the economies of scale of larger plants, once built, were more appealing to the industry. There has been interest in SMRs in the 1980s and 1990s, especially at national laboratories, as Daniel Ingersoll and Mark Peters indicate, but the push for SMRs has only recently come into focus due to increased DOE interest and growing cost of larger plants. Given climate change arguments, and a general understanding nuclear power is going to play a role in the energy portfolio of the US and the rest of the world, SMRs became the focus of industry, regulators, and the public.

Until 2009, according to Richard Lester, the DOE paid little attention to SMRs. Although starting in 2000, the DOE funded research for the development of a small nuclear power plant for use in multiple applications through the Idaho National Environment & Engineering Laboratory (INEEL) and Oregon State University (OSU), there was no significant interest in the project given other priorities. Today there is renewed interest in the technology. While there are no models currently licensed and deployed, there are several promising prospects in the works.

Daniel Ingersoll estimates that with the current regulatory hurdles, we will have operating SMRs by 2020 in the LWR category. Rob Petroski also sees 2020 as the target for the LWR SMRs, but he is also confident a prototype of TerraPower reactor, whose fuel could be adapted into an SMR, might be available by then. Stephen Maloney predicts that, if nuclear power will expand, it will be through SMRs and not large plants, though he is skeptical that many will be built by 2020. Mark Peters sees the best case scenario of operation by 2020, while Luisa Chiesa acknowledges the unresolved concerns with SMRs can push back wide-spread deployment to 2020 or later. Michael Corradini is more optimistic: the most promising LWR designs that are up for review by the NRC in 2011 or 2012 could be constructed and operational by 2015 or 2016. On the other hand, The International Atomic Energy Agency (IAEA) estimates that by 2030 at least 40 (and possibly more than 90) small reactors will be in operation. It believes more than half the countries that will build nuclear plants will choose these smaller, simpler designs.[169]

Therefore, interest in SMRs exists. Numerous studies have been published about the benefits (economic, technological and environmental of SMRs) that are discussed below, and experts generally agree that SMRs are a promising technology. Nonetheless, there are many answers about SMRs that are yet unknown, and, until there are some prototypes and test models built and demonstrated, there is a lot of speculation about how SMRs will perform, whether they make sense economically and whether they have the potential to take over, or at least complement the existing nuclear industry.[170]

II. Promising Models

SMRs have garnered significant attention in recent years, with companies of all sizes investing in these smaller, more cost-efficient nuclear reactors. Utilities are forming partnerships with reactor designers to prepare for potential future construction. While there are many different models and concepts being advanced in the US and abroad, it is important to differentiate the feasible models (ones that have the potential for deployment in the next decade or so) from the more "exotic" models that are in the concept phases. This review of the models under review by the NRC or other regulatory bodies will help narrow down the field. The list is compiled not in alphabetical order, but based on the NRC ranking and expert opinions on what models offer the most promising designs and manufacturing timeframes (see Appendix for Reactor Matrix summarizing these findings).

a. NuScale Reactor

NuScale Power is a private start-up formed to design, build and sell a dedicated design of relatively small (160 MWt, 45 MWe) nuclear modular reactors, claimed to be inexpensive, inherently safe, and proliferation-resistant. The company claims these reactors could be used for heat generation, production of electricity, and other purposes, including desalinization.[171] The basic design is based on the MASLWR (Multi-Application Small Light Water Reactor) developed at Oregon State University in the early 2000s, in cooperation with the Idaho National Laboratory. Researchers from OSU who participated in the DOE program with INEEL continued to pursue the design of a small nuclear plant that used natural circulation. The team at OSU built a one-third scale electrically-heated version of their plant as a test facility for this design. OSU granted NuScale Power exclusive rights to the nuclear power plant design, as well as the continued use of the test facility, through a technology transfer agreement completed in 2007. NuScale notified the NRC in February 2008 of its intent to pursue design certification for its technology. The company is in the pre-application review phase with the NRC. It is on track to file its formal request for design certification in 2012.[172]

NuScale is an integral pressurized-water reactor (iPWR). It is a natural circulation light water reactor with the reactor core and helical coil steam generator located in a common reactor vessel in a cylindrical steel containment. The reactor vessel/containment module is submerged in water in the reactor building safety related pool. The reactor building is located below grade, and is designed to hold 12 SMRs. Each NuScale SMR has a rated thermal output of 160 MWt and electrical output of 45 MWe, yielding a total capacity of 540 MWe for 12 SMRs (See Appendix,

Figure 27).[173] According to the NRC, design certification application is expected in the 1st quarter of calendar year 2012.[174]

Recently, there has been concern over NuScale being able to continue its work as its main source of financing, investor Francisco Illarramendi, has recently come under investigation by the SEC. The federal agency accuses Illarramendi of operating as an unregistered investment adviser and misappropriating millions of dollars from hedge funds he advises to make improper investments on his own behalf, including about $23 million he steered to NuScale.[175] On January 24, 2011 a federal judge ruled that funds that had already been disbursed to NuScale could be used by the company. There were fears that these funds would be frozen together with other assets of the investor for the duration of the investigation[176]. While this development allows the company to continue its research and, as Bruce Landry mentions, be on time with their proposed implementation timeline, there are concerns currently that NuScale will run out of funds unless there are other investors willing to support the process. This brings up the "Valley of Death" concern that all start-ups face, namely transitions from seed capital to pre-venture capital to acquisition of venture capital, and the idea the process could collapse at any time

Experts interviewed about NuScale are optimistic. It is one of the reactor types that have the potential of succeeding, and of doing so relatively soon. Paolo Ferroni mentioned that NuScale is a proven design that is a simplified version of current LWRs. Mark Peters also indicates the design is solid and the reactor has a good chance of success. Rob Petroski believes that NuScale is a mature design and that it has a good chance of success in the regulatory process. Daniel Ingersoll also believes NuScale to be one of the SMR types that has the potential to succeed based on the proven technology. Matthew Bunn, Richard Lester and James Joosten also mention NuScale as a solid design that could be a serious candidate if SMRs do indeed get adopted as a revival of nuclear takes place. Paul Genoa and Charles Ferguson identify NuScale as one of the more promising SMR designs, while Mike Snodderly also points to NuScale as a PWR reactor that is in the first-mover category for the NRC.

b. B&W mPower Reactor

The Babcock & Wilcox Company (B&W) is an established company with more than 50 years of continuous nuclear engineering and manufacturing experience. Seven of the large nuclear power plants operating in the U.S. today were designed, manufactured and installed by B&W, including reactors in Arkansas, Florida, Ohio, Pennsylvania and South Carolina. Many other operating reactors incorporate major B&W nuclear steam supply components. Today, they provide customers with nuclear manufacturing and nuclear-related services from more than 17 facilities across North America.[177]

The B&W mPower reactor is a scalable, modular, Advanced Light Water Reactor (ALWR) system, or an internal pressurized-water reactor (iPWR) which can be certified, manufactured and operated within the existing regulatory framework. It is a light water reactor with the reactor and steam generator located in a single reactor vessel located in an underground containment. It can be air-cooled, addressing water concerns. The mPower reactor has the capacity to match utility customer requirements in 400MWt thermal rated and 125 MWe output increments, while providing a 4.5 year operating cycle between refueling outages (compared to 18 or 24 month refueling cycles for currently operating large reactors)[178]. The scalable size of the B&W mPower reactor will allow industry to utilize existing electrical transmission line infrastructure and, when used to repower aging fossil-power plants, reuse existing power plant assets (see Appendix, Figure 28).

According to analysis performed by B&W, The B&W mPower reactor is intended to be a competitive source of power generation, according to Christofer Mowry, company executive testifying before Congress, with a levelized cost of electricity (LCOE), an industry standard metric for total cost of ownership, indicating that the economics range from 47 $/MWh to 95 $/MWh for a nuclear plant composed of 4 B&W mPower modules generating 500MWe, depending on the deployment configuration.[179] While modeling SMRs in the economic model was not possible due to uncertainties about overnight costs, this large range is cause for concern. This LCOE range appears competitive with new fossil generation and renewable power alternatives, according to Christofer Mowry (see Appendix, Figure 29) [180], but without solid data to support the statement it is hard to take it at face value. The NRC expects to receive a design certification application in the 4th quarter of calendar year 2012. B&W has formed a consortium with U.S. utilities, including the Tennessee Valley Authority, First Energy and Oglethorpe Power Corporation, dedicated to work together to address issues like design requirements and licensing infrastructure necessary to support the commercialization of the mPower reactor. The goal is to deploy one demonstration plant in the U.S. by 2020.[181]

Interviewed experts with technical expertise reveal the mPower reactor, along-side the NuScale project, as a serious prospect, should the regulatory process go well and the testing units built, according to Mike Snodderly. While the timeframe for operation of the reactor is unclear (B&W plans to have them built by 2020 or earlier), the consensus is that it is a solid design based on technology that has already been proven (LWR) and built by a company with significant expertise in the nuclear sector. If SMRs are to play a role in the energy mix in the US and abroad, mPower is a contender.

c. Pebble Bed Modular Reactor (PBMR)

The Pebble Bed Modular Reactor (PBMR), designed by PBMR, Ltd. is a high-temperature gas-cooled modular reactor with online refueling that generates electricity via a gas or steam turbine and which may also be used for process heat applications. It is rated at 400 MWt, and an electrical output of 165 MWe.[182] (see Appendix, Figure 30)

A PBMR is essentially a large hopper filled with graphite pebbles, about 60 mm in diameter, each filled with thousands of UO_2 fuel particles with diameters of less than 1 mm. Each fuel particle is coated with two layers of pyrolytic carbon, silicon carbide, and porous carbon, retaining the gaseous fission products. This technology claims a dramatically higher level of safety and efficiency that current LWRs. Instead of water, the PBMR uses pyrolytic graphite as the neutron moderator, and an inert or semi-inert gas such as helium, nitrogen or carbon dioxide as the coolant, at very high temperature, to drive a turbine directly. This eliminates the complex steam management system from the design and increases the transfer efficiency to about 50%. Additionally, the gases do not dissolve contaminants or absorb neutrons as water does, so the core has less in the way of radioactive fluids and greater economy than a light water reactor.[183] The NRC expects an application in fiscal year 2013 for licensing, following an initial letter of intent in 2009.[184]

PBMRs have a tumultuous history. In November 2005, South Africa announced its plans to build a large-scale PBR reactor.[185] However, due to law suits against Eskom from environmental groups opposing the project, construction faltered, and in 2009 the project was delayed indefinitely. Then, in 2010, the South African government withdrew funding and the project was closed. However, according to the NRC, licensing of a demonstration plant in South Africa is being reconsidered again, which would revive the project. However, even if the South African project remains canceled, China is planning a 10 megawatt prototype called HTR-10, a conventional helium-cooled design. The first 250-MWt plant is scheduled to begin construction in 2009 and commissioning in 2013.[186] Germany (on which the Chinese prototype is based) and the Netherlands are also exploring PBMRs.

There is excitement surrounding the PBMR concept, as it addresses issues like waste, proliferation and cost. However, since no prototypes have been built and no cost analyses have been explored, it is hard to assess the success of this model. It is unlikely that deployment will occur before 2020, ahead of LWR models. This reactor is part of the "exotic" variety mentioned by Daniel Ingersoll. Sharon Squassoni mentions problems with fires in the reactor, and other experts interviewed appear skeptical about the PBMR until a test reactor is built.

d. Toshiba Super-Safe, Small and Simple (4S) Reactor

The 4S is a fast neutron, sodium-cooled reactor, built in partnership between Toshiba and the Japan's Central Research Institute of Electric Power Industry (CRIEPI)[187]. It uses neutron reflector panels around the perimeter to maintain neutron density. These reflector panels replace complicated control rods, yet keep the ability to shut down the nuclear reaction in case of an emergency. It utilizes liquid sodium as a coolant, allowing the reactor to operate 200 degrees hotter than if it used water. Although water would easily boil at these temperatures, sodium remains liquid, exerting very low pressure on the reactor vessel even at extremely high temperatures. Fuel is uranium zircalloy enriched to less than 20%, or a U-Pu-Zr alloy with 24% Pu for the 10 MWe version or 11.5% Pu for the 50 MWe version. The actual reactor would be located in a sealed, cylindrical vault 30 m (98 ft) underground, while the building above ground would be 22×16×11 m (72×52.5×36 ft) in size. This power plant is designed to provide 10 MWe power with a 50 MW version available in the future (see Appendix, Figure 31).[188]

The NRC received the letter of intent in 2010, and expects a design approval submission by second quarter 2012. The 4S has recently been in the news due to its partnership with the city of Galena, AK. The NRC has already met with the city manager and vice mayor of Galena, Alaska, in order to discuss plans for building a proposed small nuclear reactor there.[189] The 4S is a promising design, but it is perhaps further out than the PBMR, and certainly will not get licensed before the other LWR SMRs. Experts like Daniel Ingersoll and Rob Petroski regard the 4S as an exotic design.

e. GE Hitachi Power Reactor Innovative Small Module (PRISM) Reactor

GE Hitachi Nuclear Energy, a joint venture between General Electric and Hitachi, is researching a reactor design which would use recycled spent nuclear fuel instead of creating new fuel (see Appendix, Figure 32). This design is not new, as it was originally developed at the Argonne National Laboratory back in the 1980s and 1990s.[190] GE Hitachi calls the design the Power Reactor Innovative Small Module (PRISM), which is a key component to a new fuel cycle in which spent nuclear fuel is reused instead of being stored. The PRISM reactor would use recycled nuclear fuel from a reprocessing facility known as the Advanced Recycling Center (ARC). The ARC would be located at the PRISM reactor site, and would likely use a patented electrometallurgical process in order to separate and isolate the uranium from the spent nuclear fuel.[191] The design is that of underground containment on seismic isolators with a passive air cooling ultimate heat sink; it has a modular design with two reactor modules per power unit (turbine generator).[192] Refueling would occur every 12-24 months.

NRC expects applications for licensing (long-term) to be submitted by 2012. In fact, NRC staff conducted pre-application review in the early 1990s that resulted in the publication of NUREG-1368, "Pre-application Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor (January 1994)."[193] Experts also see the PRISM is as of the exotic reactors that could play a potential role, but not an immediate contender.

f. Hyperion Power Module Reactor

Hyperion Power Generation Inc. is a privately held company formed to commercialize a small modular nuclear reactor designed by Los Alamos National Laboratory ("LANL") scientists leveraging forty years of technological advancement.[194] The Hyperion Power Module Reactor (HPM) is sealed at the factory, sited underground, and eventually returned to the factory for waste and fuel disposition after a useful life of seven to ten years. The principle materials in the core are uranium nitride (UN) fuel, stainless steel as the structural material, lead-bismuth eutectic (LBE) as the coolant, quartz as the radial reflector, B4C rods and pellets for in-core reactivity control and shutdown. The LBE permits ambient pressure operation of the core, eliminating pressure vessel requirements. The outer diameter of the entire reactor system, including the outer reflector and coolant down-comer, is limited to 1.5 m to be able to seal the reactor vessel system at the fabrication facility and transport it to the site in a conventional nuclear fuel shipping cask. The total mass of the reactor vessel with fuel and coolant is less than 20 metric tons (see Appendix, Figure 33).[195] There is little information, however, on when the NRC will receive an application. Hyperion Power Generation has entered into an agreement with Savannah River National Laboratory (SRNL) in fall 2010 that could lead to deployment of its 25MWe modular reactor at the DOE's Savannah River Site, but details on timeline are unclear. [196]

There the majority of the interviewed experts doubt the feasibility and business plan of the Hyperion reactor. First, there is no application pending, and no letter of interest with the NRC to date. The Hyperion model was changed several times, as was the design. Experts like Bruce Hamilton assert that is not a good sign. Matthew Bunn dismisses the Hyperion model completely, as does Henry Sokolski. Rob Petroski mentions it as a potential contender, but outside of the "certain" category of LWRs. Therefore, while there is a lot of media coverage and some potential partnerships exist most experts tend to regard Hyperion with more skepticism than other proposed models.

g. Russian KTL-40s Reactor

The Russians, like the Chinese and the Indians, are also working on SMRs. While the Chinese are considering the PBMR and the Indians are in the early stages of research and development, Russia has already completed construction of a floating reactor, the Akademik Lomonosov. This is a modified version of the KTL-40s mini-reactor, and is going for commissioning in 2012.[197] The first reactor was delivered in May and the second one in August 2009. Akademik Lomonosov was launched on 30 June 2010. After commissioning in 2012 Akademik Lomonosov will be deployed at Vilyuchinsk, in the Kamchatka region in Russia's Far East.[198] Russia plans to build a fleet of these reactors in order to provide district heating and electricity to national consumers and/or power supply to the developing countries, including entry to the seawater desalination market. It is a pressurized-water reactor. It is based on the commercial KLT -40 marine propulsion plant and is an advanced variant of RPs that power nuclear icebreakers (see Appendix, Figure 34). It is a proven design that according to the IAEA report, and ready for deployment.[199]

h. Westinghouse

Westinghouse is an established company making large LWR. Though originally an American enterprise, it was sold to Toshiba in 2006, but they are still regarded as a major US-based player in the global nuclear industry.[200] They are currently building AP1000 reactors at Haiyang and Sanmen in China and are earmarked for new build projects at Vogtle, GA and Calvert Cliff, SC the US.[201] The company looked at an SMR, the International Reactor Innovative and Secure (IRIS), a 335 MW PWR design, but concerns about costs and applicability led the company to abandon the project. [202] While this was a business, and not a technology decision, according to Paolo Ferroni, who spoke not as a representative of Westinghouse, but in his personal capacity, Westinghouse did not abandon the SMR idea. In February 2011, they announced the new model replacing the IRIS, a 200 MWe integrated pressurized water reactor (see Appendix, Figure 35). All primary components are located inside the reactor pressure vessel. It is designed to be completely fabricated in the factory and is scaled to be shippable by rail. Both the core and reactor vessel internals of the SMR are derived from the AP1000. The core, at the foot of the module, is composed of partial-height derivatives of the 17x17 fuel assembly used in the AP1000. The reactor vessel internals are modified for the smaller core and to provide support for the internal control drive rod mechanisms. Horizontally-mounted axial-flow canned motor pumps provide the driving head for the reactor coolant system, and a compact steam generator and pressurizer integrated into the reactor vessel head completes the design.[203]

i. General Atomics EM_2 Reactor

General Atomics (GA) is in the early stages of a 12-year, $1.7 billion endeavor to design, secure regulatory approval for, and build its first EM_2 reactor.[204] This 285 MWe reactor would use graphite spheres containing enriched uranium fuel kernels (10-19.9 percent enriched) inserted into hexagonal graphite blocks. The design is based on the Fort St. Vrain reactor.[205] Similar to other GA designs, the EM_2 has an inherent passive safety system and would require refueling only about every 30 years. With the helium cooled EM_2 that does not require a nearby water source, GA is looking to employ fast reactor technology and use spent fuel and nuclear waste to create power. It would do all of this without traditional reprocessing of spent fuel. The reactor might be useful in the fertilizer or chemical processing industries because the reactor operates at very high temperatures but does not require water. Other potential industrial applications include desalination and petroleum refining (see Appendix, Figure 36).[206]

j. Traveling Wave Reactor

Another design worth mentioning is the Traveling Wave Reactor concept from TerraPower (formerly Intellectual Ventures). The project, according to Rob Petroski is exciting because it is an idea that would solve the waste problem. Engineers at TerraPower are motivated by getting a prototype completed and licensed, even if they have to do it outside the US. TerraPower is working to develop a traveling wave reactor, which could avoid the well-known limitations of current plants, nearly all of which employ nuclear reactor technology that dates back to the 1950s. Today's reactor designs require enriched uranium fuel, but can extract only a small fraction of the energy from that fuel. 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. An established fleet of TWRs could operate without enrichment or reprocessing for decades. 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.[207]

However, as it currently is designed, it is not a technology that is scalable to SMRs (it would only make sense at 900+ MWe). However, if the fuel and its processing are developed, it can be applied to other reactors, including some SMRs. The NRC is not currently equipped to look at this type of reactor (focuses on LWR), so the licensing may be done outside the US, but it is a concept funded by Bill Gates[208], and that may in fact develop into a technology that can be applied to SMRs and improve the industry.

k. Other models

France (through Areva) is considering a reactor, the New Technology Advanced Reactor Energy System (ANTARES). It would be a 285 MWe reactor using graphite spheres containing enriched uranium fuel kernels (10–19.9 percent) inserted into hexagonal graphite blocks.[209] Argentina is licensing and building an iPWR (CAREM) that is supposed to simplify the larger designs. While the initial unit will be 27MWe, the plan is to scale it up after demonstration to 150-300MWe. The reactor is meant mostly for the domestic market, but has potential for export.[210] South Korea is also considering the SMART reactor as a co-generation plant, currently in the pre-licensing process. It would be a 100MWe reactor, but further details are unknown.[211]

Other reactor types are under consideration (gas-cooled, liquid metal-cooled, lead cooled, etc.) but they are in incipient phases, and little is known about their characteristics or future.

III. Industry/Regulatory Action to Date

SMRs came into focus in the past decade, beginning with the joint project started in 2000 between INEEL and Oregon State, as costs of nuclear power have risen and discussion of carbon legislation has increased.[212] According to Richard Lester and Daniel Ingersoll, who has over eight years of experience working on SMRs, the renewed interest is rather encouraging. While no SMRs will be built before 2015 at the earliest, the interest in the legislature, regulatory branch and especially in the private manufacturing and utility sectors may stimulate a fast development of the industry based on SMRs. In addition, other countries' interest in the topic is also high, leading to a competition for development and potential market share which will accelerate the industry. According to a Heritage Foundation 2011 report, most of the development is occurring without government involvement. Private investors and entrepreneurs are dedicating resources to these technologies based on their future prospects, not on government set-asides, mandates, or subsidies (excluding insurance and liability), and despite the current regulatory bias in favor of large light water reactors (LWRs).[213]

The DOE is supporting this research and development through its R&D Roadmap. A strong supporter of nuclear power, the DOE presented the Roadmap for nuclear energy to Congress in 2010, supporting the development of nuclear power. Numerous hearings have been held by Congress, with testimony from experts such as Charles Ferguson and Warren Miller, as well as industry and utility representatives such as Christofer Mowry in support of the Roadmap. The DOE states four goals in its 2021 Roadmap:

- Develop technologies and other solutions that can improve the reliability, sustain the safety and extend the life of current reactors
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the administration's energy security and climate change goals
- Develop sustainable nuclear fuel cycles
- Minimizing the risks of nuclear proliferation and terrorism[214]

Part of the roadmap includes support of SMRs through the SMR program, demonstrating the DOE's commitment to the technology.[215]

In November of 2009, the U.S Senate Committee on Energy and Natural Resources introduced legislation that would provide funding to the Department of Energy for the development of small nuclear reactors. The Nuclear Power 2021 Act (S. 2812) would allow the federal government to fund 50% of the cost of the development and licensing of two different small modular reactor designs.[216] One of the co-sponsors of the bill, Senator Lisa Murkowski of Alaska, hopes that one of these new small reactor designs will be built in Alaska, and Toshiba is already speaking to the town of Galena, AK and the NRC about the possibility to do so. In the proposed 2012 Fiscal Budget, the Obama administration has reinforced the DOE commitment to nuclear power and SMRs by requesting $500 million over five years, at a national laboratory facility. This would constitute half of the estimated cost to build two designs and secure the Nuclear Regulatory Commission's approval. The reactors would be built almost entirely in a factory and trucked to a site like modular homes.[217] This would be necessary despite current public involvement because the cost is still relatively high and a demonstration unit has not yet been built. With government support in this area, the will likely be first movers.

Other countries are supporting SMR development. Russia is funding the KTL-40s reactors, China is investing in research of PBMRs with German technology at its university research facility in Beijing, India is analyzing the opportunities for SMRs, and South Africa, while initially looking to close the PBMR project, is now reconsidering funding. Argentina and South Korea are also looking at small and medium reactors, and pre-licensing discussion are occurring now, though nothing has yet been built.[218]

However, the regulatory environment is still unclear. The NRC, which is the primary authority on LWRs and whose decisions inform the IAEA and the world community, is not yet equipped to analyze SMRs. Mike Snodderly indicates that it would be hard to justify developing tools and building capacity to look at SMRs until designs are submitted, mostly due to cost constraints (industry is billed by NRC for analysis and building up inspection capacity, which would be hard to justify without designs). Expertise may exist at national labs, but not currently at NRC. If NRC were to receive applications, and if DoE would assist with testing facilities, the situation would change, as regulators could then contract in-house help for licensing. Mr. Snodderly also indicates that pre-application is important in order to speed up the process, designing independent modeling that can be benchmarked against NRC code, as well as staying true to the submitted design, since design variations lengthen the process.

There is a current backlog of applications for large plants, and given the lack of a specific certification process and licensing methodology for the new technology, SMRs need to be moved quickly in order to be viable and make an impact in the nuclear field. Bruce Hamilton mentions that the NRC should speed up the process of certifying SMRs, while Matthew Bunn and Stephen Maloney assert that, even with a more streamlined process, until SMRs are built and operational, it will be hard to design a flawless process for licensing. However, significant work is being done in this area by the NRC. Starting in 2010, the Commissioner has looked into speeding up the process for certification in a memorandum to the agency, and studies have been released with suggestions on how to streamline the process and take risk into account.[219,220]The policy of the Commission on advanced reactors states:

> *To provide for more timely and effective regulation of advanced reactors, the Commission encourages the earliest possible interaction of applicants, vendors, other government agencies, and the NRC to provide for early identification of regulatory requirements for advanced reactors and to provide all interested parties, including the public, with a timely, independent assessment of the safety and security characteristics of advanced reactor designs. Such licensing interaction and guidance early in the design process will contribute towards minimizing complexity and adding stability and predictability in the licensing and regulation of advanced reactors.*[221]

According to the NRC, most SMRs are not merely scaled down versions of large-scale reactors, but rather new in design, siting, construction, operation, and decommissioning. Accordingly, the legal and regulatory issues these units will generate will not merely be scaled down versions of the issues. Many problems can only be solved by amending regulations. Perhaps most concerning, the NRC Office of New Reactors, which is already working on the licensing of a number of large-scale reactors, is already over-burdened and will need to make resource adjustments to handle SMR applications. It is likely that SMRs will take a back seat to large-scale plants for the time being, unless designs are submitted by 2012, as currently predicted, according to Mr. Snodderly. This would happen because the NRC needs to allocate resources to SMRs, and a delay would cause the scarce resources available to be involved with other projects. To mitigate the burden, DOE is proposing a cost-share partnership for SMR design and licensing that may be initiated as early as 2011, but details on this are not yet clear.[222] It is also unclear whether this is a good option given that the government would be the regulator and the designer for SMRs in the program, which may create a conflict of interests. However, it could also be the case that, since they have the design in place, regulation will be easier.

The Heritage Foundation study indicates most of the designs have been created by industry without much government support.[223] Partnerships between utilities and manufacturers are emerging, and funding comes from private sources, like Francisco Illarramendi or Bill Gates. There is a significant interest in small nuclear because of their mobility, scalability, lower initial capital cost, fast deployment and remote usage not only for electricity generation, but also for desalinization, mining, or replacing old fossil fuel plants.

IV. Advantages of SMRs

SMRs are attractive for several reasons. They share many of the attractive qualities of large reactors, such as providing low operating cost, emissions-free power, while adding new features that could make them more appropriate for certain applications, such as providing power to rural communities or for dedicated industrial use. SMRs are not yet positioned to take the place of traditional large LWRs, but they represent an important growth area for the commercial nuclear industry. These attributes would potentially mitigate some of the financial and regulatory problems that nuclear energy has recently faced. SMRs potentially cost less (at least in up-front capital), are more mobile and multifunctional, and can largely be produced by existing domestic infrastructure in the US, according to the Heritage study.[224]

First is the economic cost. Large plants are, as was previously discussed, expensive and utilities find it hard, without government support and given their market capitalization, to fund a large nuclear plant. This is one of the major reasons why, in the US, there have been no new plants built in the past 30 years. However, SMRs present a new alternative. While they appear to be higher in cost that large nuclear per kW produced (according to the model large nuclear is around 6 cents per kWh, while B&W cites a price of 8 or 9 cents per kWh, and others, like NuScale are in the same range), and in fact might be more expensive than large nuclear power plants, as is the case with the Russian KTL-40S according to Matthew Bunn, the upfront cost of building an SMR is in the hundreds of millions of dollars range, not billions. And while it is true that to get to a capacity of over 1 GWe, a utility would need to spend billions on SMRs, their modularity and scalability allows utilities to stagger the construction and therefore incur lower capital and financing costs for incremental units. Again, it is important to note that since no reactors have been built, it is impossible to determine the actual cost of a unit and an array, which is an important point when comparing small nuclear with its larger cousin.

According to the Economist, a plant with 12 reactors, each with its own electricity-generating turbine, would cost about $2.2 billion and produce roughly a third as much power as a big facility. Since large plants can cost roughly three times as much, the cost of electricity would be similar. Moreover, a modular facility would generate revenue as soon as the first reactor is fired up, after a few years of construction, while a big reactor traditionally takes a decade to erect.[225] Furthermore, while large plants provide economies of scale, once SMRs start being produced industrially, a learning curve and resulting price reduction are likely to occur, according to industry experts, lowering the price and making them more competitive.

Second, SMRs are small, allowing for installation in diverse locations, and are versatile enough to fit in places where large plants would not be feasible. This is especially interesting from an urban planning perspective, allowing for new developments and urban development in the developing world. This argument is supported by James Joosten, John Banks and Paul Genoa, and would support William Moomaw's suggestion for provision of affordable energy services to the developing world as a solution not only to poverty, but also to CO_2 emission and climate change.[226] SMRs could provide a new approach to planning and infrastructure for development of small and medium cities. SMRs could be used for power generation for a small city (the B&W could provide power to a city of 50,000), could be used for remote areas (like the KLT-40s in remote Siberian villages, where power is sporadic and, being far from the grid, expensive with diesel generation, as is the case with Alaska or Canada)[227]. SMRs could be used for providing power on mining sites, or being used in arid areas for desalination plants. Industrial use is also a potential beneficiary of SMRs. The chemical industry, manufacturing, plastics, oil refineries and others require energy that could be produced on site with an SMR. TVA is considering the B&W for replacing aging coal plants with modular reactors, while other utilities are looking at SMRs for their versatility in operating in areas where the grid is not developed or cannot support the power produced by a large reactor. Energy services are required for development worldwide, and SMRs could provide an affordable way to provide it on islands, in rural areas and elsewhere.

Third, SMRs could be produced domestically. While the US has lost most manufacturing capacity for nuclear containment vessels and other components for large plants, SMRs could be produced in the US and the country could regain its competitive advantage in the industry. According to an Energy Policy Institute study, SMRs could produce up to 600,000 jobs annually in the best case scenario, and an economic impact of $113.5 billion in annual sales, $54.6 billion in annual value added impacts, $35.2 billion in annual payroll earnings, and $3.1 billion in annual indirect business taxes. Cumulatively through 2030, the domestic operation of SMRs could be responsible for approximately 200,000 jobs, $57.1 billion in sales, $36.4 billion in value added, $14.8 billion in earnings, and $4.9 billion in indirect business taxes. This is based on a prototypical 100 MW SMR costing $500 million to manufacture and install on-site is estimated to create nearly 7,000 jobs and generate $1.3 billion in sales, $627 million in value-added, $404 million in earnings (payroll), and $35 million in indirect business taxes.[228] The scenario also assumes building of 85 SMRs in the next 20 years, but even with a much lower adoption, the impact would be significant. Similar arguments have been made by Christofer Mowry and others in hearings in Congress.

Two criticisms apply to this argument, however. First, unless SMRs generate electricity at a lower cost than other power sources, this argument becomes meaningless, since no one will invest in them. Second, the same critique of this argument made for large reactors applies for SMRs: there is an opportunity cost of using this capital for more productive job-creating activities that is impossible to quantify. This therefore becomes a matter of considerations for policy-makers when deciding what industries to support for domestic job creation: should they target SMRs or other investments to produce the jobs required by the economy? If SMRs provide to be the right technology, then there may be a strong case for supporting them for job creation.

There are those who claim that SMRs will inherently be safer to operate and would reduce the risk of terrorism, proliferation and waste management. Since some will be buried underground, they would be less accessible to terrorists wishing to sabotage them or steal fuel, according to Roger Howsley. Since they are small, the redundant systems that are built into large plants can be simplified or reduced due to size and simplicity of design, and the operation and supervision made easier. As they are built in factories, they can be standardized and a new workforce can be trained to deal with safety of operation and emergencies, rather than site-specific training as is done today. Finally, proliferation concerns are reduced since some of these reactors do not need to be refueled for their useful life, and others have longer and easier refueling cycles than existing plants. The waste issue remains, as SMRs would add to the total stock of waste worldwide, but since they are smaller and some may use reprocessed fuel, waste management for them will likely not altering the status quo on the waste issue.

V. Concerns about SMRs

Since no SMRs have yet been built, some of the arguments for their development and widespread adoption, leading to a nuclear renaissance are also working against them, as Mark Kirshe indicates. Firstly, Arjun Makhijani and Michele Boyd indicate that costs will likely have overruns and the cost of $8000 - $10,000 per kW electricity built is going to be more than the cost of a large plant, already too expensive. In addition, since the modularity requires space, the initial cost to site a modular plant will still be high, at least for the first reactor as the containment building is built. This will not decrease costs and would make SMRs as unsuccessful as large plants.[229] Henry Sokolski agrees with this point, saying economics do not work in favor of SMRs and that there are no economies of scale to be gained.

Doug Koplow supports this argument, saying that even for SMRs government intervention would need to occur to support the development, which would lead to the same problems of subsidies plaguing the industry. James Joosten, Sharon Squassoni, John Banks, Paul Genoa and Charles Ferguson also agree cost is a significant unknown variable for SMRs. No one can currently predict whether they will be cheaper. Until test models are built, and until the cost estimates of manufacturers can be verified, cost remains an unknown that casts doubt on SMRs.

Second, according to the Economist, licensing and building small plants will take far too long to be profitable. As the costs of solar, wind and biogas power continue to fall, investors will increasingly favor household energy-producing kit and transmission technologies that let consumers sell excess production to neighbors and utilities, in essence delaying and ultimately preventing the nuclear renaissance.[230] Even though the NRC and other regulatory bodies are indicating steps to speed up the process of licensing for SMRs, the entire process would take too long and make them uncompetitive. Mike Snodderly indicates that the NRC is unable to determine how long the process would take until it receives the application. However, he also mentions that the more information the manufacturers provide and the easier it is to verify that information, the speedier the process will become.

Third, there is concern about waste, as spent fuel management for SMRs would be more complex, and therefore more expensive. According to Makhijani, because the waste would be located in many more sites, the cost and complication of dealing with waste would increase.[231] The current infrastructure in place for spent fuel management is geared toward light-water reactors at a limited number of sites. That would change with a large number of small reactors spread out not just all over the US, but all over the world. This will create additional problems, be expensive and, in the absence of a repository, cost US taxpayers more money. It is true that some of these reactors advertise the fact that no refueling would be necessary for the operating lifetime, but the real viable projects (NuScale and mPower) are LWRs that require refueling. Sharon Squassoni mirrors that argument, as does James Joosten: it is hard to tell how widespread these reactors will be, but producing spent fuel on more sites and further apart can create logistical problems, as well as cost and public acceptance issues.

Another issue that critics raise is the safety aspect of SMRs. Currently the NRC has a system for evaluating LWRs. However, with a new set of reactors and standards, that system may erode, especially as pressure is put on the regulatory bodies to pass new rules and review processes to promote the new technologies. There is also concern about containment structures, control devices for the reactors and environmental impacts of operating reactors in smaller sites. Sodium reactors have problems with fires, as do PBMR, as Sharon Squassoni points out. Other newer reactors are not tested and there is no telling how they would react under intense use, which is different from models. Rob Petroski indicated that the TerraPower reactor is currently only a concept and that the assumptions are based on modeling, but until a test model is built, it may be hard to tell whether the modeling is reliable. There is also concern about quality of materials and quality of labor, since some of these reactors will be produced in other countries. Concerns about safety also arise with regards to cutting staff equivalent from large plants, training personnel for the new reactors and handing emergencies. In particular Mike Snodderly points to the number of operators required for SMR arrays (two to three versus seven to eight for large plants), security personnel to guard the site (which may be easier to deal with given design enhancements), as well as siting and the emergency evacuation zone around an SMR array.

Fourth, proliferation issues abound. If the IAEA prediction is correct and 30 or more countries will place orders for SMRs in the next 20-30 years, then the issue of proliferation is a serious one. While in the US this would likely not be a concern, if the US will export these reactors, then policy-makers should address this issue. Henry Sokolski points to this threat as a serious one that has to be considered. Sharon Squassoni is not concerned with floating reactors, but some of the models are worrisome because they use HEU. Rogue states may have access to this technology and use it for nefarious purposes. Terrorists could acquire one, or divert the fuel, which is easier to handle than rods at a large plant. While Daniel Ingersoll disagrees that fuel for SMRs would be easier to divert, since fuel rods would still weigh 50-60 pounds each and, for LWRs will not be enriched enough for a nuclear device, concerns about dirty bombs are valid and, based on the volatile situation in some of the areas that are considering the technology, this could be problematic. In addition, if enrichment facilities are built to supply these reactors, that creates another possibility for terrorists or rogue states to obtain the enriched material. Roger Howsley disagrees with this critique, asserting that in the US that would be unlikely and outside the US the IAEA has good control over the existing plants for that to be a concern, though additional supervision may be in order. However, if the number of SMRs grew and the reactors spread beyond the current nuclear states, that might be a strain on the IAEA that would be hard to handle by the agency.

Another concern is the R&D and manufacturing capabilities of the companies proposing these models, as Mark Kirshe indicates. While some of them have a lot of experience and capitalization behind them (B&W, Westinghouse, Areva), others are start-ups. This poses a problem, because, in case reactors are built and something goes wrong, they cannot cover the liability costs and would therefore be in a difficult position should something go wrong. The ownership structure is not right for these projects. The analogy given by Doug Koplow is the BP oil spill in the Gulf of Mexico in 2010. BP is a large company, with large capital to cover such a disaster. NuScale or Hyperion would not be able to do so in case of a malfunction, and that is a concern that regulators and legislators should be aware of when making decisions.

The more general “Valley of Death” argument applies to SMRs. Some of their challenges are associated with all start-ups, including transitions from seed capital to pre-venture capital to acquisition of venture capital. This means some of the companies involved may either cut corners if resources are not available, or simply abandon a promising project for lack of funding. This is a general truth in any industry, and SMRs are no exception.

Paolo Ferroni also mentions that SMRs would not solve the public concern over nuclear power. To the general public, they would still be nuclear facilities, something that they do not understand and fear. Unless they were proven and demonstrated, opposition would exist even for the smaller demonstration projects. The NIMBY attitude would likely preclude SMRs from being a game changer for nuclear power, unless something changes dramatically, not only incrementally, in public perception. Furthermore, Makhijani and Boyd argue that SMRs would not even address the climate change problem since their development will take likely another decade, they constitute a waste of money and resources, as renewable sources are already becoming cheaper than nuclear.[232] Robert Bryce disagrees with this argument in *Power Hungry*, saying that nuclear provides baseload power, while renewables are peak power at most, and sometimes do not even provide that. While he makes a valid point, it is hard to assess what the renewable industry could do to improve its track record, including capacity and price if it had the resources large nuclear has had for the past decades. This again comes to the opportunity cost of investing a technology to the detriment of others, in effect picking winners.

Overall, there are serious concerns and unknown variables about SMRs, issues that plague the large reactors and that threaten to deflate the excitement surrounding the new solution for a nuclear revival, at least until some are built and can address some of the objections empirically.

Part Three – Analysis and Policy Recommendations

The purpose of the previous sections was to present nuclear power, both large and small, in its full array of costs and benefits in order to inform policy recommendations. The model provides the quantitative background for the analysis, while the expert interviews provide a plethora of opinions and recommendations for the future of the industry, whether it be continued or abruptly cut off. The purpose of this section is to analyze the findings and propose policy recommendations to be undertaken with regards to nuclear power.

According to Thomas Dye, it is important to define the problem and issues in a policy analysis.[233] In this case the problems were laid out in terms of costs and benefits, and the issues are constituted by the future actions pertaining to the technology. Furthermore, Carl Patton emphasizes that simple solutions are needed in order to deal with the policy and planning issues of today. Policymakers should analyze all aspects of nuclear power before making any committing decisions.[234] Roger Cobb further mentions it is important to frame an issue and develop an agenda for implementation.[235] Finally, according to Dietz, good decisions are not necessarily the easiest or most obvious ones.[236]This is relevant for analyzing and prescribing government involvement and policy-making with respect to large reactors, but also to the new-comer SMRs. This section will make the distinction that government should remain involved in large nuclear to keep it alive, but slowly move out of the industry. The same approach however should not be attempted for SMRs. If the technology is viable, only minimal support will help it achieve its potential. Policy-makers should not pick winners, but should nonetheless follow through with their decisions once they are made.

I. Nuclear Power and Large Plants

Based on the research from the literature and the interviews conducted with experts, the case for or against nuclear power is not easy to make. Although nuclear brings many advantages and benefits over conventional energy sources, it is plagued by problems that seem almost insurmountable. Nonetheless, the conclusion of this paper is that national authorities and industry should pursue nuclear power as part of their energy mix in the years to come.

Despite other arguments, it all boils down to economics. There are alternatives to nuclear power. The US could continue building coal-fired power plants, based on its abundant coal resources (22.6% of world reserves)[237], or could replace coal plants with gas-fired or combined-cycle plants, as gas contains two thirds the CO_2 content of coal, as mentioned earlier. Initial capital investment costs for conventional power plants are significantly below nuclear power plants (as was show in the model, around 48% of total cost compared to 87% for nuclear at 10% cost of capital). Nonetheless, if volatility of fuel prices and emissions costs were included, the case for conventional plants becomes less attractive. If price of natural gas increased to $8/million BTU for example, then levelized cost of electricity would be 9.8 cents, closer to nuclear's 12.4 cents/kWh (see Appendix, Figure 16). What if legislation finally enforces a carbon price? According to the model, a carbon price of $25/ton CO_2 would not make a large difference, taking the price of electricity from 7.9 to 8.7 cents for coal and from 7.3 to 7.7 cents for natural gas. However, if the tax were $200, the required cost of electricity to meet the 12% IRR requirement would be over 10 cents per kWh, over 20% increase from the current levels.

What if stricter regulations restrict shale gas exploration? The additional costs could make nuclear power more competitive. Advanced technologies like Carbon Capture and Storage (CCS) or IGCC would also become viable alternatives to conventional sources in use today. According to Gardiner Hill, a special advisor on CCS with BP's Alternative Energy division, in order for CCS technology to be financially viable today or in the near future, a $150 - $200 dollar tax on CO_2 needs to be established, making it a very unlikely event in the near future.[238] This assertion was verified in the model, as the price of CCS technologies is competitive with non-CCS production with a carbon tax over $200 dollars (raising the price of coal from 7.9 cents to 21.5 cents (compared to 14.1 cents for CCS), and natural gas from 7.3 cents to 12.9 cents, while the CCS technologies would cost 12.4 cents (see Appendix, Figure 17).

Renewable options are also available. Solar, wind, biomass and others present the advantage of low or zero emissions in replacing current energy production facilities. In a Vermont Law School study, Mark Cooper asserts that efficiency and renewable costs at an average of 6 cents per kilowatt hour, while the cost of electricity from nuclear reactors is estimated in the range of 12 to 20 cents per kWh. That is highly uncompetitive and would in effect suffocate the nuclear industry.[239] Robert Bryce, in *Power Hungry*, disagrees. He believes renewables are not a solution for the short to medium term, and that pursuing them exclusively as an energy policy would be a mistake. He asserts LCOE of nuclear compared to solar and wind ($158 - $308 and $55 - $77 per MWh, respectively) are lower, and since renewables cannot provide baseload power, they have a weak case against technologies like nuclear.

The model supports this argument. Prices for solar range from 33.1 cents for large photovoltaic to 39.2 cents/kWh for small photovoltaic at 10% financing cost and 12% IRR, while for wind the prices range from 10.9 cents for onshore wind to 26.2 cents for offshore wind (see Appendix, Figure 20). While this does not mean that these technologies should be abandoned, the ranges are almost double the 12.4 cents/kWh for nuclear, leading to the conclusion that nuclear power presents a somewhat strong argument compared to renewables.

Other experts range across the spectrum. Doug Koplow, Henry Sokolski and Stephen Maloney see nuclear as too expensive and heavily subsidized and do not see a future for the industry in its current form. Were subsidies and government guarantees removed, nuclear, according to them, would not exist as an industry. Daniel Ingersoll, Mike Peters, Rob Petroski, Paolo Ferroni, Richard Lester, James Joosten and Paul Genoa are more optimistic, claiming nuclear is an important part of the energy mix. Roger Howsley asserts nuclear should have another term before it is phased out, as do Luisa Chiesa and Michael Corradini.

Sharon Squassoni, John Banks, Charles Ferguson and Matthew Bunn are skeptical supporters that acknowledge nuclear has a role to play, but see the cost as a major impediment. Cost overruns also make nuclear power unappealing to utilities. For example, Duke Energy raised the expected construction costs of its proposed Lee Nuclear Station (2 units of 1117 MWe each) to $11 billion, excluding financing costs. That is roughly twice the company's original estimates of approximately $5000/kWe.[240] Some of the increase is due to current commodity prices. While in recent years steel prices have declined, as have other materials, in the future they could rise, which would bring up the cost of building nuclear. Plant construction costs are therefore hard to forecast, an uncertainty that does not appeal to utilities. One positive aspect is that electricity rates are likely to increase, according to Moody's Corporate Finance, New Nuclear Generation, Special Report (October 2009), regardless of whether new nuclear generation is built or not, so utilities will get a return but would need to assess what options makes the most sense given the circumstances.[241]

Therefore, the literature consulted and interviewed experts have mixed feelings, and while most support nuclear as a technology, they see a difficult case for it in the current economic and political climate. Considering other zero-carbon alternatives currently available for baseload power, it is unclear what could replace nuclear. While the obvious replacements for baseload power are coal and natural gas, as demonstrated by the model, they are not zero-carbon, and consequently nuclear should at least be considered as part of the energy portfolio.

Most agree the existing power plants should be maintained and operated at as close to full capacity as possible. They do not pose a security threat. They operate at 90% capacity 365 days a year (except for when they are being refueled). They are already built and capital cost has been sunk. They cost little to operate, and they are competitive with fossil fuel sources at this point, having been in operation for close to 40 years and therefore being amortized. They produce no carbon emissions in their operating phase, and they provide 20% of the nation's electricity needs, and 14-15% of the world. While they also produce waste, and that issue remains to be addressed, it is unclear why any of them should be shut down before their useful life is completed.

However, since the current ones cannot operate forever and would need to be decommissioned after 40 or 60 years (if an extension is granted), there arises a need to replace them with something as they start coming offline. While the financial crisis has slowed economic growth and with it demand for energy and electricity, this trend will likely not continue, requiring additional capacity in the future. By any forecast, be it EIA, BP or Exxon, energy demand in the world will grow exponentially by 2030. Amory Lovins and others propose pursuing renewables. But as Bryce, Tucker and Cravens, among others, point out there are no guarantees, since renewables cannot currently provide baseload power.[242]

The solution therefore is to have a diversified portfolio, which should, based on all opinions, include new large nuclear, but only if it can make sense economically. The hard truth is that if the economics are worked out, all other issues take a back seat. Utilities are the decision-makers in this game. The public, regulators, legislature, banks, and other institutions can influence their decisions, but in the end, if nuclear power is economically viable, utilities will invest in it since they are concerned, like any business, with the bottom line. Utilities, however, are risk adverse, and even with the volatility of gas prices and the uncertainty about carbon legislation, they will likely be reluctant to build new nuclear capacity. When the technology becomes economically viable, it will develop, since the market determines the winners. This is of course less true in regulated markets, where politics determine the winners. Nuclear has been propped up for a long time by subsidies, loan guarantees and regulatory support. It has also been plagued by protests, opposition and some tragic accidents that tarnished its image. But despite the risk, despite public opinion, if it becomes economically viable, it will develop fast. Based on experts' opinions, therefore, for the time being, our societies should maintain it in place until something else comes along that can replace it at a lower cost and similar benefits.

Nuclear is an attractive technology, and, because it currently plays such an important role in the energy mix of not just the US, but the world, unless something else can take its place immediately, it should be pursued in domestic policy as part of a larger energy portfolio. The following steps are recommended for US policy, though they can be expanded internationally:

1. Continue funding the 2010 initiative to reduce costs through new design certification, site banking, and combined construction and operation licenses
2. Streamline the NRC process for licensing and commissioning, and provide more resources for the regulatory body to assess new projects
3. Support market entry by providing incentives for "first-mover" expenses for a limited number of power plants that adopt safety-enhancing evolutionary reactor designs
4. Expand the 2005 Energy Policy act to provide production tax credits as incentive to complete and operate plants by utilities that are on the fence
5. Reassess the Yucca Mountain project and the new Blue Ribbon Commission report due this spring and broaden the long-term waste R&D program to include engineering

studies, investigation of alternative geological environments and deep bore-hole disposal. A system of central facilities to store spent fuel for decades prior to geologic disposal should be integral of waste management strategy

6. Collaborate with the IAEA on authority to inspect all suspect facilities and develop a worldwide system for materials protection, control, and accountability beyond accounting, reporting, and periodic inspections
7. Realign federal R&D programs to assess the feasibility of reprocessing fuel facilities and uses in reactors
8. Conduct through the national labs additional nuclear system analysis, modeling, and simulation to assess alternative nuclear fuel cycle deployments and technologies
9. Work towards adopting a carbon tax in order to internalize costs of fossil fuel generation. This would not only be beneficial for nuclear, but also for renewable sources that are finding it hard to compete today. Based on industry estimates (see John Rowe comments earlier), a tax of at least \$25/ton CO_2 is needed, but assertions like BPs renewable energy director sees that tax at over \$200 before it would have a serious impact. This is shown in the model, where at a \$25/ton CO_2 tax does not make a large difference (increases price from 7.9 to 10.3 cents for coal and from 7.3 to 8.0 cents for natural gas). At a level of \$200/ton CO_2, that gap between coal/gas and nuclear narrows significantly, going to 21.5 cents for coal and 12.9 cents for gas).
10. Design better public or private financing mechanisms to allow amortization over time of capital costs (perhaps following the model of utilities in regulated electricity markets), in order to amortize initial capital cost faster for utilities wishing to pursue nuclear power.

11. Encourage industry sharing information and better communication for full assessment of regulatory and non regulatory issues (similar to Electric Power Research Institute model)
12. Consider nuclear upgrades instead of new reactors. Allow license modification and increased capacity of existing plants. James Joosten indicates industry could achieve a 20% increase, leading to 100 extra GW, or the equivalent of 12-15 new reactors.
13. Explore the possibility of thorium as an alternative fuel and fund R&D into the topic through the national labs.

These recommendations may add additional cost and subsidies, but they would be incremental to what is currently being provided by government. If, after following these steps, the economics of nuclear power are still not more attractive to utilities, then it becomes clear that new large nuclear is not the solution that should be pursued.

Public opinion should also be addressed. Paolo Ferroni strongly supports scientists being more vocal and visible about nuclear power. Just as the IPCC has problems casting away the shadow of doubt over climate change despite having renowned scientists and presumably solid scientific evidence, the nuclear industry is ineffective in communicating to the public the nuclear benefits and science. Environmentalists who oppose the technology are vocal and address the issue not in scientific terms, but rather in common language that appeal to the public. The public should be educated on nuclear power. A majority of people living close to nuclear plants approve the technology. But these are people who have targeted training and education programs to make them aware of the risks, as well as the benefits; the general public is not as educated on nuclear power. It is a failure of the industry and scientists that should be corrected. While economics will play a primary role in utilities' decision to pursue nuclear power, if public opinion changes, the transition will likely be easier.

Another issue that needs attention is that, even if the US and the world decide to embark on a massive expansion of large-scale nuclear power, constraints would limit that expansion dramatically. Therefore, adequate planning and support should be given to industry, and indications should come in advance, allowing for training, manufacturing and operations facilities to be expanded. Charles Ferguson mentions in his 2008 study that a limitation of expansion is manufacturing capacity, as, since the 1960s, the US has outsourced all its large scale nuclear manufacturing facilities for reactor pressure vessels and other components.[243] Therefore, only a small number of reactors could be built on short notice, even if interest was larger in the US, and they would have to compete for resources with China, France, Russia, Japan, Finland and others who are aiming to expand their nuclear programs. The same applies to qualified construction staff, technical experts, nuclear operators and waste management. Unless there is a program to expand these facilities and production capacity for these items in the US (which would in turn create more jobs, an important aspect in today's economy), there is little hope for a nuclear renaissance domestically, and if world capacity does not expand proportionally, there is little hope to meet Pacala and Socolow's predicted need for nuclear as a wedge for CO_2 mitigation.[244]

Once the recommendations in this brief are adopted, providing the basic support, the market should be allowed to determine the future of the industry. Nuclear fuel cycle subsidies should be removed, as should insurance subsidies, loan subsidies and other non-R&D related subsidies, according to Doug Koplow. Mark Peters sees industry-government partnerships as the solution. If nuclear can be competitive without subsidies then it will be the logical choice for utilities. Government support therefore, while perhaps necessary today, should be phased out gradually as nuclear expands; then private insurance companies can assess and price risk based on different guidelines. It is unlikely that this will happen in the near term, but such actions may in fact help the nuclear resurgence that is talked about in recent years.

II. Small Modular Reactors

Based on expert interviews mentioned in this paper, SMRs present a rather compelling case in civilian nuclear power. They are not a replacement to large plants, but rather a complement, and should be regarded and pursued as such. Paolo Ferroni does not see them as the game changer of the industry, because they are still nuclear power generators, and one cannot mask that from public opinion, which will likely reject them. James Joosten sees them as a complement, not a game changer, and more appropriate for distributed generation and small countries. Sharon Squassoni and Henry Sokolski worry about the proliferation and safety issues of SMRs, as discussed. However, a large part of experts and literature agrees that SMRs can play an important role in nuclear power and could determine the future of the industry. SMRs cannot hurt nuclear power, and, should there actually be one, they should be a part of the nuclear resurgence world-wide.

However, the recommended approach and support for SMRs should be different from the approach that legislators have taken or are taking with large reactors. While in the case of large reactors, as discussed in the previous section, subsidies and support are necessary still in the short term, for SMRs that is not entirely the case. So far, industry has demonstrated that it can take a lead on R&D, marketing, technology innovation and public-private partnerships in support of their ideas. Firms have been able to secure funding from private investors, and that is a very encouraging sign, given that nuclear is currently not a money-making enterprise, at least not in the short timeframe that investors usually operate under. This leads the Heritage Foundation, but also experts like Mike Peters, to recommend reducing or eliminating government subsidies for

SMRs, or at least focusing on R&D and licensing only. This will ensure that SMRs have a level playing field, and firms developing and commercializing them have a case to the market.[245]

The economics of SMRs appear more attractive due to their size and the amount of the initial investment, at least as presented by manufacturers today. It is impossible to assess whether this is the case until some are built and tested, but since more utilities could afford SMRs, unlike large reactors, the manufacturing process and delivery would become more attractive. Financing costs would also likely be more manageable because it would be undertaken in smaller increments, and run-up time or cost overruns would be minimized, since the reactors are standardized. In addition, since the manufacturing would likely primarily take place in the US, at least at first, the advantage is that utilities could work with the manufacturer in partnership for the development, delivery and operation of the plant.

Since there aren't sufficient clean energy technologies to meet the world's baseload electricity needs, SMRs can fill the void until those technologies are developed. This does not mean that they would take the place of large plants, but where a 1000MWe plant might not be needed, a 300 – 500 MWe modular array may be ideal. Even if large nuclear power expands, despite the hurdles, opposition and constraints on manufacturing, some areas in the world will not be provided with that power given inadequate grids, remote locations or specialized consumption of energy in industrial processes. SMRs can complement that market segment, along with planning in small and medium communities, and play a vital role in meeting the world's energy demand. In the event of enacted carbon legislation, price volatility for fossil fuels, economic or political crises in volatile areas, or other shocks, SMRs could provide a steady baseload stream of energy that can be used not only in the US, but around the developed and developing world.

The nuclear industry appears to be moving along on SMRs. Interest exists not only in the US, but also China, India, Russia, and it is likely that, if new reactors are built soon and prove to be all the industry hopes for, then France, Japan, South Africa, Finland, Sweden and others will follow suit, creating an even larger market for SMRs, not only for direct generation (stand-alone or replacing carbon emitting plants), but also for desalination, mining or industrial processes. This is why SMRs have a role to play and may prove to be an important solution in the 21st century future of nuclear power.

There is also an argument to pursue SMRs now for competitive advantage. The US currently has the lead in developing SMRs, according to Daniel Ingersoll, Mike Peters and Michael Corradini. In order to maintain that edge, the industry should continue pushing for design certification and construction. A booming SMR manufacturing industry in the US that is competitive worldwide can bring back jobs from overseas, a situation that is extremely important for policymakers in today's economic environment. The US, which has lost manufacturing capacity for civilian nuclear power and no longer has the lead in nuclear development after having invented and developed the industry, could retake that lead in SMR manufacturing.

Henry Sokolski disagrees, especially because, in recent history, first-mover advantage did not materialize, and in fact cost the first-mover more money (as is the case with the Areva/Siemens-built Olkiluoto 3 European Pressurized Reactor), leading to overruns and more taxpayer money being wasted. [246] He suggests that the US should let others built SMRs, and after they prove to be viable, develop an industry and commercialize them, following the Japanese car manufacturer model of improving on American technology. Sharon Squassoni agrees that first-mover advantage in the space is not important and that US manufacturers should work at a reasonable pace and learn from other's mistakes rather than rush into things.

From a policy perspective, government should continue to do what it is currently doing, but in some areas pull back on the support it is providing for SMRs. Since SMR development has occurred without significant government support (different from large nuclear), the recommendations are straightforward in order to make them self-sustaining and viable:

1. Support commercialization of SMRs near ready for deployment at the federal level through assistance with regulatory process and fees, as well as loan guarantees for deployment of several test units only
2. Continue to improve regulatory process and build expertise and manpower for licensing LWR SMRs, as well as advanced reactors within an acceptable timeframe
3. Support the NRC in becoming the leader in SMR certification, just as it is the leader and standard to follow in LWR certification. This should be done in order to maintain control over the technology as it is developed and deployed worldwide
4. Support investment in advanced reactor R&D through national labs. Currently, the Obama administration allocated money for building test reactors ($500 million). Similar levels of funding as the past should be allocated in order to develop new technologies.
5. Encourage private– public partnerships for development and commercialization of reactors and provide support where needed, whether technical expertise or financial
6. Encourage and provide technical expertise to private partnerships and consortiums looking at SMR development
7. If the technology proves to be economically viable and a large-scale deployment is deemed appropriate by utilities and parties interested, provide tax and other incentives for manufacturing and development facilities once reactors are completed

8. Consider purchasing several SMRs for use on military or other federal facilities not requiring permitting to demonstrate the technology for the general public[247]
9. Require private liability insurance private liability insurance and ensure that government does not enter the insurance guarantee business (as it does for large scale) for SMRs
10. Continue to explore waste management solutions and adapt them to SMR spent fuel

From a safety perspective, according to Roger Howsley, the IAEA should take a leading role in developing and licensing the technology worldwide, and hire or train experts in SMR design, manufacturing and operation for inspections. Existing nuclear states have a strict regime in place to monitor nuclear activity, safety in operation and compliance with IAEA regulations. This aspect would presumably not change with the introduction and widespread adoption of SMRs. In the US, for example, the NRC monitors power plant operation and safety, so SMRs would fall under its purview as well. A notable example of compliance was given by the transport of spent fuel from Serbia to Russia, under the auspices and supervision of the IAEA.[248] While that was a joint international effort, similar structures can be put in place for monitoring, inspecting and removing fuel from SMRs worldwide.

In the case of new-comers in the nuclear field (countries that wish to take advantage of the technology), strict guidelines need to be put in place to ensure safe operation and management of SMRs. Aside from having to be a signatory to the NPT, new adopters need to agree to IAEA monitoring, security guidelines and constant evaluation of operation subject to periodic review. IAEA inspectors need to be granted access to facilities at all times, and spent fuel removal needs to take place in similar safety and security conditions as the Serbian episode. This would be required by contract before any company would be willing to sign a sales agreement with any government, and strict analysis and screening of potential candidates can be performed in a pre-approval process before actual deployment and operation occurs. This methodology would ensure safety and security and likely appease skeptics of SMRs.

Conclusions

This paper has attempted to present an analysis of nuclear power, with a particular focus on Small Modular Reactors. While not meant to be an exhaustive study, and not purporting to have all the answers, it relied on literature review, expert opinions and economic modeling to arrive at its recommendations. Nuclear power is a topic that has been amply analyzed and discussed in the US and abroad, and the renewed attention to the topic is encouraging. However, given the financial crisis, climate change concerns, low gas prices or economic concerns about jobs, not much appears to be occurring with SMRs and nuclear power at the moment. Therefore, a document offering policy recommendations was seen as adding value to the debate.

On the topic of large-scale nuclear power, it is apparent that the opinions are so divided and so diverse, and the convictions and arguments on both sides so well articulated and valid that it is a hard argument to make either way. The paper attempted to collect as much information as possible and present it to the reader in an easy to follow and straightforward manner. Nuclear power has significant benefits, but also costs that appear at times insurmountable. Economics drives the argument for large plants, and currently the economics are against the expansion of the industry. Despite arguments of climate change, reduced emissions, high capacity factors and cheap operation, the high capital cost, cost overruns and utilities capitalization, cost of capital, the insurance and risk liability, waste management expenses, coupled with an overall negative public perception on the issue are holding what some have dubbed a "renaissance of nuclear power" to just an idea for now, in the United States and abroad. While China, France and other countries where the government is supporting nuclear expansion are moving forward, the future for nuclear power, on a large scale, does not appear bright.

Nonetheless, existing nuclear capacity should be maintained, while new large-scale capacity should be economically viable before being added. This of course requires some government support, because, even if climate change is not of concern, energy security and exposure to price volatility of fossil fuels should be. Electricity demand, as predicted by the EIA will increase, as will electricity rates in the US and abroad.[249] Since renewable technologies are not fully developed yet, and are also recipients of heavy subsidies from the government, as Doug Koplow mentions, exploring new nuclear through moderate supports suggested here should be a preferred approach, as a technology that is mature, proven and with good safety record. However, the subsidies should be limited to first-movers, R&D and regulatory overhaul, and the government should be only marginally involved. Support for the industry is undoubtedly needed, but that does not have to be the case in perpetuity. If the nuclear industry is able to stand on its feet without support, and compete on a level ground with other sources (be it fossil or renewable), then the economics will change and utilities would have an easier case when making a decision for investment in nuclear.

Next, SMRs are a game changer, but not in the sense that they will revive the industry overnight. They are not as a substitute for large plants, but rather a complement, a new (or in some cases modified) technology filling a niche that is ever expanding in the nuclear sector, given development goals in the world. SMRs have a place in both developed and developing countries. Energy services are needed worldwide, and, as William Moomaw believes, provision of energy services and access to them by the world's poor will lead to development. While deploying SMR technology to developing countries before being tested and approved is not an option, SMRs have the capacity to provide energy services cost effectively, carbon neutrally and, presumably, safely. While some experts may disagree, SMRs present an opportunity to modify the way nuclear power is regarded in the world. Public opinion could be changed if engineers and scientists make the effort to present nuclear in a positive light. There are unexplored opportunities that should be considered to do this.

SMRs require less policy support than large reactors, leading to less government involvement in the process than with large nuclear. That is not to say that no support is needed, and the paper has argued for steps the government should take to assist in SMR technology and deployment. Assistance with the regulatory process streamlining to deal with SMRs, incentives for manufacturing onshore, establishing the industry as a leader that others will follow and that will dominate the SMR market for the foreseeable future in exports of units and expertise are paramount. It is also important to facilitate near-ready models for deployment, testing and demonstration. Like any incipient industry, government support can be helpful, as long as it is not suffocating and creating a distortion in the market. Again, if producers get the economics right, widespread adoption limited only by capacity constraints will follow.

There is of course no guarantee that these recommendations will be followed, or that indeed the predictions of the literature or of experts will materialize. There is no telling what technologies will be available in a decade, what developments will occur on the world or domestic energy markets, or whether SMRs will indeed prove to be as successful and have as large an impact as suggested by the early stages of development. However, like any other policy and business situation, making a decision with the available information is the best that can be done. More research needs to go into SMRs. Regulatory hurdles have to be overcome. The world is at least five years away from seeing an operational model and a decade from a widespread adoption, but yet SMRs present an intriguing prospect. The development of mini-reactors, similar to large reactors, depends on a combination of technical, commercial and regulatory factors. But the process has been started and is moving ahead at an encouraging pace.

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Ferroni, Paolo. Senior Engineer, Westinghouse. Personal Phone Interview, January 28, 2011

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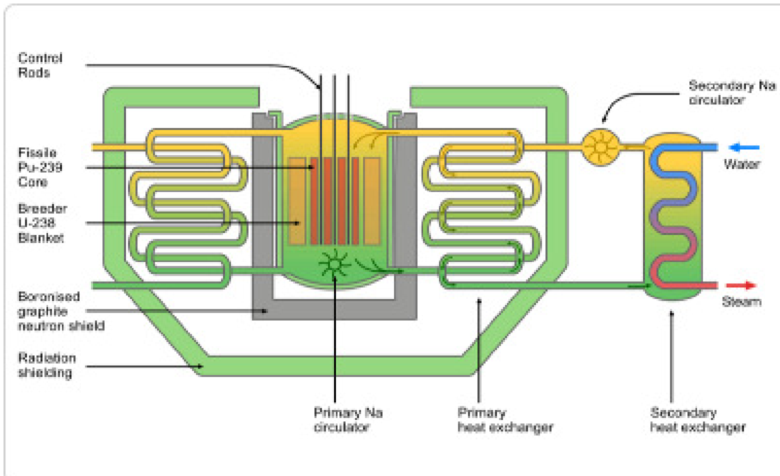
Sokolski, Henry. Executive Director of the Nonproliferation Policy Education Center. Personal Phone Interview, January 29, 2011

Squassoni, Sharon. Director and Senior Fellow of the Proliferation Prevention Program at the Center for Strategic & International Studies (CSIS). Personal Interview, February 24, 2011, Washington, DC

Appendix

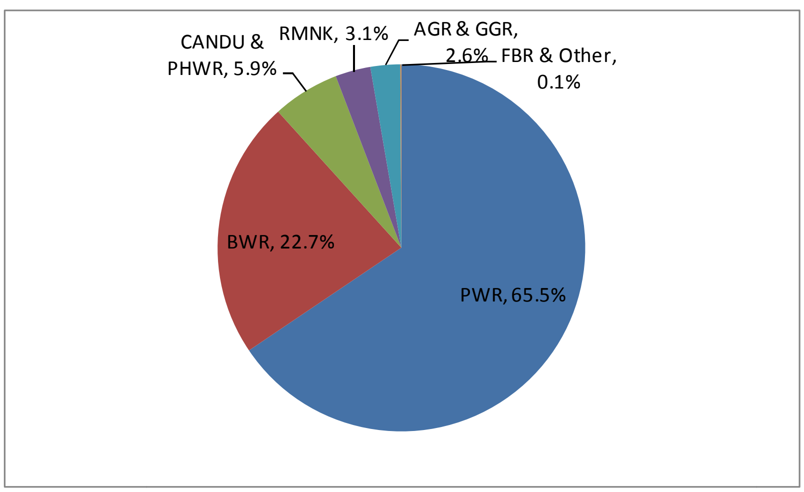
I. Charts and Figures

Figure 3 - The Fast Breeder Reactor



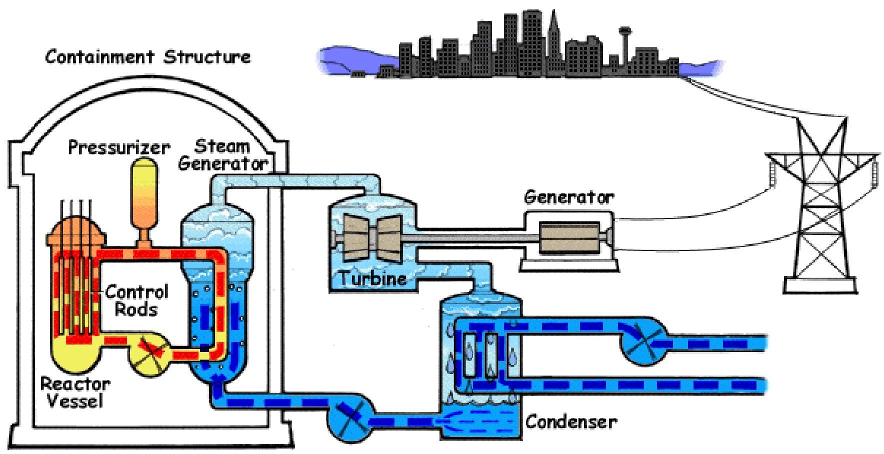
Source: http://www.ecology.at/nni/index.php?p=type&t=fbr

Figure 4 - Distribution of World Reactors (2008)



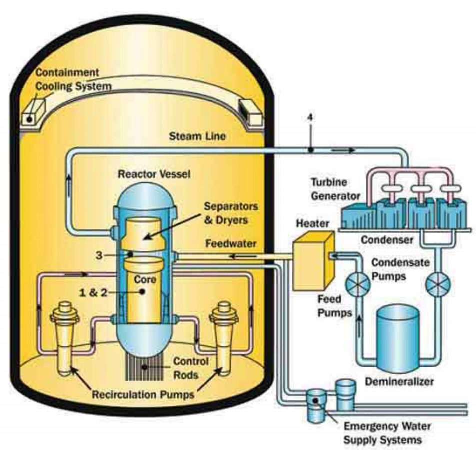
Source: http://www.oecd-nea.org/pub/nuclearenergytoday/net/nuclear_energy_today_ch1.pdf, Chart by Eugen Taso

Figure 5 - The Pressurized Water Reactor (PWR)



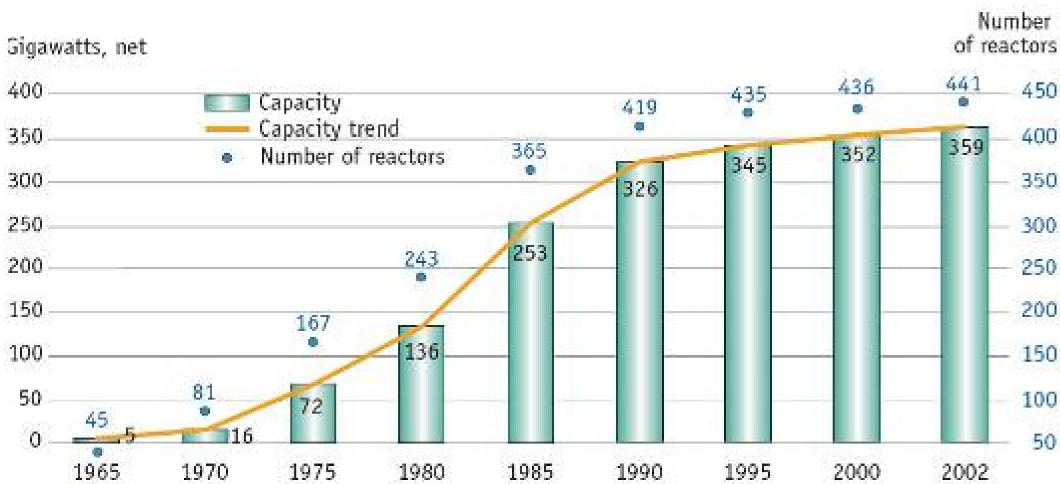
Source: http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

Figure 6 - The Boiling Water Reactor (BWR)



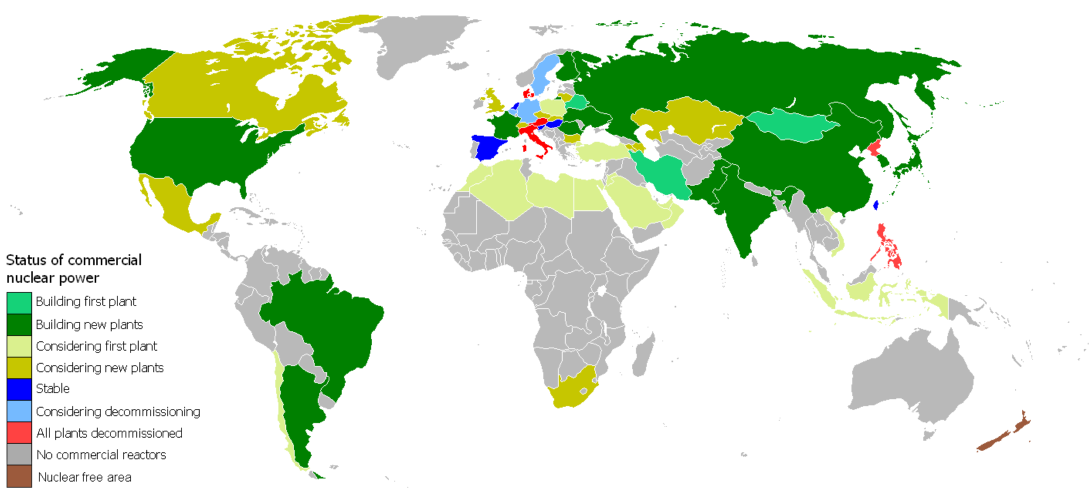
Source: http://www.nrc.gov/reactors/bwrs.html

Figure 7 - Historical Growth of Nuclear Energy (1965-2002)



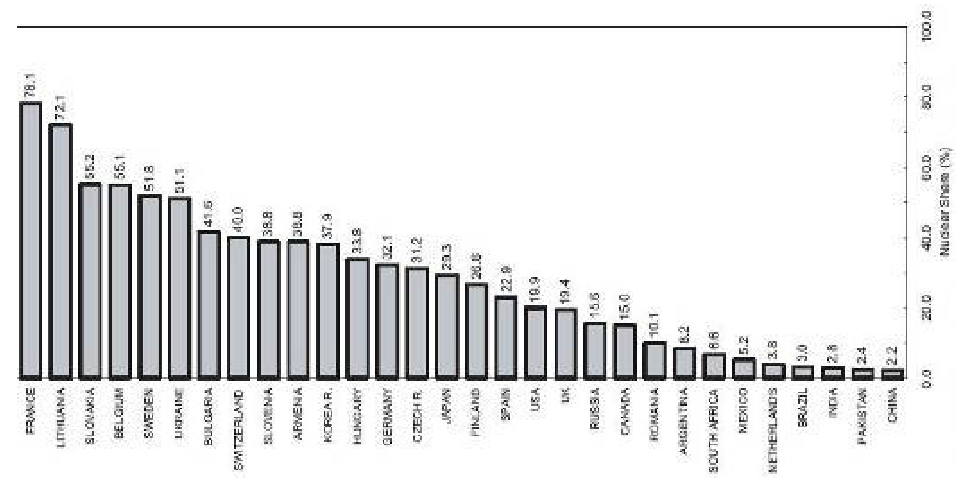
Source: http://www.oecd-nea.org/pub/nuclearenergytoday/net/nuclear_energy_today_ch1.pdf

Figure 8 - Status of Commercial Nuclear Power (2009)



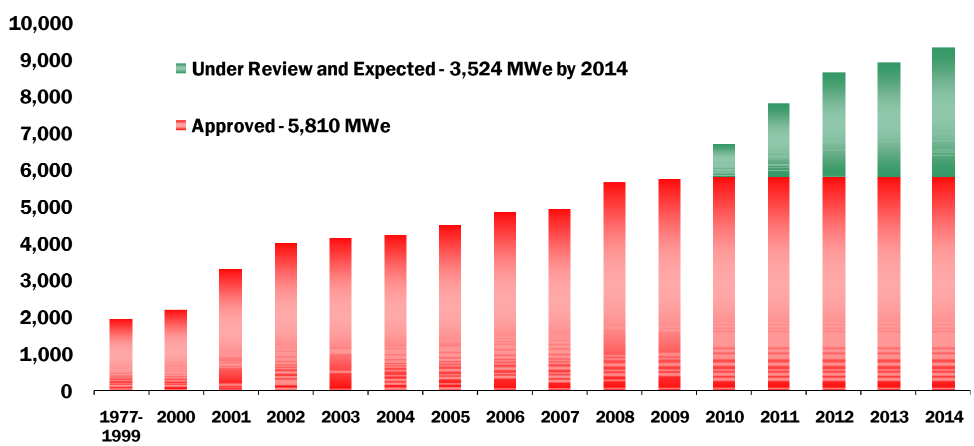
Source: http://www.oecd-nea.org/pub/nuclearenergytoday/net/nuclear_energy_today_ch1.pdf

Figure 9 - Nuclear Share of Total Electricity Generation in 2007 by Country



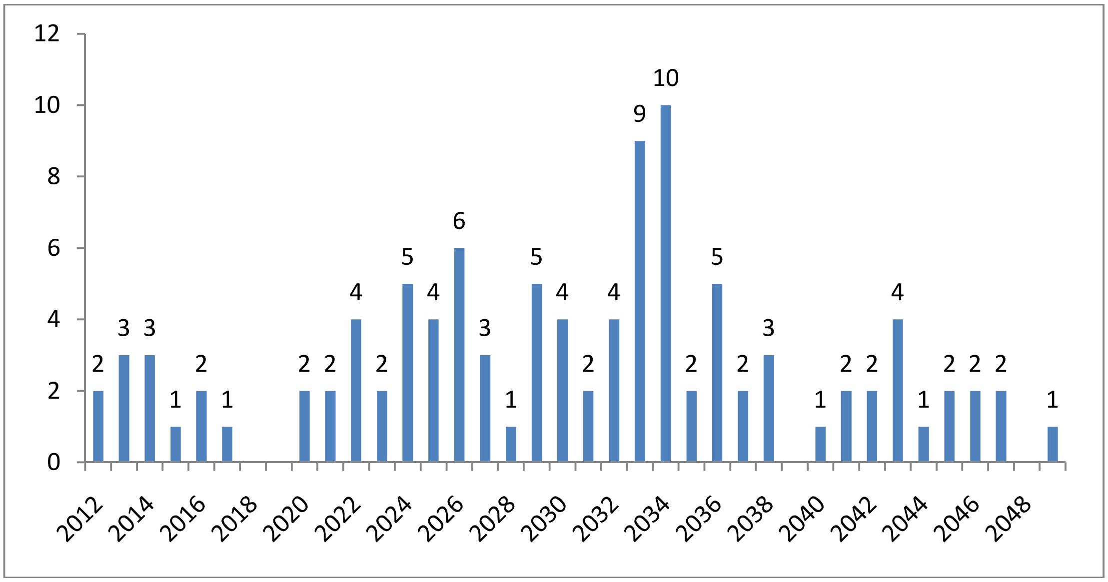
Source: http://www.ncpa.org/pdfs/ba683.pdf

Figure 10 - Cumulative Capacity Additions at U.S. Nuclear Facilities



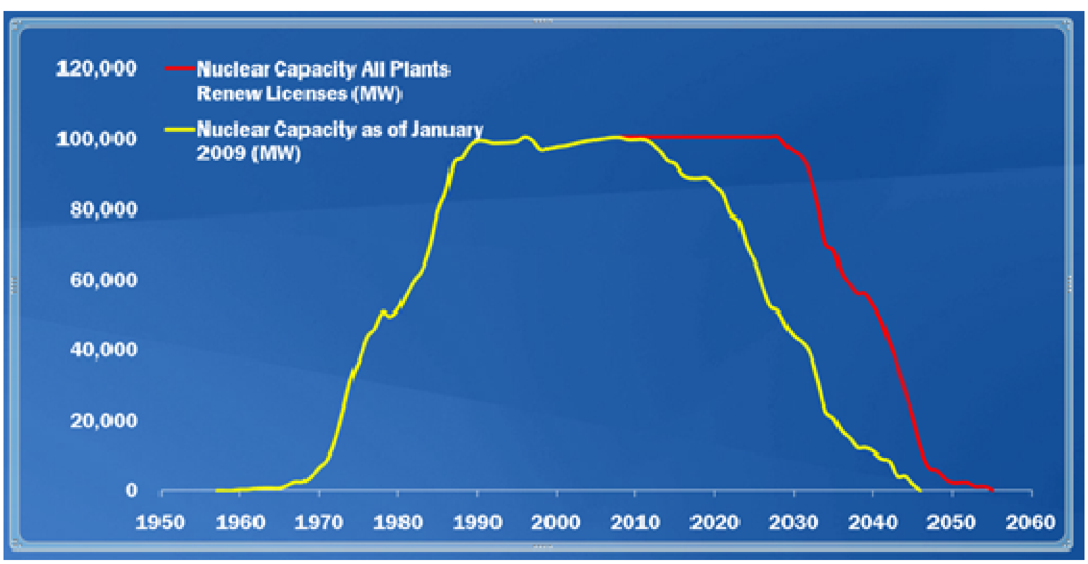
Source: Source: NEI “Latest Nuclear Stats” Presentation, October, 2010

Figure 11 - U.S. Nuclear Plant License Expirations



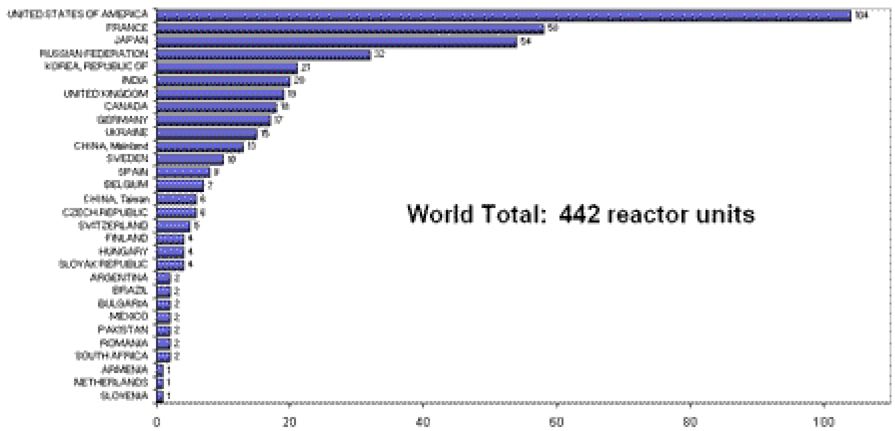
Source: Source: NEI "Latest Nuclear Stats" Presentation, October, 2010; Chart by Eugen Taso

Figure 12 - All U.S. Nuclear Plants Apply for License Renewal



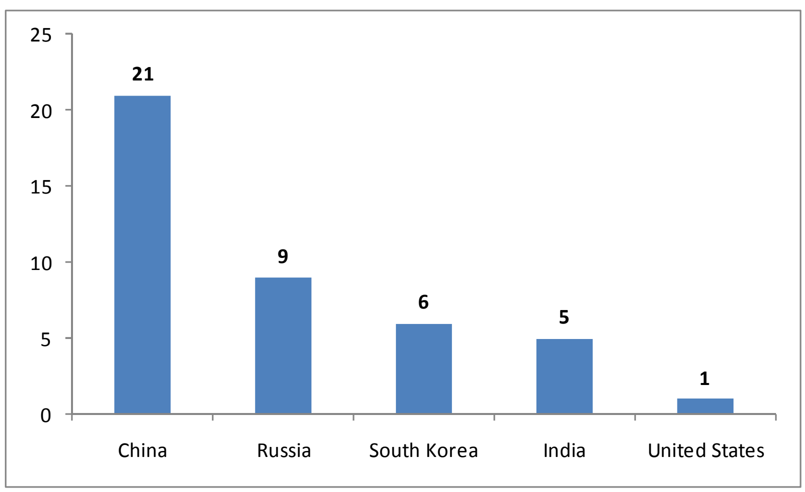
Source: NEI "Latest Nuclear Stats" Presentation, October, 2010

Figure 13 - Number of Reactors in Operation Worldwide



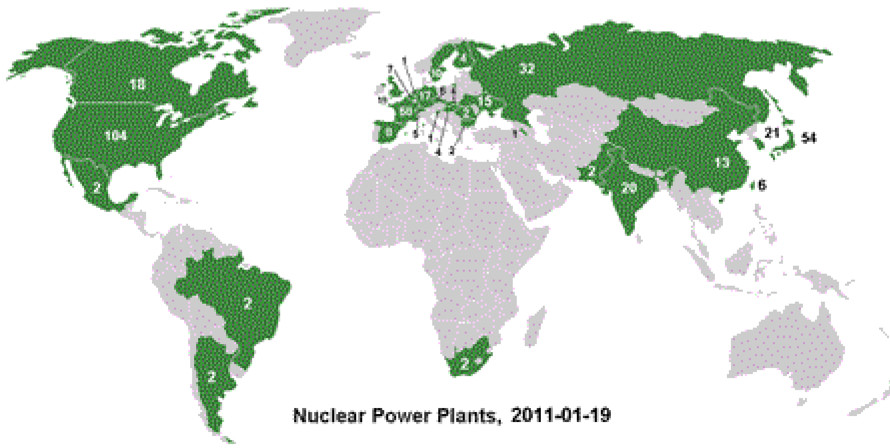
Source: Euronuclear.org

Figure 14 - New Nuclear Reactors under Construction



Source: http://www.ncpa.org/pdfs/ba683.pdf

Figure 15 - Existing Nuclear Power Plants (2011)



Source: Euronuclear.org

Figure 16 - Model Output: Price of Electricity with Natural Gas @ $8/million BTU

	Production Cost ($/kWh/year)*	Internal Rate of Retun for Investment	Required Price of Electricity ($/kWh)*
Coal	$0.074	12%	$0.079
Coal w/ Carbon Tax	$0.141	12%	$0.138
Coal w/ CCS	$0.114	12%	$0.141
Natural Gas	$0.128	12%	$0.098
Natural Gas w/ Carbon Tax	$0.166	12%	$0.130
Natural Gas w/ CCS	$0.177	12%	$0.153
OnShore Wind	$0.057	12%	$0.109
OffShore Wind	$0.131	12%	$0.262
Small Solar	$0.195	12%	$0.392
Large Solar	$0.150	12%	$0.331
Nuclear	$0.057	12%	$0.124

Source: http://www.eia.doe.gov/oiaf/beck_plantcosts/index.html#2, Eugen Taso Analysis

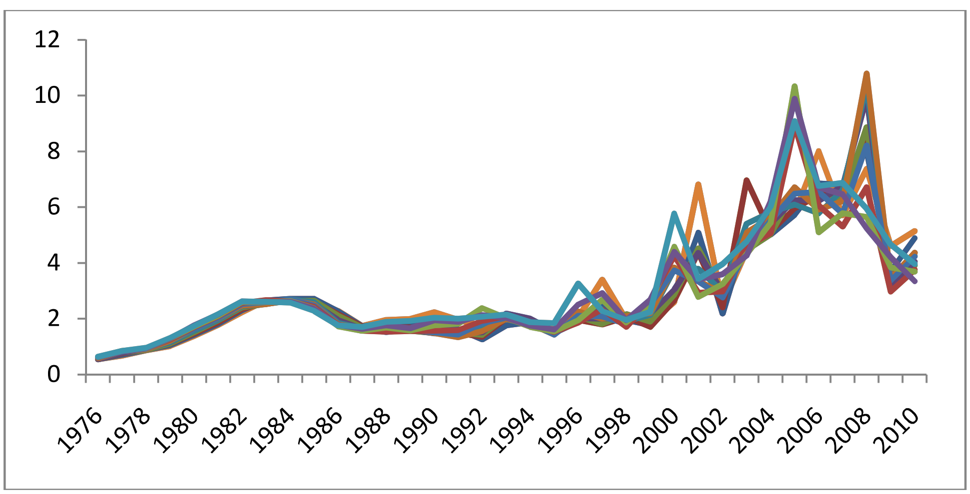
Figure 17 - Model Output: Price of Electricity with Carbon Tax of $200

	*Production Cost ($/kWh/year)**	*Internal Rate of Retun for Investment*	*Required Price of Electricity ($/kWh)**
Coal	$0.074	12%	$0.079
Coal w/ Carbon Tax	$0.232	12%	$0.215
Coal w/ CCS	$0.114	12%	$0.141
Natural Gas	$0.092	12%	$0.073
Natural Gas w/ Carbon Tax	$0.157	12%	$0.129
Natural Gas w/ CCS	$0.136	12%	$0.124
OnShore Wind	$0.057	12%	$0.109
OffShore Wind	$0.131	12%	$0.262
Small Solar	$0.195	12%	$0.392
Large Solar	$0.150	12%	$0.331
Nuclear	$0.057	12%	$0.124

* Average total cost over lifetime divided by production/year
* Price needed today to get the required IRR for the investment

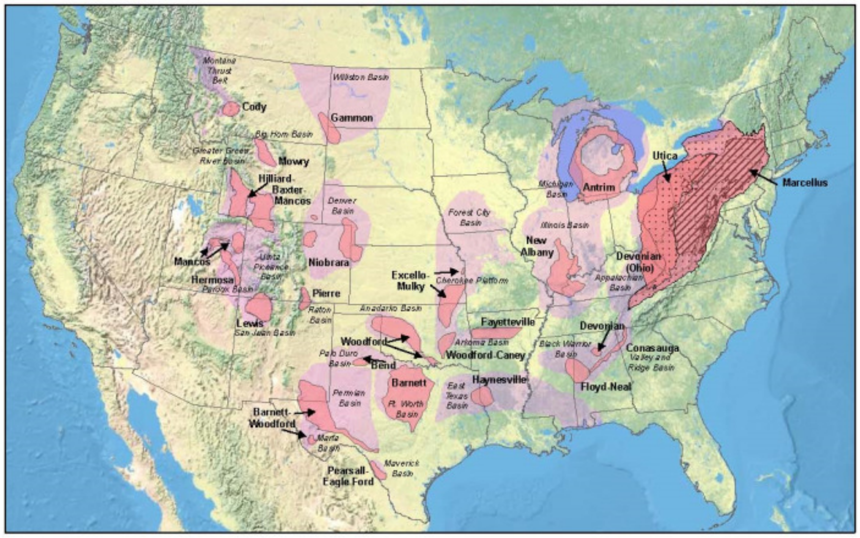
Source: http://www.eia.doe.gov/oiaf/beck_plantcosts/index.html#2, Eugen Taso Analysis

Figure 18 - US Natural Gas Monthly Wellhead Prices (1976 - 2010)



Source: http://www.eia.doe.gov/finance/performanceprofiles/pdf/overview.pdf; Eugen Taso Chart

Figure 19 - US Shale Gas Reserves, 2008



Source: http://www.eia.doe.gov/oil_gas/rpd/shaleusa2.pdf

Figure 20 - Model Output: Comparative Pricing for Generation Sources

	Production Cost ($/kWh/year)*	***Internal Rate of Retun for Investment***	***Required Price of Electricity ($/kWh)****
Coal	$0.074	12%	$0.079
Coal w/ Carbon Tax	$0.101	12%	$0.103
Coal w/ CCS	$0.114	12%	$0.141
Natural Gas	$0.092	12%	$0.073
Natural Gas w/ Carbon Tax	$0.100	12%	$0.080
Natural Gas w/ CCS	$0.136	12%	$0.124
OnShore Wind	$0.057	12%	$0.109
OffShore Wind	$0.131	12%	$0.262
Small Solar	$0.195	12%	$0.392
Large Solar	$0.150	12%	$0.331
Nuclear	$0.057	12%	$0.124

* Average total cost over lifetime divided by production/year
* Price needed today to get the required IRR for the investment

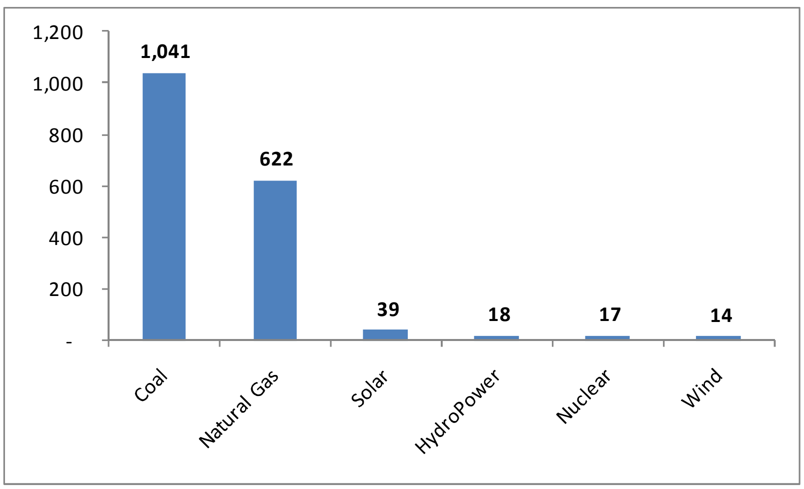
Source: http://www.eia.doe.gov/oiaf/beck_plantcosts/index.html#2, Eugen Taso Analysis

Figure 21 – Model Output: Operation and Maintenance Costs (per kWh per year)

	Fixed O&M	Variable O&M	Fuel Costs	Total per kWh
Coal	$0.005	$0.006	$0.027	$0.037
Coal w/ CCS	$0.010	$0.012	$0.037	$0.059
Natural Gas	$0.004	$0.024	$0.061	$0.089
Natural Gas w/ CCS	$0.008	$0.059	$0.072	$0.139
OnShore Wind	$0.011	$0.000	$0.000	$0.011
OffShore Wind	$0.020	$0.000	$0.000	$0.020
Small Solar	$0.017	$0.000	$0.000	$0.017
Large Solar	$0.011	$0.000	$0.000	$0.011
Nuclear	$0.011	$0.001	$0.000	$0.012

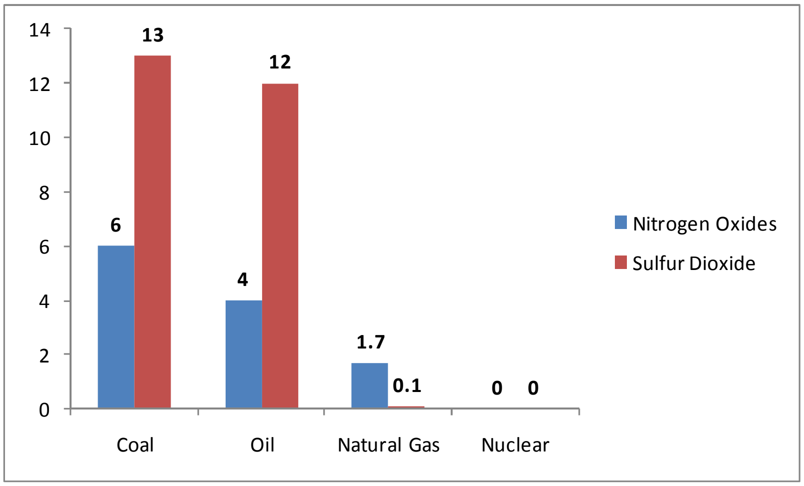
Source: http://www.eia.doe.gov/oiaf/beck_plantcosts/index.html#2, Author Analysis

Figure 22 - Tons of CO_2 Emitted per GWh



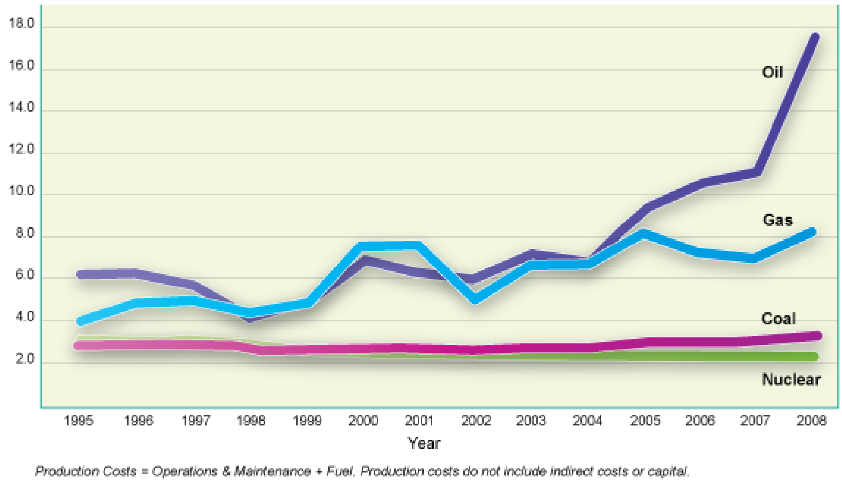
Source: http://www.ncpa.org/pdfs/ba683.pdf

Figure 23 - Power Plant Emission (pounds per MWh of electricity)



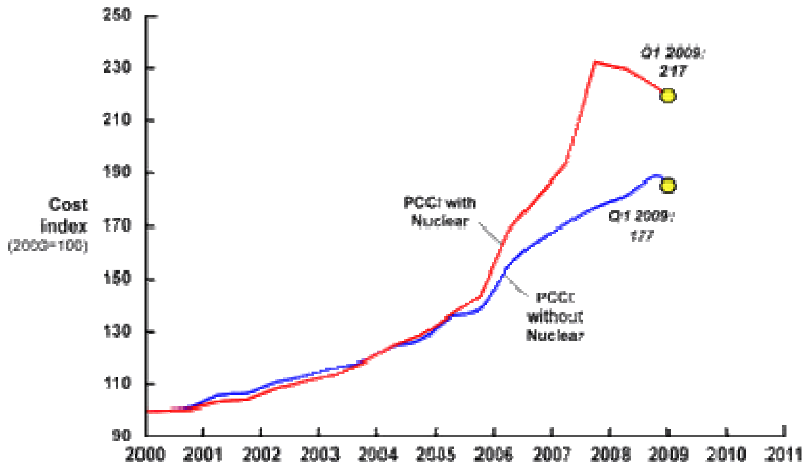
Source: http://www.ncpa.org/pdfs/ba683.pdf

Figure 24 - US Electricity Production Costs (constant 2001 cents/KWh)



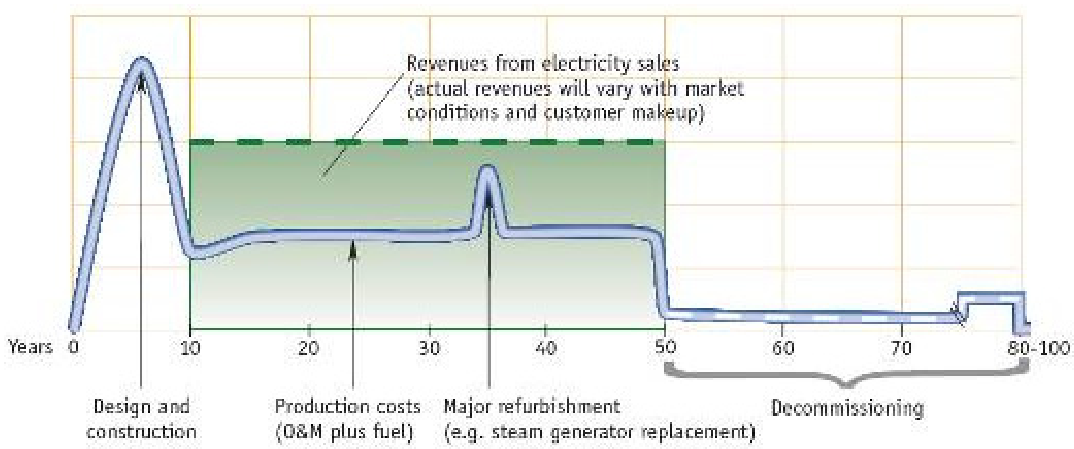
Source: http://www.world-nuclear.org/info/inf02.html

Figure 25 - PCCI with and Without Nuclear



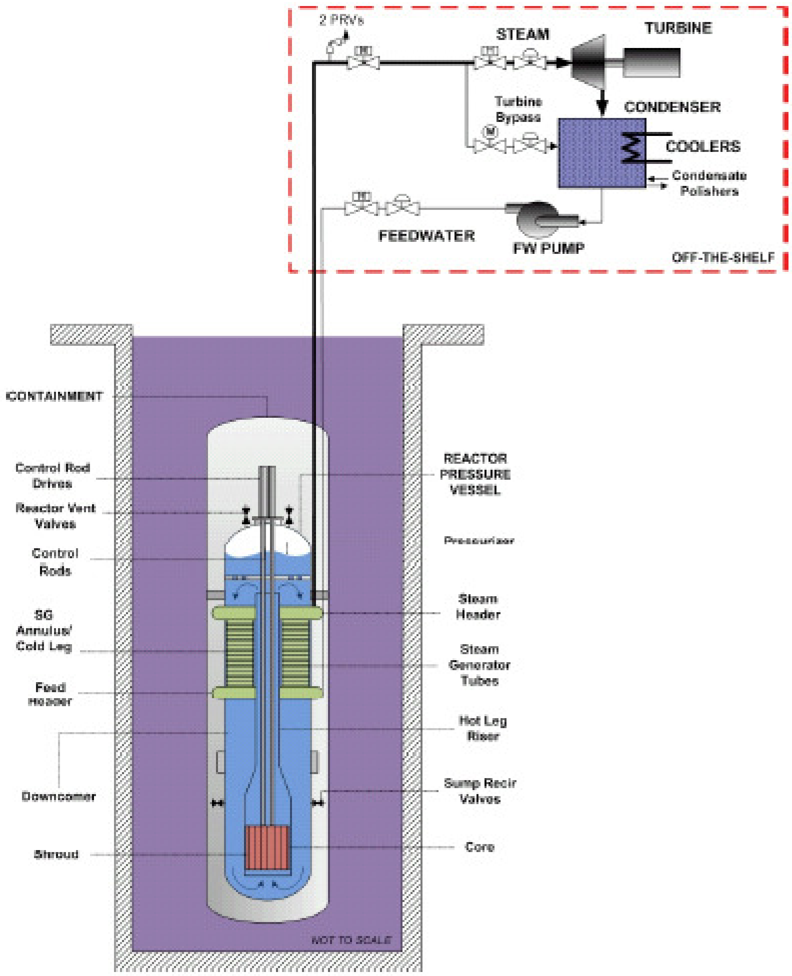
Source: http://www.ihsindexes.com/NR/rdonlyres/5A493A73-169C-4755-819B-A6AEFCABFDF7/0/121708IHSCERAPCCINov2008.pdf

Figure 26 - Illustrative Cash Flow for a Nuclear Power Plant



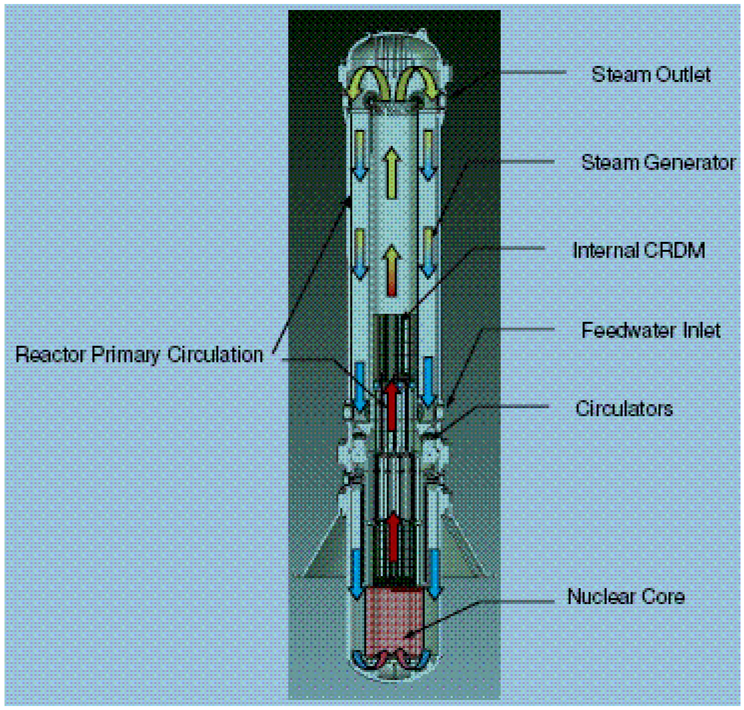
Source: http://www.oecd-nea.org/pub/nuclearenergytoday/net/nuclear_energy_today_ch1.pdf

Figure 27 - NuScale Power Reactor Design



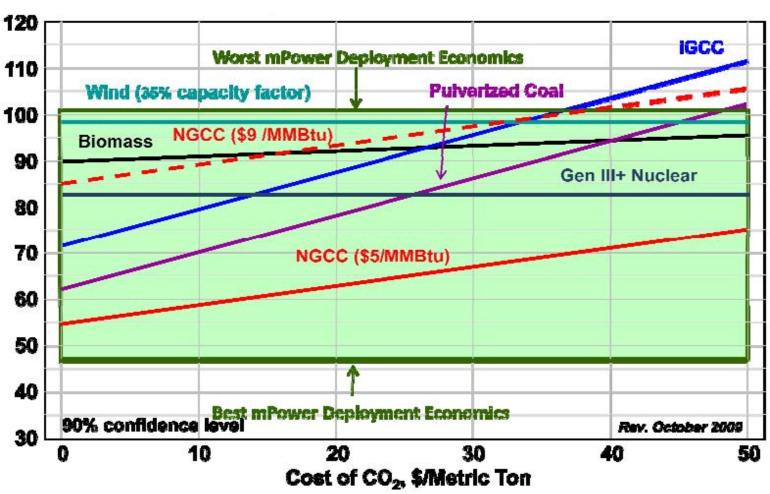
Source: http://www.nrc.gov/reactors/advanced/nuscale.html

Figure 28 - B&W mPower Reactor Design



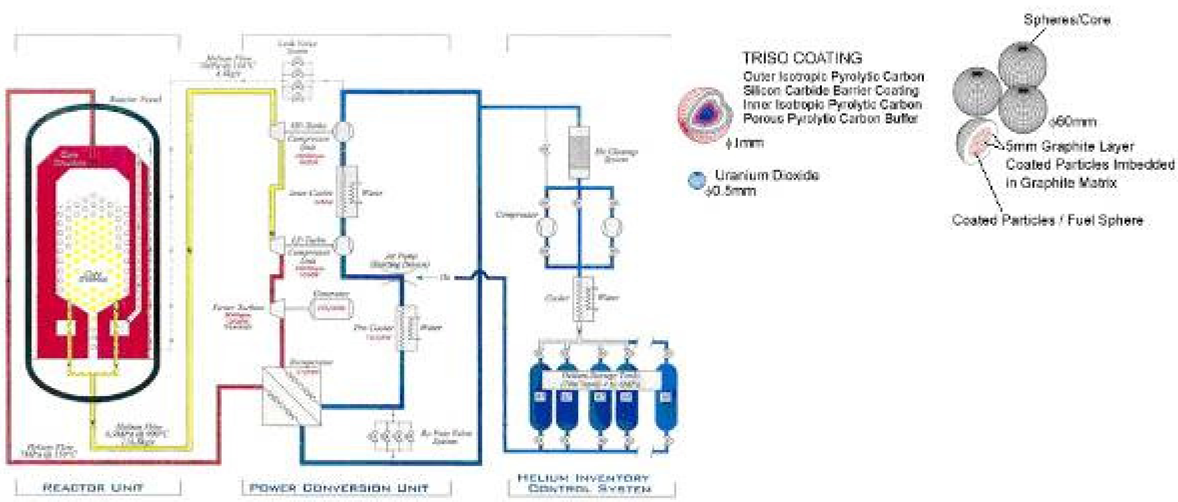
Source: http://www.nrc.gov/reactors/advanced/mpower.html

Figure 29 - Levelized Cost of Electricity, B&W mPower Reactor



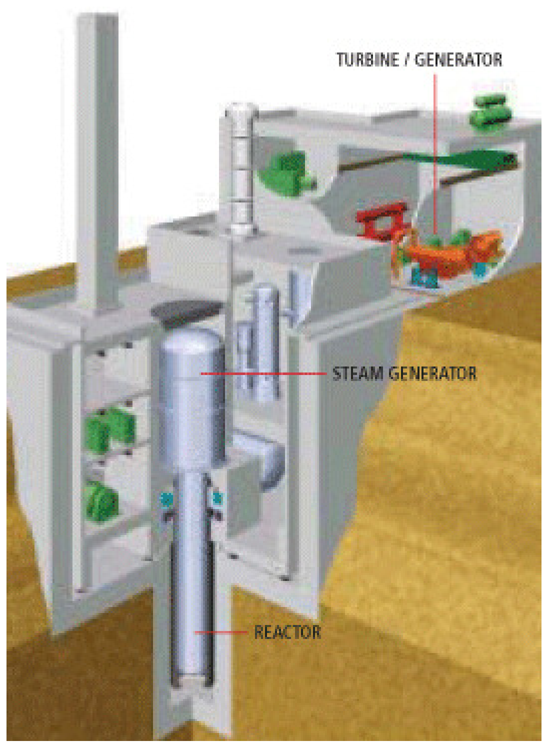
Source: https://smr.inl.gov/Document.ashx?path=DOCS%2FCongressional.pdf

Figure 30 - Pebble Bed Modular Reactor Design



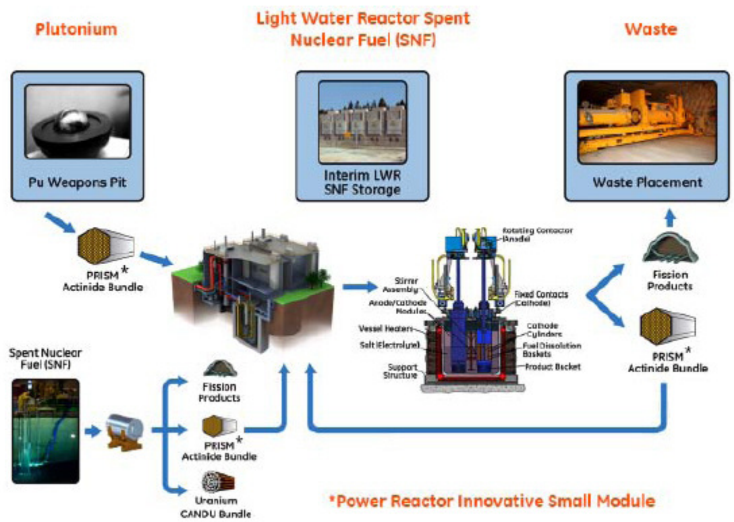
Source: http://www.nrc.gov/reactors/advanced/pbmr.html

Figure 31 - Toshiba 4S Reactor Design



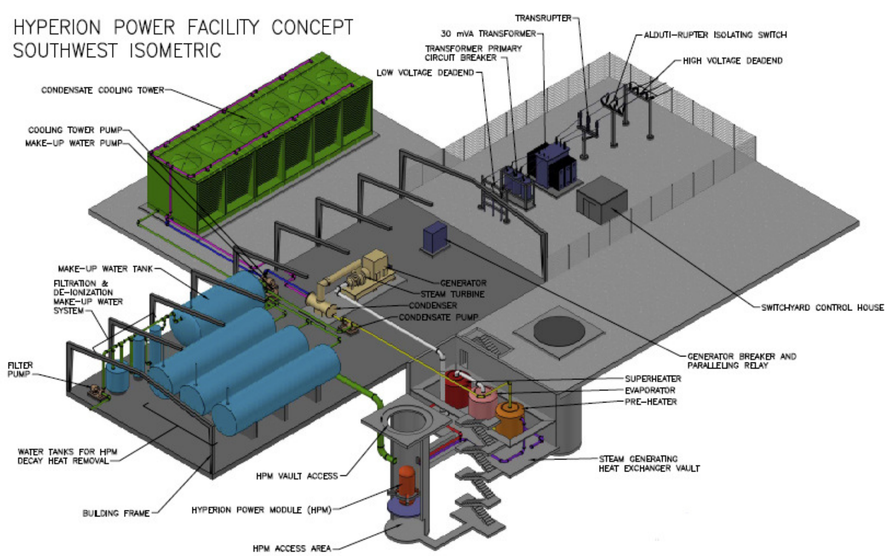
Source: http://www.nrc.gov/reactors/advanced/4s.html

Figure 32 - GE Hitachi PRISM Reactor Cycle



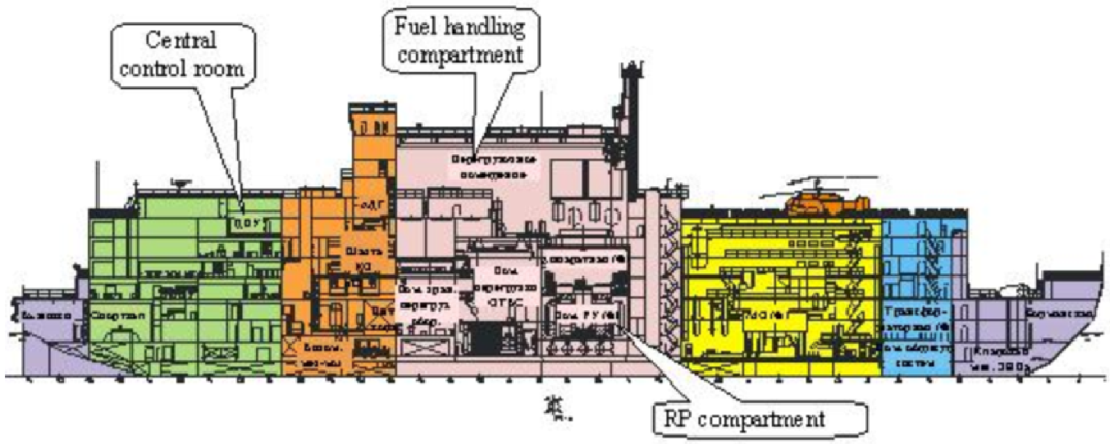
Source: http://www.nrc.gov/reactors/advanced/prism.html

Figure 33 - Hyperion Power Module Reactor Design



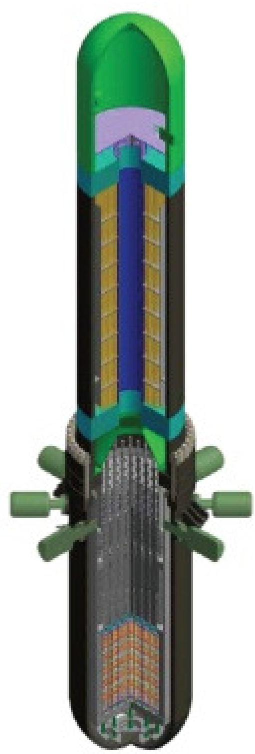
Source: http://www.nrc.gov/reactors/advanced/hyperion.html

Figure 34 - Russian KTL-40S Floating Reactor Design



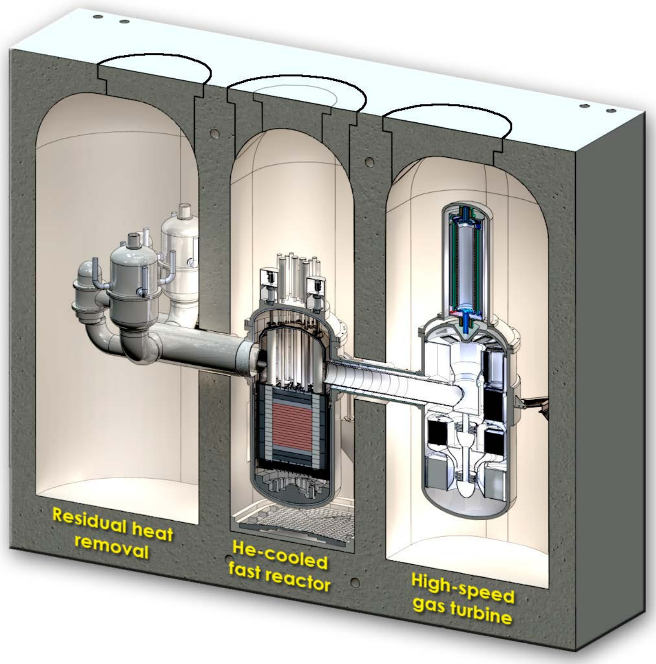
Source: http://aris.iaea.org/ARIS/download.cgi?requested_doc=report&doc_id=73&type_of_output=pdf

Figure 35 - Westinghouse SMR Reactor Design



Source: http://www.westinghousenuclear.com/smr/fact_sheet.pdf

Figure 36- GA EM2 Reactor Design



Source: http://www.ga.com/energy/em2/pdf/FactSheet-TechnicalFactSheetEM2.pdf

II. Biographies of Interviewed Experts

As part of the research for this thesis, I was extremely fortunate to have the opportunity to interview, either by phone or in person, a wide panel of experts, ranging from regulators of nuclear power, to academics, nuclear engineers, think tank experts, industry representatives and environmental activists. While their input is interspersed throughout the thesis, I though it easiest to include a list of the interviewees and their brief biographies here.

Mr. John Banks is Non-Resident Fellow in the Foreign Policy Program at the Brookings Institution, where he provides scholarly leadership and conducts research in support of the Energy Security Initiative (ESI). Currently, he is participating in an ESI study to recommend ways to improve the nuclear industry's role in strengthening the non-proliferation regime. Mr. Banks worked on power reform issues in Azerbaijan, Bangladesh, Guyana, India, Mozambique, Nigeria, the West Bank, Zambia and several other countries. He currently serves as Adjunct Professor at Johns Hopkins University's School of Advanced International Studies and is an Adjunct Professor at Georgetown University. He has contributed to dozens of energy reports and has provided expert testimony to the US Congress and the California Energy Commission.

Professor Matthew Bunn is an Associate Professor at Harvard University's John F. Kennedy School of Government. His research interests include nuclear theft and terrorism; nuclear proliferation and measures to control it; the future of nuclear energy and its fuel cycle; and policies to promote innovation in energy technologies. Before coming to Harvard, Bunn served as an adviser to the White House Office of Science and Technology Policy, as a study director at the National Academy of Sciences, and as editor of Arms Control Today. He is the author or co-author of some 20 books or major technical reports, and over a hundred articles in publications ranging from Science to The Washington Post. He is an elected Fellow of the American Association for the Advancement of Science; a recipient of the American Physical Society's Joseph A. Burton Forum Award for "outstanding contributions in helping to formulate policies to decrease the risks of theft of nuclear weapons and nuclear materials"; and the recipient of the Hans A. Bethe Award from the Federation of American Scientists for "science in service to a more secure world."

Professor Luisa Chiesa is Assistant Professor, Department of Mechanical Engineering at Tufts University. Dr. Chiesa's primary research area is superconducting materials for energy application. She recently received a $750,000 early career award from the U.S. Department of Energy for her work to enhance the durability of superconducting wires

Professor Michael Corradini is a mechanical and nuclear engineer with research interests centered primarily in thermal hydraulics and multiphase flow. He especially emphasizes the areas of reactor operation, reactor safety, reprocessing, and recycle and risk assessment. He is Chair of the Energy Institute, Faculty Governance Committee and the Director of the college's Wisconsin Institute of Nuclear Systems. He has spent 30 years in academia and has also worked for Sandia National Laboratory for a good part of his career.

Dr. Charles Ferguson has been the president of the Federation of American Scientists since January 1, 2010. At the Council on Foreign Relations (CFR), he most recently served as the project director of the Independent Task Force on U.S. Nuclear Weapons Policy. In addition to his work at CFR where he specialized in arms control, climate change, energy policy, and nuclear and radiological terrorism, Dr. Ferguson also is an adjunct professor in the security studies program at Georgetown University and an adjunct lecturer in the national security studies program at the Johns Hopkins University. Previously, from 2002 to 2004, Dr. Ferguson had been with the Monterey Institute's Center for Nonproliferation Studies (CNS) as its scientist-in-residence. Dr. Ferguson also has consulted with the Oak Ridge National Laboratory, Sandia National Laboratories, and the National Nuclear Security Administration. From 2000 to 2002, he served as a physical scientist in the Office of the Senior Coordinator for Nuclear Safety at the U.S. Department of State, where he helped develop U.S. government policies on nuclear safety and security issues. After graduating with distinction from the United States Naval Academy, he served as an officer on a fleet ballistic missile submarine and studied nuclear engineering at the Naval Nuclear Power School.

Dr. Paolo Ferroni holds a PhD from MIT in nuclear engineering. He is currently a senior engineer at Westinghouse, working on the AP1000 reactor and looking at fast reactors. He has participated in studies of SMRs from design perspective.

Professor Kelly Sims Gallagher is Associate Professor of Energy and Environmental Policy at The Fletcher School. She is a faculty associate of the Center for International Environment and Resource Policy's (CIERP), and its Energy, Climate, and Innovation (ECI) research program. She is also Senior Research Associate and a member of the Board of Directors of Belfer Center for Science and International Affairs at Harvard University, where she previously directed the Energy Technology Innovation Policy (ETIP) research group. Broadly, she focuses on energy and climate policy in both the United States and China. She is particularly interested in the role of policy in spurring the development and deployment of cleaner and more efficient energy technologies, domestically and internationally. A Truman Scholar, she has a MALD and PhD in international affairs from The Fletcher School at Tufts University, and an AB from Occidental College. She speaks Spanish and basic Mandarin Chinese. She is the author of China Shifts Gears: Automakers, Oil, Pollution, and Development (The MIT Press 2006), editor of Acting in Time on Energy Policy (Brookings Institution Press 2009), and numerous academic articles and policy reports.

Mr. Paul Genoa is the Director of Policy Development at the Nuclear Energy Institute. His focus is on developing unified industry policies and effectively communicating those policies to key stakeholders. His technical, regulatory and political experience makes him a valuable resource to policymakers on nuclear energy and environmental issues. He is Vice Chair of the Industry Trade Advisory Committee chartered by Congress to advise the U.S. Secretary of Commerce and the U.S. Trade Representative on energy issues. His professional career in the nuclear industry has spanned 25 plus years working as a Health Physicist on radiation protection and environmental issues at the Florida Power Corporation - *Crystal River Nuclear Plant*, the Arizona Public Service - *Palo Verde Nuclear Generation Station*, and at the Consumers Power - *Big Rock Point Atomic Plant.* He joined the Institute in March of 1995. Mr. Genoa received his B.S. Degree in Environmental Health at Colorado State University's *School of Veterinary Medicine & Biomedical Sciences*. He received his M.B.A. from NOVA University's *School of Business and Entrepreneurship.*

Mr. Bruce Hamilton is president of Fuelco LLC, a privately held joint venture of Ameren, Luminant, and Pacific Gas & Electric. Fuelco manages the global fuel supply for its owners' nuclear power plants in Missouri, Texas, and California. The uranium procured by Fuelco produces enough electricity for five million American homes. Prior to becoming President of Fuelco, he held various management positions at Luminant's Comanche Peak Nuclear Power

Plant. Before joining TXU (now Luminant) in 2003, Mr. Hamilton served as a naval officer for over twenty-four years, retiring as a Captain in 2002. While on active duty, he had assignments in nuclear-powered cruisers and aircraft carriers, he commanded the destroyer USS John Paul Jones in the Persian Gulf, and he served as Reactor Officer for the aircraft carrier USS Nimitz during the ship's mid-life refueling overhaul, startup certification, and 2001 home-port shift from Virginia to California. In the mid-1990s, he worked at Headquarters, United States European Command as Policy Desk Officer for the former Yugoslavia where he covered the war in Bosnia and participated in the Dayton Peace Accords negotiations. Mr. Hamilton holds a B.S. from Texas A&M University, an M.A. from the U.S. Naval Postgraduate School, a graduate degree from the Naval War College, and a Ph.D. from the Fletcher School of Law & Diplomacy. He is a registered professional engineer in the state of Texas, and while at Comanche Peak, he held a Senior Reactor Operator license with the U.S. Nuclear Regulatory Commission.

Dr. Roger Howsley is the Executive Director of the World Institute for Nuclear Security (WINS) based in Vienna, Austria. He was former Director of Security, Safeguards and International Affairs for British Nuclear Fuels Ltd. And has over 25 years of international experience relating to nuclear non-proliferation and security across the nuclear fuel cycle, working with the IAEA, Euratom, National Police Forces and security organizations. Between 2001 and 2010 he was appointed to serve on the IAEA Director General's Standing Advisory Group on Safeguards Implementation. He was Chairman of the UK's Atomic Energy Police Authority on a biennial basis between 1996 and 2005 and managed it s transition to become the Civil Nuclear Constabulary in 2005, an armed police force responsible for the protection of the UK's civil nuclear sites. He led BNFL's response to the terrorist attacks of 9/11, assessing and leading the program of security enhancements at BNFL sites and interacting with Government at all levels, including an 18-month investigation into nuclear security by the Parliamentary Office for Science and Technology.

Dr. Daniel Ingersoll is a Senior Program Manager for the Nuclear Technology Programs Office at Oak Ridge National Laboratory. He recently served as Campaign Director for the Grid-Appropriate Reactors program within the Global Nuclear Energy Partnership has participated in several advanced reactor programs, including the Advanced High Temperature Reactor project, the International Reactor Innovative and Secure project, and the Space Reactor Technology Program. During his 32 years at ORNL, he led various ORNL research groups and sections dedicated to radiation transport modeling and reactor physics analysis. He holds a PhD in nuclear engineering, and has recently focused on SMRs. Pending appropriation from Congress for 2011 budget; he will be named technical director on SMRs nation-wide

Mr. James Joosten is the Senior Energy Analyst for the U.S. Energy Information Administration in Washington DC. He has about 35 years of nuclear experience in both the private sector and government sector. Prior to his work at the EIA, he was Senior Reactor Operator and Control Room Supervisor at the Zion 1 & 2 reactors with Commonwealth Edison, Technical Assistant to an NRC Commissioner and the NRC Executive Director of Operations, reactor safety inspector for the IAEA, and the Principal Administrator for Nuclear Development at the OECD Nuclear Energy Agency in Paris. Jim holds Bachelor and Master's degree in Nuclear Engineering and Engineering Physics from the University of Wisconsin, as well as a Master's Degree in National Security Studies from Georgetown University. He has personally examined over 150 nuclear facilities worldwide.

Mr. Mark Kirshe is a 30 year veteran of the nuclear industry, encompassing the commercial, industrial, institutional and governmental markets. He has been directly involved in operational projects, market development from the "front end" to the "back end" of the fuel cycle. He has worked to develop new nuclear power plant facilities, (Front End; UniStar/Constellation/EDF/AREVA), as well as spent fuel, D&D and disposal projects (Back End; Chem. nuclear/Duratek/EnergySolutions) for existing plants. He has extensive experience with "at plant" operational support services at operating nuclear power plants, numerous technical papers and a patent for low level liquid waste processing via reverse osmosis.

Mr. Doug Koplow founded Earth Track in 1999 to more effectively integrate information on energy subsidies. Over the past 20 years, Mr. Koplow has written extensively on natural resource subsidies for organizations such as the National Commission on Energy Policy, the Organization for Economic Cooperation and Development (OECD), the United Nations Environment Programme (UNEP), Greenpeace, the Alliance to Save Energy, and the U.S. Environmental Protection Agency. He has analyzed scores of government programs and made important developments in subsidy valuation techniques. His work outside of the subsidy area has included water conservation, wastewater treatment, hazardous waste tracking, recycling, and brown fields redevelopment. Mr. Koplow holds an MBA from the Harvard Graduate School of Business Administration and a BA in economics from Wesleyan University. He served on United Nations Environment Programme's Working Group on Economic Instruments from 2001-2004; and the National Recycling Coalition's Policy Workgroup from 1998-2003.

Professor Richard Lester is Japan Steel Industry Professor and Head of the Department of Nuclear Science and Engineering (NSE) at the Massachusetts Institute of Technology, where he is also the faculty co-chair and founding Director of the MIT Industrial Performance Center. His research focuses on innovation management and policy, with an emphasis on the energy and manufacturing sectors. He is currently leading the Energy Innovation Project, a major MIT study of strategies for upgrading the U.S. energy innovation system. He currently serves as faculty advisor to the MIT President’s Council on Regional Engagement. He is a co-author of the widely-cited recent MIT reports on The Future of Nuclear Power (2003) and The Future of Coal (2007), and has published many articles on the management and control of nuclear technology. Professor Lester obtained a doctorate in nuclear engineering from MIT, and has been a member of the MIT faculty since 1979. He serves as an advisor or consultant to corporations, governments, foundations and non-profit groups, and lectures frequently to academic, business and general audiences throughout the world.

Mr. Stephen Maloney is former nuclear navy officer, currently a consultant on risk management for energy markets. He has extensive experience with power plants, is a chief engineer and CIW reactor certified. He consulted in nuclear safety, fire protection, and station blackout. He has also had experience with the regulatory process and has worked with purchase and sale of nuclear plants, testifying on cost overruns.

Professor William Moomaw is Professor of International Environmental Policy at the Fletcher School of Law and Diplomacy, Tufts University, where he is the founding director of the Center for International Environment and Resource Policy, the Tufts Climate Initiative and co-founder of the Global Development and Environment Institute. He is a physical chemist with a PhD from MIT. He was a coordinating lead author of the 2001 Intergovernmental Panel on Climate Change chapter on greenhouse gas emissions reduction, and for the special report on renewable energy due in 2010. He was a lead author of three other IPCC reports (1995, 2005 and 2007). The work of the IPCC was recognized with the 2007 Nobel Peace Prize. He also was an author for the Millennium Ecosystem Assessment on nitrogen and serves on the Integrated Nitrogen Committee of the EPA Science Advisory board. He was the first director of the Climate, Energy and Pollution program at the World Resources Institute, and directed the Center for Environmental Studies at Williams College where he held an endowed chair in chemistry. Dr. Moomaw currently serves on the Board of Directors of The Climate Group, Clean Air-Cool Planet (which he co-founded), Earthwatch Institute, Center for Ecological Technologies and the Consensus Building Institute.

Dr. Mark Peters is Argonne National Laboratory's Deputy Director for Programs and leads the development of the long- and short-term strategic plan for Argonne's science and technology mission. Prior to this, he was the deputy associate laboratory director for Energy Sciences and Engineering at Argonne, where he was responsible for the management of ongoing energy and environment programs coupled with development of new program opportunities at the laboratory, management and integration of the energy and environment-related Laboratory Directed Research and Development program (LDRD), and support of the DOE Advanced Fuel Cycle Initiative (AFCI). Peters was also responsible for program management and development in high-level nuclear waste disposal across Argonne, management and technical leadership of Department of Energy (DOE) long-term science and technology work related to radionuclide source terms and advanced waste forms, and technical support to senior DOE management on the Yucca Mountain Project (YMP)

Dr. Robert Petroski has a PhD in nuclear engineering from MIT and an undergraduate degree in engineering from Berkeley. He currently works for Terra Power (Intellectual Ventures prior to that) on reactor analysis for the Traveling Wave Reactor (TWR).

Mr. Michael Snodderly is Technical Assistant to Commissioner George Apostolakis with the Nuclear Regulatory Commission. He has worked for the NRC since 1989, and has a current focus on SMRs. He has extensive experience in the nuclear field, largely with issues pertaining to Light Water Reactors, pressure vessels and other regulatory items.

Mr. Henry Sokolski is the Executive Director of the Nonproliferation Policy Education Center, a Washington-based nonprofit organization founded in 1994 to promote a better understanding of strategic weapons proliferation issues among policymakers, scholars and the media. He was appointed by the U.S. Congress to serve on the Commission on the Prevention of Weapons of Mass Destruction Proliferation and terrorism, which filed its final report in December 2008. Sokolski has been a resident fellow at the National Institute for Public Policy, the Heritage Foundation and the Hoover Institution. He currently serves as an adjunct professor at The Institute of World Politics in Washington, D.C., and has taught courses at the University of Chicago, Rosary College, and Loyola University.

Ms. Sharon Squassoni serves as Director and Senior Fellow of the Proliferation Prevention Program at the Center for Strategic & International Studies (CSIS). Prior to joining CSIS, Ms. Squassoni was a senior associate in the Nuclear Nonproliferation Program at the Carnegie Endowment for International Peace. From 2002-2007, Ms. Squassoni advised Congress as a senior specialist in weapons of mass destruction at the Congressional Research Service, Library of Congress. Before joining CRS, she worked briefly as a reporter in the Washington bureau of Newsweek magazine. Ms. Squassoni also served in the executive branch of government from 1992 to 2001. Her last position was Director of Policy Coordination for the Nonproliferation

Bureau at the State Department. She also served as a policy planner for the Political-Military Bureau at State. She began her career in the government as a nuclear safeguards expert in the Arms Control and Disarmament Agency. She is the recipient of various service awards and has published widely. She is a frequent commentator for U.S. and international media outlets. Ms. Squassoni received her B.A. in political science from the State University of New York at Albany, a Masters in Public Management from the University of Maryland, and a Masters in National Security Strategy from the National War College.

III. List of Interview Question

Note: This is not an exhaustive list, but rather meant as a starting point to inform the discussion

General Background Questions:

1. What is your opinion on nuclear power and its possible role in the energy field in the US and abroad (figures, stats, etc)?

2. What, in your opinion, are the main challenges of nuclear power today (safety, public perception, waste, cost, etc.)?

3. How would you address them?

4. Do you believe the costs outweigh the benefits when it comes to nuclear power?

5. Do you believe nuclear power has a better chance given the ongoing climate change debate?

6. Will there be a significant impact with proposed carbon legislation for the cost of nuclear power? How is nuclear power going to be affected?

7. With recent discoveries of shale gas, the price of natural gas has declined dramatically (to around $4) in the US. Do you believe this weakens the case for nuclear power from an economic standpoint?

8. If the US were to pursue a nuclear strategy wholeheartedly, what can reasonably be expected, given regulatory, financing, construction and material constraints?

9. What is your opinion on fuel reprocessing? Is it a viable alternative, or is pursuing a repository the right approach?

10. What can be done (and what has been done or attempted) to change public perception on nuclear power?

Small Modular Reactor Questions:

1. What is your opinion on Small Modular Reactors? Are they a viable technology?

2. What is your expertise with SMRs? Do you believe there is a future for them in the current US and world climate?

3. Are SMRs a game changer for nuclear power and for the energy and electricity markets worldwide?
4. Why are SMRs the new hype? The technology and concept has been around for a while, but only recently were they brought into focus.
5. Do you believe SMRs can change the playing field in the nuclear debate?
6. Can SMRs be deployed fast enough and will they have a major impact?
7. When can we reasonably expect to have functioning SMRs, if they are approved?
8. What are the most promising models, in your opinion? Why?
9. What are the benefits of SMRs?
10. What are some of the drawbacks? Are they large enough to outweigh the benefits?

IV. Small Modular Reactor Matrix

Small Modular Reactor Matrix (Promising Models)*

Manufacturer	Country of Origin	Reactor Name	Reactor Type	Reactor Capacity (MWe)	Reactor Size (m, Diam, Height)	Coolant	Fuel Type	Refueling (#, Months)	Spent Fuel Storage	Service Life (Years)	NRC Application (Expected)	Notes
NuScale Power, Inc.	USA	NuScale	MASLWR (iPWR)	45	4.3 x 18	Water (gravity)	4.95% Enriched Uranium	24	On-Site	40+	1st Quarter, 2012	NuScale has recently run into financing trouble, but its reactor is deemed by experts and the NRC to be a promising design that could be among the first to be certified
Babcock & Wilcox Cmpany.	USA	B&W mPower	ALWR (iPWR)	125	4.5 x 23	Water	5% Enriched Uranium	60	On-Site	60	4th Quarter, 2012	B&W are in advanced talks (non-binding agreement with TVA to build a reactor, and are in advanced licensing talks with the NRC
PBMR, Ltd/ESKOM	South Africa, China, Germany, Netherlands	Pebble Bed Modular Reactor	Fast Reactor (High Temperature, Gas-Cooled)	165	Graphite pebbles 60 mm diam	Pyrolytic graphite moderator, inert or semi-inert gas (helium, nitrogen or carbon dioxide)	UO_2 particles 1mm in diam	36	In pebbles	36	2013	PBMRs have had a long history and their history is uncertain. There have been instances when the fuel caught on fire. South Africa is not puruing it currently, but China is
Toshiba CRIEPI	Japan	Toshiba 4S	Fast Neutron	10 / 50	30m undergound, building 22×16×11	Sodium	20% enriched Uranium or 11.5 – 24% MOX	Never	Not Applicable	30	2nd Quarter 2012	Partnership with city of Galena, AK for a reactor, and good candidate for the 2012 budget funding for SMRs if design is licensed
GE Hitachi	USA/Japan	GE Hitachi PRISM	Fast Reactor	311	Underground Containment	Sodium	Recycled fuel from Advanced Recycling Center (Pu or DU)	12 to 24	ARC on site - reuse spent fuel	40+	2012 or 2013	NRC staff conducted pre-application review in the early 1990s, resulting in NUREG-1368, "Pre-application Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor (January 1994)."
Hyperion Power Generation, Inc.	USA	Hyperion Power Module Reactor	Fast Reactor	25	1.5 x 2m	Lead-bismuth eutectic (LBE)	20% enriched Uranium	Never	N/A	7 to 10	Unknown	Hyperion entered an agreement with Savannah River National Laboratory (SRNL) in fall 2010 to deployment the 25MWe modular reactor at the US Department of Energy's (DOE) Savannah River Site (SRS); details on timeline are unclear
Atomenergoprom/OKBM	Russia	KTL-40s	PWR	70	21,500 tonnes Length: 144.4 meters, Beam: 30 meters, Height: 10 meters Draught: 5.6 meters	Water	90% enriched Uranium-235	36	On Barge	12	Not Applicable	Based on the commercial KLT -40 marine propulsion plant, an advanced variant of RPs that power nuclear icebreakers. The first reactor was delivered in May and the second one in August 2009. Akademik Lomonosov was launched on 30 June 2010
General Atomics	USA	General Atomics EM2	Sodium-Cooled	285	Unavailable	Helium	12% Uranium 253	Never	Not Applicable	30	Unknown	Unclear timeline, as design in in incipient phases
Westinghouse	USA	Westinghouse SMR	iPWR	200	Unavailable	Water	4.95% Enriched Uranium	Unavailable	Unavailable	Unavailable	Unknown	Released on February 17, 2011, many details yet unavailable
Areva	France	ANTARES	Fast Reactor	285	Unavailable	Nitrogen/Helium mixture	graphite speres, 10 - 19.9% enriched Uranium	Unavailable	Unavailable	Unavailable	Unknown	
INET & Huaneng	China	HTR-PM	High Temperature, Gas-cooled PBMR	100	Unavailable	Graphite	UO_2 particles	Unavailable	Unavailable	Unavailable	Not Applicable	Full-size demonstration module expectved in 2013. License application filed and under review
Bhaba Atomic Research Center	India	Unknown	AHWR	300	Unavailable	Boiling water coolant, heavy water moderator	233U-Pu-Th	Unavailable	On-Site	Unavailable	Not Applicable	Pre-licensing negotiations with the Atomic Energy Regulatory body of India. Construction expected in the next decade
Invap/CNEA	Argentina	CAREM	iPWR	27	Unavailable	Water	3.5% enriched PWR fuel	Unavailable	On-Site	Unavailable	Not Applicable	CAREM reactor is a test reactor for larger, 150-300MWe units to be built mainly for domestic market
KAERI	South Korea	SMART	Co-generation plant	100	Unavailable	Unavailable	Unavailable	Unavailable	Unavailable	Unavailable	Not Applicable	Currently in pre-licensing process

Notes:

* Information obtained from manufaturer's website and other sources (WINS, etc). Information should be treated as preliminary until models are built

V. Institutional Review Board Determination

Tufts
UNIVERSITY

OFFICE OF THE VICE PROVOST

Social, Behavioral, and Educational Research
Institutional Review Board
FWA00002063

Re: IRB Study # 1102011
Title: 21st Century Civilian Nuclear Power and the Role of Small Modular Reactors
PI: Eugen Taso
Department: Fletcher
IRB Review Date: 2/8/2011

February 8, 2011

Dear Eugen,

This is the official notification that your project, *Civilian Nuclear Power in the 21st Century: The Case for Small Modular Reactors*, protocol # 1102011 does not meet the definition of human subject research under the Code of Federal Regulations Title 45 Part 46.102(f); therefore is not subject to review by the Institutional Review Board.

Please be sure to file this notification.

Sincerely,

pp Jeanne Eisenlin

Yvonne Wakeford, Ph.D.
IRB Administrator

20 Professors Row, Medford, MA 02155 | TEL: 617.627.3417 | FAX: 617.627.3673 | EMAIL: SBER@tufts.edu