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The "Delayed Effect": An Exploration of the Aging Process of the American Nuclear Fleet

Sixteen different American nuclear power plants celebrated their respective 40th birthdays during the last two years, outliving their original life expectancy predictions. Most of these nuclear power plants have been granted an additional 20 years of life through extensions of permitting agreements.[1] However, no new nuclear generated capacity has been introduced to the United States electricity grid in almost twenty years. No new nuclear construction permits have been granted in thirty-five years. And with the recent political struggle following the full meltdown of the three reactors at the Daiichi Nuclear Power center in Fukushima, Japan, it appears that both of these droughts will continue for years to come. Therefore, there are a few important questions that must be asked: Which of the fifty states in the United States are exposed to the most risk given the aging of the American nuclear fleet? How long can these existing reactors remain active, safe, profitable, and efficient? This paper will explore the previous questions through data analysis and visualization as well as case studies of older nuclear reactors.

THE "CHINA SYNDROME"

There is no way to begin an analysis of the aging American nuclear generating fleet without starting with "The China Syndrome," a 1979 full-length movie that tells the story of a reporter and her cameraman who discover safety cover-ups at a Los Angeles nuclear power plant. It starred Jane Fonda, Michael Douglas, and Jack Lemmon and was a major box office hit released in theaters and advertized all across the country a mere two weeks before the accident at the Three Mile Island

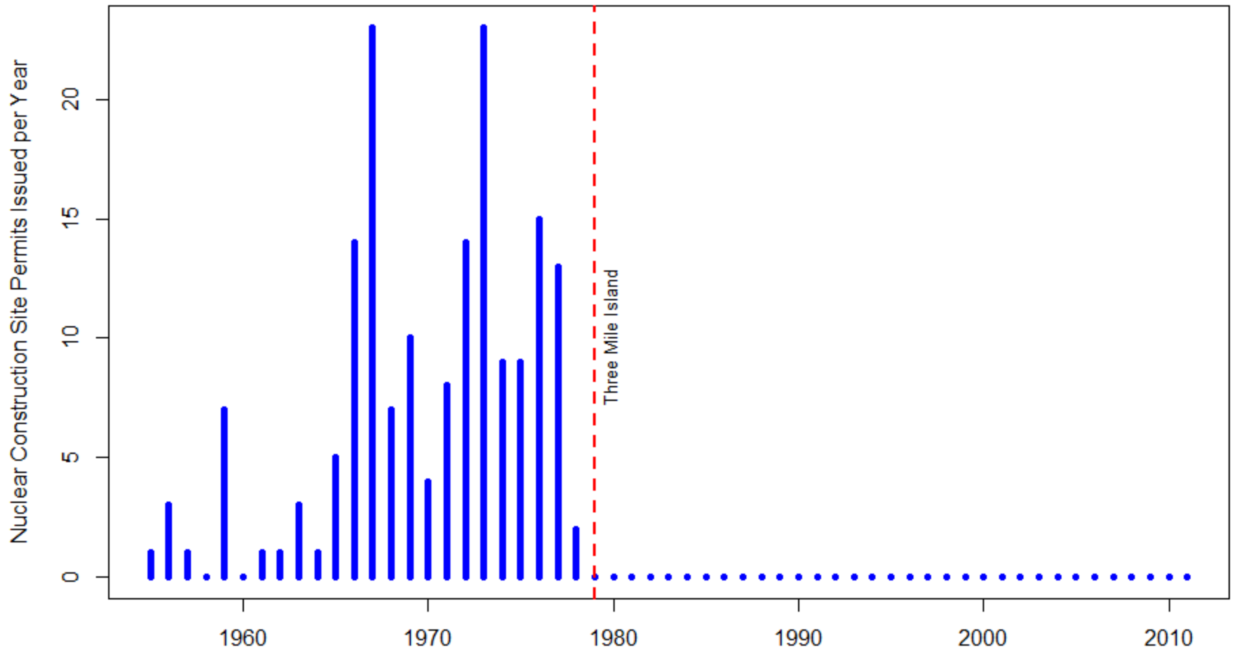
[1] State Nuclear Profiles." *Energy Information Agency*. Web. 17 Apr. 2013. <www.eia.gov/nuclear/state/pdf/snp2010.

Nuclear Generating Station near Harrisburg, Pennsylvania. The catchy title "The China Syndrome" is a reference to an off-hand comment in the film by one of the characters that describes the completely fictional worst case result of a nuclear meltdown: the reactor components melt through their containment structures and into the underlying earth "all the way to China". Despite the fact that this nuclear meltdown "all the way to China" is not physically possible, the concept stuck with audiences all around America.

Naturally, it frightened the people who had just watched "The China Syndrome" to see the news stories of the accident at Three Mile Island less than two weeks later because they equated the fictional meltdown "all the way to China" (and lack of safety precautions exhibited at the fictional Los Angeles facility) with the partial meltdown in Pennsylvania which would have been easily averted had the warning lights and buttons in the control room been placed in a more intuitive pattern. Of course, one of these scenarios was real and one was fictional, but as the years have progressed, those two scenarios separated by just two weeks have merged together in the minds of most Americans.

THE "DELAYED EFFECT"

Nuclear power construction site permits were introduced in 1955 as a way for the federal government to regulate and approve where nuclear power plants were built. There were as many as twenty three site permits granted during the peak years of 1967 and 1973, but there has not been a single nuclear power generation site construction permit approved since the release of "The China Syndrome" and the accident at the Three Mile Island Nuclear Generating Station – as is seen in the figure on the following page:



It is important to note that many construction permits do not lead to nuclear power units. Since 1950, there have been 177 nuclear construction site permits granted and yet there have only been 132 nuclear power generating reactors built over that same time period.[2] A construction permit does not guarantee that the plant will be built, but it does significantly increase the likelihood. The construction of 40 reactors has been cancelled by state and federal regulatory agencies for any number of reasons – especially after the incident at Three Mile Island.

Additionally, not all construction site permits are alike. The main difference in these permits is that roughly two-thirds have authorized breaking ground at a completely new site while the other third have authorized the creation of a new nuclear generating reactor next to or nearby an already existing unit. The process to approve the latter case has historically been an easier endeavor given that the larger battle with the local community has already been won. In fact, a large proportion of the construction site permits granted after the year 1970 (but before 1979) were for new reactors being constructed on sites with at least one nuclear generating reactor in production.

[2] "Table 9.1 Nuclear Generating Units,1955-2011."*U.S. Energy Information Admin. (EIA)*. Web.17 Apr 2013.

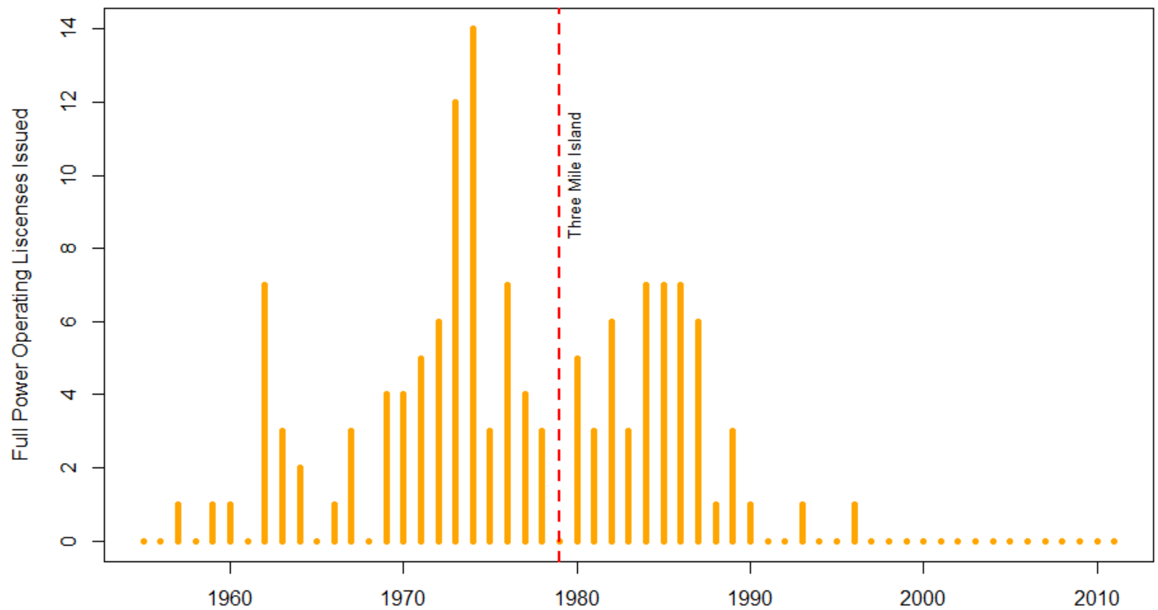
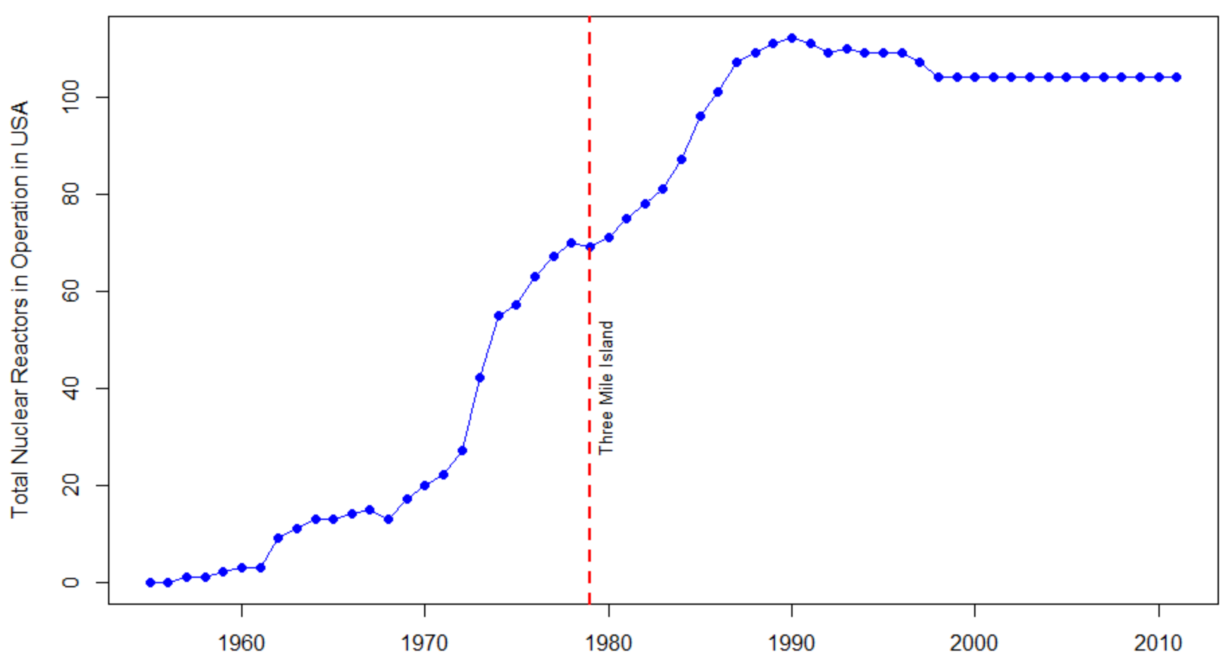
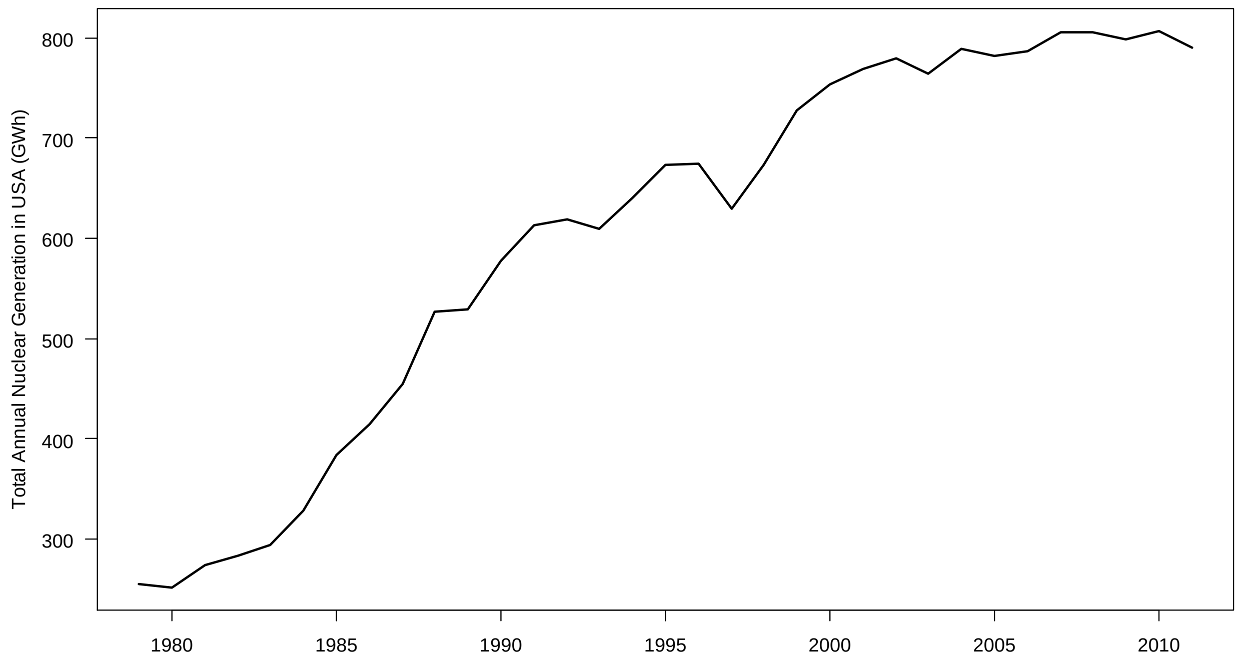


Figure 2 shows that many of the nuclear power plants under construction prior to 1979 were allowed to go forward and this new nuclear capacity was added to the grid off and on until 1996. Between the years of 1979 and 1996, this delayed additional capacity helped to offset the 15 nuclear power generating reactors that were decommissioned during that period, but Figure 3 shows that the additional reactors decommissioned during the 1990s began to diminish the overall nuclear fleet size.



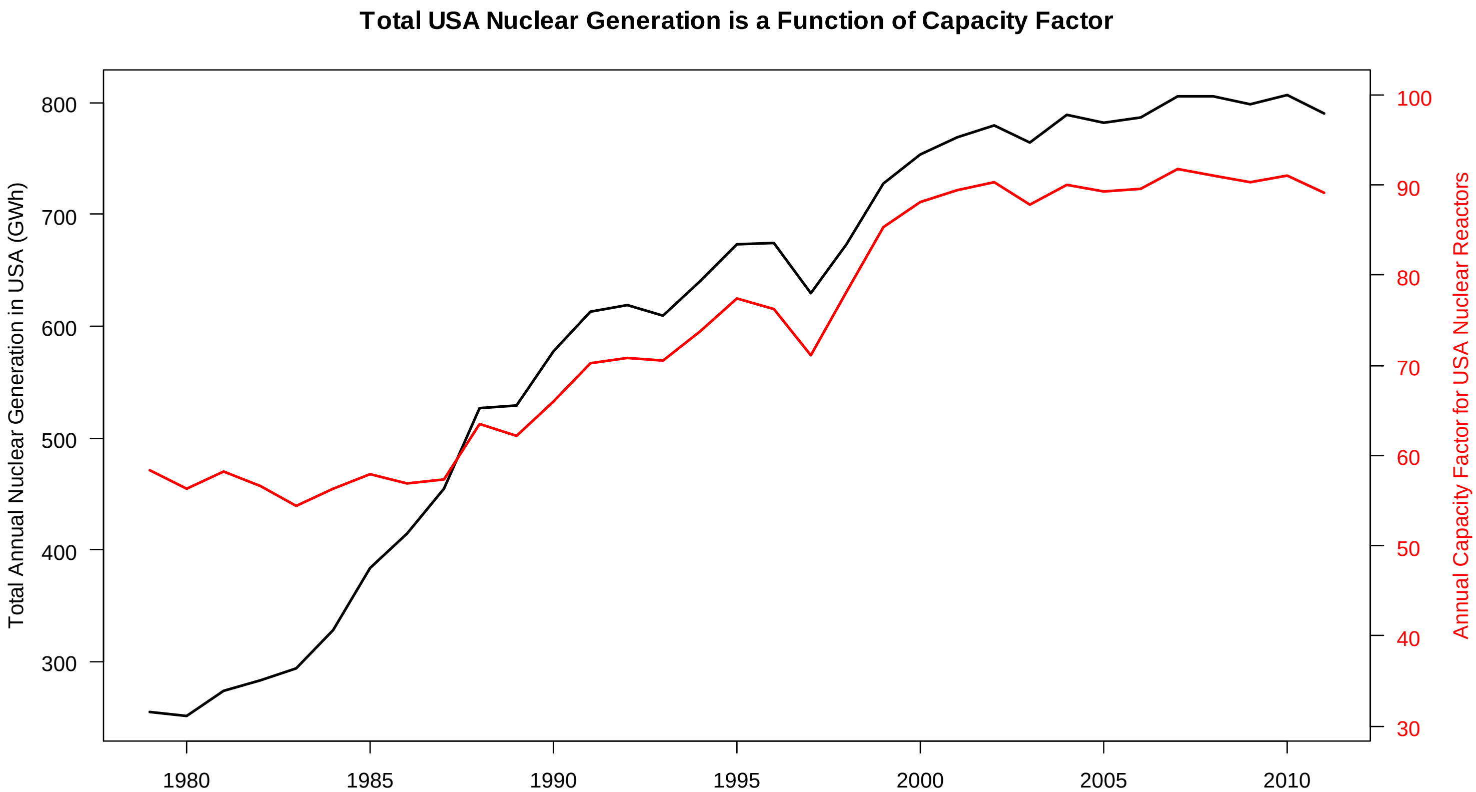
THE ALL-IMPORTANT "CAPACITY FACTOR"

Although there has not been a nuclear construction site permit approved since 1979 (Figure 1) and there has not been a new nuclear power plant brought onto the grid since 1996 (Figure 2), there has not been the drop in total nuclear generating capacity in the United States over the last few decades that one would expect given the contraction of the American nuclear energy portfolio. In fact, the plot below emphasizes that there has actually has been an increase in total nuclear generating capacity over the last twenty years:[3]



This apparent contradiction between Figure 4 and Figure 3 is due to the simple fact that the nuclear engineers – many of them are former navy nuclear engineers – have made their nuclear reactors more efficient. The efficiency of a nuclear reactor is called its "capacity factor" and this incorporates 'down time' as well as system efficiency. Using EIA data, I overlaid the aggregated capacity factors of all nuclear plants across the United States for each year on top of the total nuclear generation curve that is shown above:

[3] "Table 9.2 Nuclear Power Plant Operations,1957-2011."*U.S.Energy Information Admin*. Web 17 Apr, 2013.



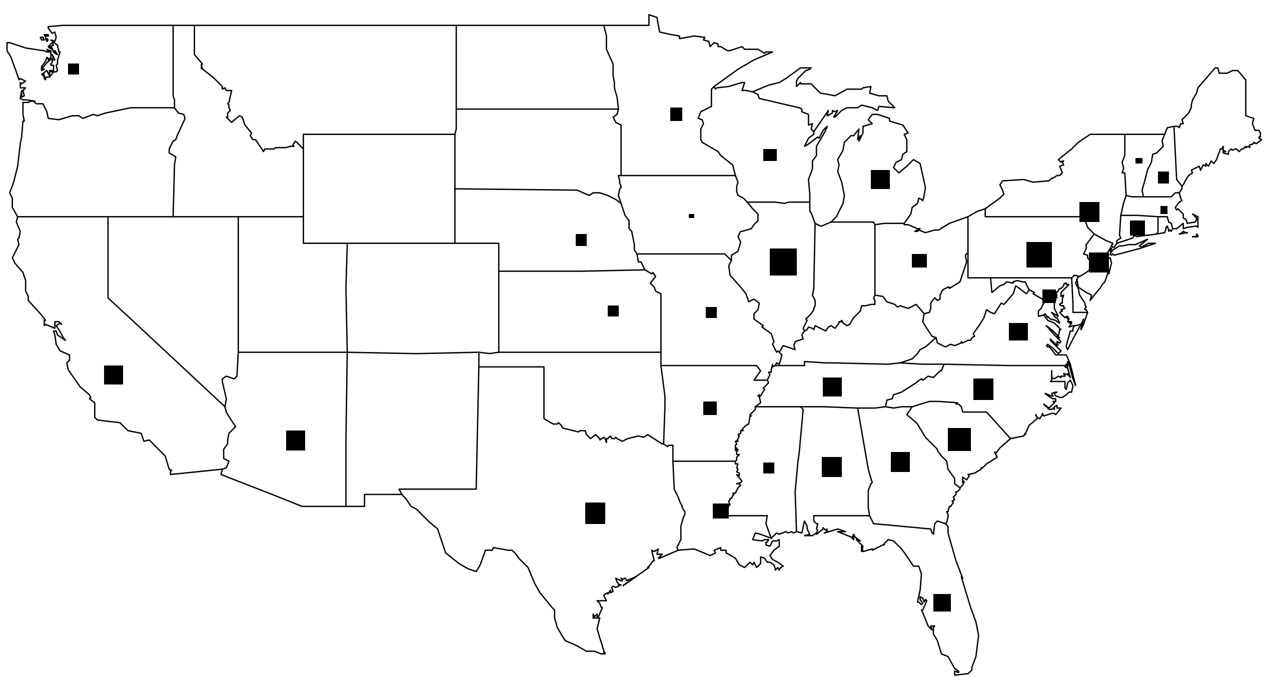
The above plot shows the essence of the "delayed effect": in the years since 1996, the increased efficiency of the nuclear generating facilities has offset the increasing number of decommissioned nuclear reactors and the lack of new nuclear reactors being given site permits and being built. In fact, after the year 1990, the amount of total nuclear generated capacity can be largely predicted as a function of the capacity factor.

It is not a given that this capacity factor will remain as high over the next decades as it is today. In fact, as our aging nuclear energy infrastructure leads to more and more nuclear reactors being decommissioned and a plummeting capacity factor (due to more downtime and maintenance time), we will likely see the "delayed effect" of a lack of nuclear site permits and construction of nuclear generating reactors in the last two decades: a sharp drop in the American nuclear generating capacity over the next twenty years.

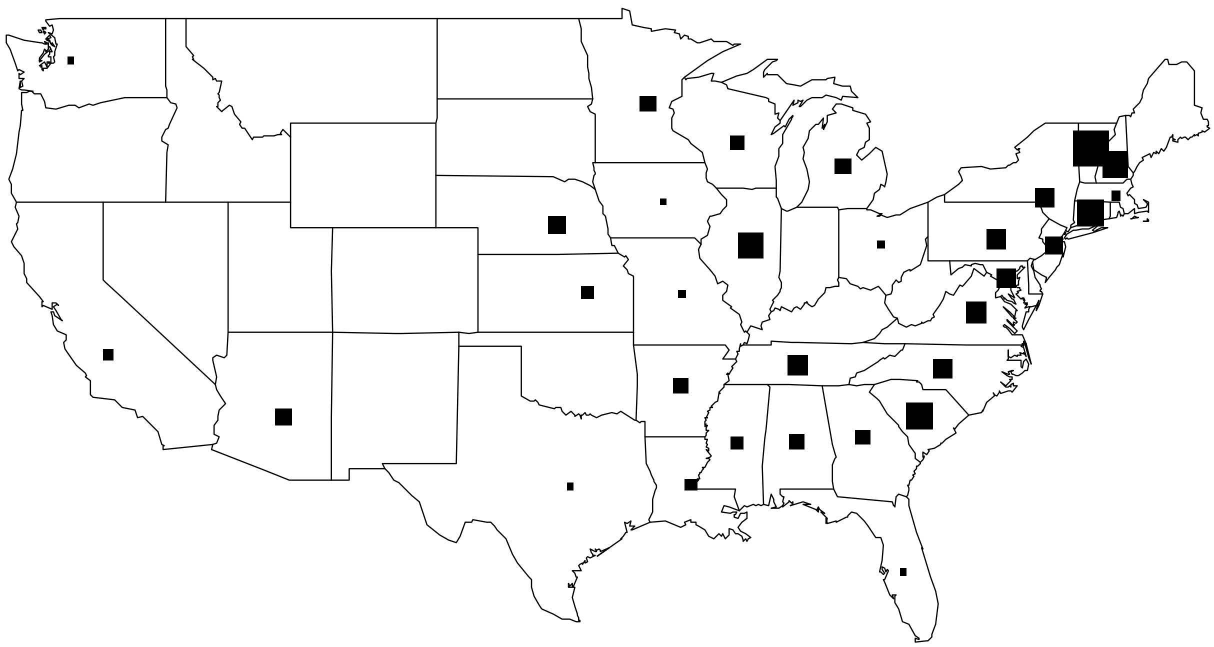
RISK FACTORS FOR THE 50 STATES

If we can assume that there will be a sharp drop in nuclear generating capacity over the next twenty years, it seems like a reasonable endeavor to determine which states within the United States will be most affected by this drop given their current energy portfolio. In order to understand the situation from the perspective of each of the fifty states, it is best to visualize the situation through three distinct levels of analysis: the statewide nuclear capacity, the age of specific nuclear generating reactors within each state, and the individual electrons produced from these units.

The net nuclear generating capacity for each state on a MWh basis is shown in figure 6. To give the reader an idea of the magnitude of the difference between dot sizes, Illinois has about ten times the nuclear generating capacity of the state of Washington.[4] Only thirty-one states have a nuclear component of their energy portfolio and it evident that most of the nuclear capacity is spread out across the eastern half of the United States.



[4] "State Nuclear Profiles." *Energy Information Agency*. Web. 17 Apr. 2013. <www.eia.gov/nuclear/state/pdf/snp2010.

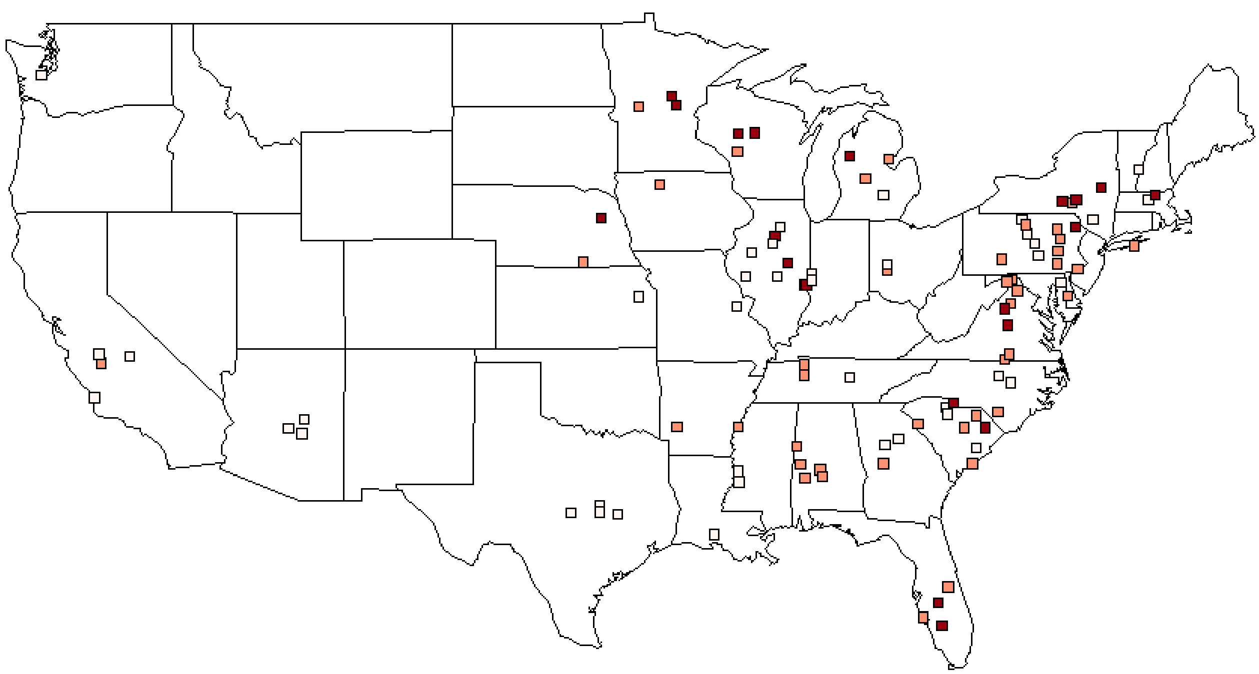


Another way of considering the risk that the drop in nuclear generating capacity will have on each state is examining that drop within the context of that state's electric power generation – looking at the percentage of electric power net generation that can be attributed to nuclear reactors within that state. While figure 6 is skewed towards the most populous states, figure 7 shifts the focus towards smaller states that have a higher dependence on their nuclear generating fleet. Vermont, New Hampshire, Connecticut, and South Carolina are all good examples of small states with at least 50 percent of the net electricity generation provided through nuclear power units.[5] Figure 7 shows the reader that there is a distinct bias towards nuclear power on a percentage basis along the east coast of the United States. It stands to reason that the states with a larger percentage of electricity generated from nuclear power will have to make a more radical adjustment in their energy portfolio as the nuclear reactors begin to be decommissioned over the coming years.

[5] "State Nuclear Profiles." *Energy Information Agency*. Web. 17 Apr. 2013. <www.eia.gov/nuclear/state/pdf/snp2010.

However, given that older nuclear reactors have historically been more likely to fail safety inspections and be decommissioned, perhaps it makes the most sense to focus on the states which have a higher proportion of their nuclear energy coming from *older* nuclear power units. This can be assessed in two main ways.

First, I have produced a visualization of all of the nuclear power generating reactors in the United States according to their age.[6] The three colors on the plot below correspond to nuclear reactors that are older than 40 years (dark red), nuclear reactors that are between 30 and 40 years old (pink), and nuclear reactors that are less than 30 years old (white). This is an interesting plot to derive information from in a qualitative manner, but it does not give us information on the size and productivity of each of these nuclear reactors or the exact age of these units.



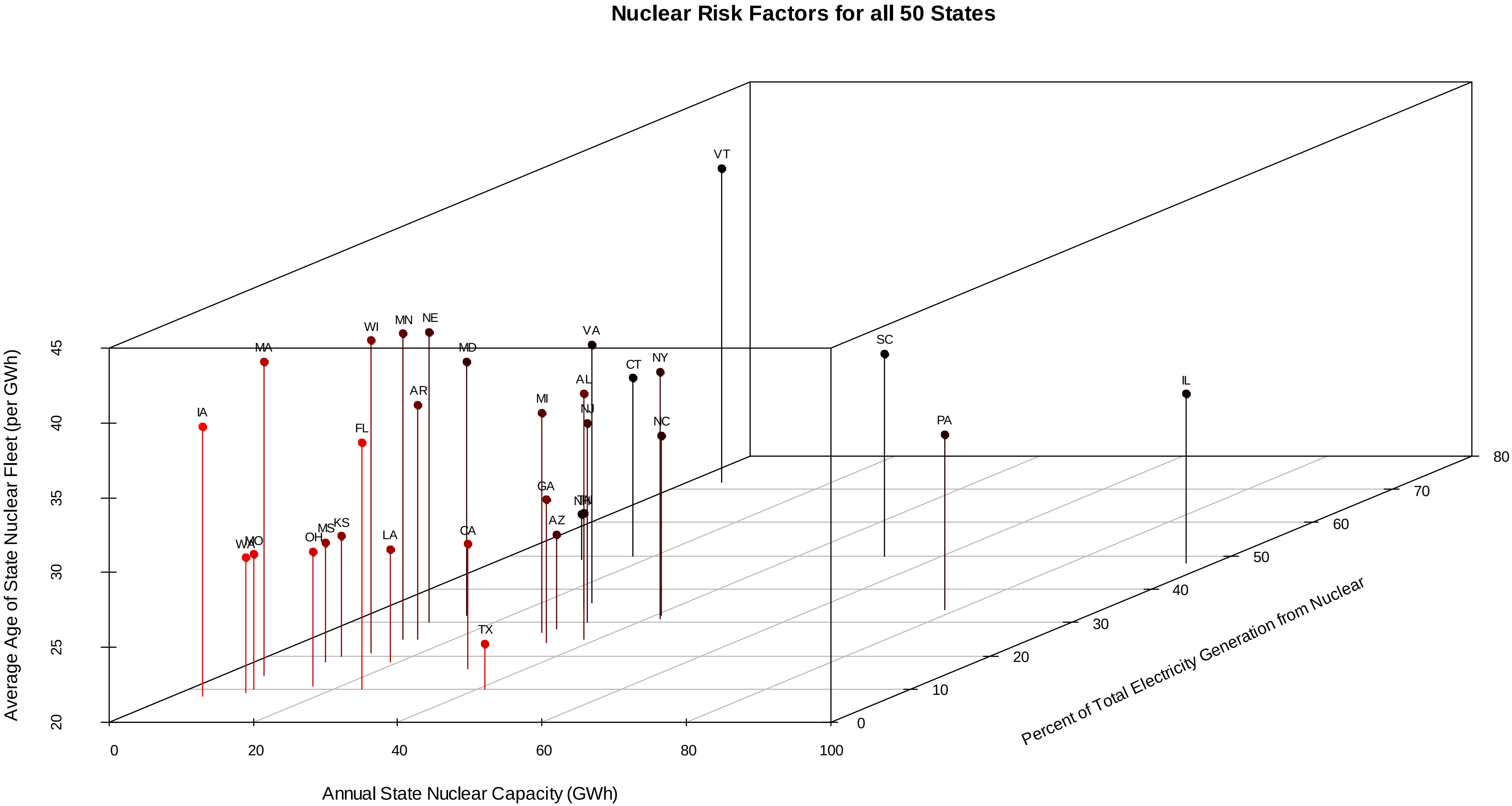
[6] "State Nuclear Profiles." *Energy Information Agency*. Web. 17 Apr. 2013. <www.eia.gov/nuclear/state/pdf/snp2010.

State	Average Age of State Nuclear Fleet (per GWh)
MA	41.0
VT	41.0
WI	40.8
MN	40.4
NE	39.4
IA	38.0
VA	37.2
MD	37.0
NY	36.5
FL	36.5
AL	36.4
AR	35.6
MI	34.7
SC	33.5
NJ	33.3
NC	32.1
CT	31.9
PA	31.7
IL	31.3
GA	29.5
MO	29.0
WA	29.0
OH	29.0
CA	28.3
KS	28.0
MS	28.0
LA	27.6
TN	26.4
AZ	26.3
TX	23.0
NH	23.0

To quantify these two factors, Table 1 shows the result of a calculation for the average age of each state's nuclear fleet (aggregating all of the nuclear generating capacity for each state and weighting it according to the age of each nuclear unit) because this will normalize out the natural effects of population as well as the different generating capacities of each nuclear unit. In other words – given that an electron was produced via nuclear generation – the following calculation is an estimate for the age of the nuclear reactor which produced that electron.

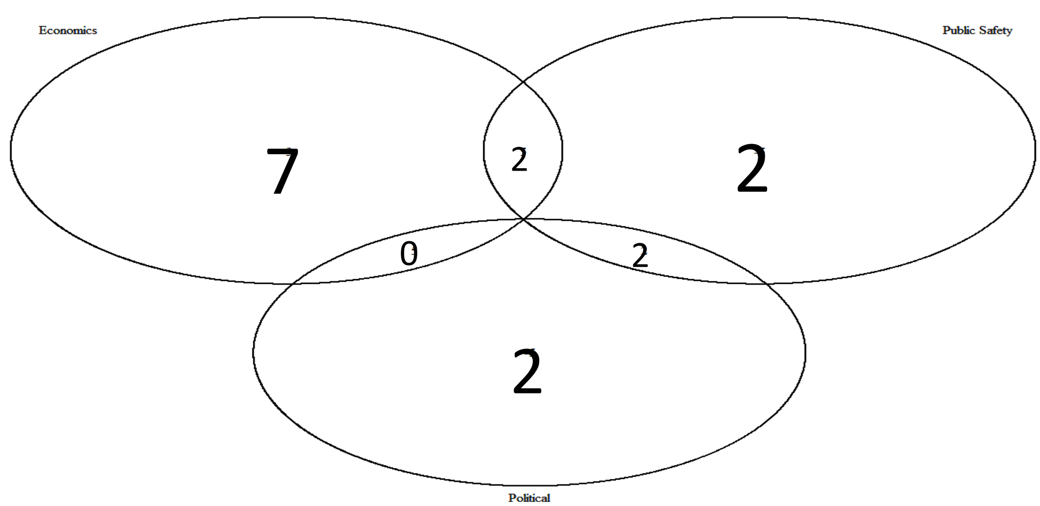
As is shown in Figure 6 and Figure 7, the average age of a state nuclear fleet is simply one risk factor for a state with respect to the projected drop in overall nuclear capacity in the coming years. For example, while Massachusetts and Iowa score high according to the metric displayed in Table 1, they have extraordinarily low risk when it comes to the factors displayed in Figure 6 and Figure 7.

On the following page, Figure 9 shows a way of visualizing the three separate risk factors in conjunction (GWh of Nuclear Generation, Percent Generated Capacity Coming from Nuclear, and Average Age of Nuclear Fleet). I have added color to each of the lines according to a maximizing function that weights all three risk factors appropriately: red corresponds to states with lower risk and black corresponds to states with higher risk given their unique combination of risk factors. While not highest on the list for any of the three risk factors, states such as South Carolina, Pennsylvania, Illinois, New York, and Virginia are exposed in Figure 9 given that they rank reasonably high in *all* three measured categories.


Nuclear Risk Factors for all 50 States
Average Age of State Nuclear Fleet (per GWh)
Annual State Nuclear Capacity (GWh)
Percent of Total Electricity Generation from Nuclear
20
25
30
35
40
45
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80
VT
SC
IL
PA
IA
MA
WI
MN
NE
MD
VA
CT
NY
AL
AR
MI
NJ
NC
FL
GA
AZ
WA
MO
OH
MS
KS
LA
CA
TX

CASE STUDIES ON "RETIREMENT"

The number of years that a nuclear reactor remains in operation depends on a number of factors, including local political resistance, legitimate safety concerns, and economic cost-competitiveness. All of these factors are in some way related to the nuclear reactor licensing process. By default, all approved nuclear reactors are given a 40 year license and then required to gain explicit approval before operations can be extended for another twenty years. There is currently no firm process in place to extend the operating lifetime of a nuclear reactor beyond sixty years. Of the 104 nuclear reactors in operation in the United States, 73 have already been granted a twenty year production extension, with the others either currently applying for the extension or too young to apply for the extension. However, it is important to note that of the 28 reactors decommissioned to date in the United States, none were decommissioned explicitly because they failed to receive a twenty year extension. All of these nuclear reactors reached a roadblock before that point, with the most common case being a failure to produce electricity at an economically viable price. The Venn diagram below shows the main reason (or reasons) for the decommissioning of the fifteen nuclear reactors above 250 MWh that have been shut down:[7]



[7] "Reactors Shut Down or Decommissioned." *Nuclear Energy Institute*. Web. 17 Apr. 2013.

The following four case studies are current examples of the economic, political, and public safety related debates that are ongoing during the recertification process and decommissioning discussions for nuclear reactors.

In October of 2012, Dominion Resources announced that it plans to shut down Wisconsin's Kewaunee Power Station by May 2013.[8] While the reactor was operating at a high capacity factor and had received no opposition to an additional twenty year production extension, lower natural gas costs and resultant lower electricity prices created an electricity market in which the plant could not compete.

In February 2013, Duke Energy announced that Crystal River 3 would be decommissioned, the first reactor to be shut down in almost fifteen years. The reactor had been functioning at an extraordinarily low capacity factor since 2009 and had required a variety of maintenance, including replacement of its steam generators as well as concrete delamination.[9] By October 2012, it was believed that larger structural issues would require about two billion dollars worth of repairs. This was determined to not be economically viable given that the reactor would need to be recertified in 2016 for a twenty year production extension.

The two reactors at San Onofre (California) Nuclear Generating Station have not been in operation since January 2012 due to premature wear discovered on parts of the steam generators, which contributed to a release of a small amount of radioactive steam in 2011.[10] Over the last year, the extended maintenance period has led to large costs to buy the electricity necessary to replace the production of San Onofre; San Diego County has relied on a number of previously retired natural

[8] "Kewaunee nuclear power plant shutdown cost is nearly $1 billion." *Milwaukee and Wisconsin News, Sports, Weather, Business, Opinion, Investigative Reporting | Milwaukee Journal Sentinel*. Web. 17 Apr. 2013.
[9] "NRC: Crystal River Concrete Containment Separation." *NRC: Home Page*. Web. 17 Apr. 2013.
[10] "San Onofre Nuclear Plant Closed After Radiation Leak." *ABCNews.com - Breaking News*. Web. 17 Apr. 2013.

gas plants as well as coal plants in surrounding counties in order to avoid blackouts. Electricity prices have skyrocketed for citizens during the maintenance period.

Indian Point Energy Center, located 24 miles north of New York City in the city of Buchanan, is currently applying for a twenty year production extension. Indian Point exemplifies the dilemma between necessity and safety which many of these older plants' applications exhibit: while Indian Point supplies a whopping 30% of the electricity used by New York City and Westchester County, it has had various environmental and safety concerns in recent years (the power plant's water-intake system kills nearly a billion aquatic organisms a year and a minor explosion occurred in the main transformer for unknown reasons in November 2011).[11] However, Indian Point has undergone extensive renovations in order to change with the times – to become safer and more environmentally friendly.

A complicating factor that Indian Point Energy Center will have to contend with in the next year as its fate is being decided: Governor Andrew Cuomo and the political climate in New York. Cuomo's father, former New York Governor Mario Cuomo, took great pride in decommissioning the Shoreham Nuclear Power Plant in 1989 and Andrew Cuomo is following in his father's footsteps: Cuomo has taken a strong stance against the recertification process for Indian Point and appears resolute to shut it down when its current license period ends in 2014.

[11] "New York State Assembly - Member Section." *New York State Assembly*. Web. 17 Apr. 2013.

CONCLUSIONS

While this paper is pragmatic in that it has focused on managing and understanding the challenges that the United States faces in the coming years due to a dwindling nuclear fleet, it has not explicitly looked at the most obvious solution to this problem: add more nuclear reactors. It seems obvious to say this, but when a nuclear reactor is decommissioned, every electron produced by that nuclear reactor must be replaced with an electron generated via coal or natural gas or other energy source. As a country, we will have to decide what is the lesser of evils: a largely defined, manageable risk (nuclear power), or an undefined, largely unmanageable risk (hydrofracturing techniques, climate change, and temperature rise)? All energy resources come with trade-offs and so nuclear must be considered as a viable option in the coming years with the following approach:

Instituting a mandatory "retirement age" for nuclear power plants at age sixty is simply not a sustainable practice because no new nuclear plants have been built in the United States during the last fifteen years to take their place. Sixty years has even been defined by those in the industry as an "arbitrary" amount of time. Given that many of the American nuclear reactors have different designs, the United States has some of the most specialized nuclear maintenance personnel in the world in terms of being able to monitor and understand the risks inherent in specific reactors. Americans have an 80-year life expectancy; what if American nuclear power plants can live for 80 years as well?

Nuclear power as it is portrayed today in the media combines "invisible" physics with emergencies and cancer risk. Increasing the understanding of the physics concepts behind nuclear technology is a longer term goal that coincides with the American public education system as well as the perception of science in the United States. But we need to also demand that the media be equally honest about the dangers inherent in other energy technologies. Nuclear power plants need to develop better public relations campaigns through regimented tours and engaging with the communities that surround them, showing the safety and longevity of these nuclear facilities.

Finally, it is not advisable for the United States to continue ignoring the root cause: it needs to add more nuclear reactors to the current nuclear fleet. But instead of breaking ground at a large number of new sites, the focus should – initially, at least – be on adding additional capacity to existing nuclear sites. This takes advantage of economies of scale and also avoids stirring up too many new battles with local communities.

In the meantime, this paper has defined how states should consider the impact of an aging nuclear fleet: the nature of the "delayed effect", the importance of a high capacity factor going forward, and three factors that allude to the relative burden each of the states will carry over the next decades. Regardless of past failures to improve the state of nuclear energy in the United States, it is important to remember that nuclear power is still a twenty percent wedge of the United States electricity generation portfolio. Any significant changes to the size of this wedge will likely have a much larger and more differentiated effect than we could ever anticipate and so it is worth considering this effect on our economies, our environment, and our communities.