**Intro: California Dreaming**

"I'd be safe and warm if I was in LA" (Mamas and the Papas)

Energy runs the world. Every action, from keeping warm to powering a nation, requires energy. Over our collective life span humans have constantly sought out more scalable and efficient sources of energy. The discovery of fire was groundbreaking. The realization that we could take things from our surroundings, and through a process, receive light and warmth, cook, and stay safe was revolutionary. This first form of energy created by burning wood, served humans well and lit the way for… everything (EIA [2]).

Today's energy landscape is much more diverse. Wood is still available, though on a much smaller scale than it was 300 years ago. Humans have figured out how to harness the power of moving water; coal, gas, and oil are burned much like wood was, and currently provide the world with most of its energy needs. Then there are the newer technologies: wind, solar, biofuels, and nuclear energy. Oil, coal, and gas are finite resources, which is why people have begun investing in newer, more sustainable energy sources (EIA [2]). As global energy demand increases we have to find ways to supply energy that is infinite and from a sustainable resource. Determining how much of these newer sources get used depends largely on one thing: price. Availability, scale, and policy also play a role in renewables use, but as in any market, the energy market is driven by prices. As technology for these energy sources improves the price is coming down, and as a result we are using more of them. In fact, "renewable generation capacity is expected to account for most of the 2016 capacity additions," and currently accounts for 13.44% of domestically produced electricity (EIA [3]). Still, it remains to be seen whether modern renewable energy sources can provide enough energy to meet the demands of an increasingly energy dependent society. Therefore, other energy sources will still have an important role to play.

One modern energy source is facing more scrutiny than the renewable sources: nuclear energy. All new energy sources have to deal with criticisms and competition, but nuclear energy is perhaps the most controversial due to its rather complicated history and potential risks. It would not be controversial if *everyone* was worried about it; many people have expressed concerns, but many are in favor of it because of its almost non-existent carbon footprint and its high level of efficiency. Some countries are ramping up their nuclear power capabilities, like Japan, and others, such as Germany, are reducing theirs. This report will examine a case a little closer to home.

California is one of America's leading states when it comes to using renewables: 29% of its electricity comes from them (EIA[4]). Instead of utilizing more nuclear, the state is actually rolling back nuclear energy plants in favor of renewable energy. Here we will look into the U.S nuclear industry, look at a cost benefit analysis of California rolling back its nuclear programs, and discuss some of the implications California's decision will have on nuclear energy's future role in America's energy portfolio.

**History of Nuclear Energy**

Nuclear power works like so: atoms hold tremendous energy within their tiny masses and when isotopes from some elements split, energy from the breaking atoms is released as heat (U.S. Department of Energy ii). "This splitting is called fission" and when Uranium-235's isotopes undergo this process it creates fission products (reduced matter that is released with the heat and bounces around). If these fission products hit other isotopes, they can set off a chain reaction of splitting atoms, and if there is enough of the isotope to amount to what is called a critical mass, then a self-sustaining chain can be created, which releases a lot of heat and can be used to help generate electricity (U.S. Department of Energy iii). As in other power plants, nuclear energy uses water to create steam, which turns turbines to generate electricity; the heat from the self-sustaining chain reactions then boils the water (U.S. Department of Energy iii).

The theory behind nuclear energy sounds simple enough, but it has been in the making for hundreds of years. The history of the study of nuclear energy stretches back as far as Ancient Greece, when "philosophers first developed the idea that all matter is composed of invisible particles called atoms" and includes almost every big name researcher discussed in any physics or physical science class (U.S. Department of Energy 3). Philosophers and scientists alike toyed with the idea during the $18^{th}$ and $19^{th}$ centuries, but it was not until the early 1900s that nuclear science started to pick up the pace. Physicist Ernest Rutherford earned the title of "father of nuclear science" due to his contributions to the theory of the atomic structure. Specifically, in 1904, he hypothesized, "If it were ever possible to control at will the rate of disintegration of the radio elements, an enormous amount of energy could be obtained from a small amount of matter" (U.S. Department of Energy 3).

After Rutherford, Einstein developed his $E=mc^2$ theory, which was a formula expressing the relationship between mass and energy. In the 1930s, Einstein's theory was proven correct, first in 1934 by Enrico Fermi an Italian physicist, and then in 1938 by German scientists Otto Hahn and Fritz Strassman and Austrian scientist Lise Meitner. Both groups discovered that when uranium was "bombarded with neutrons" the left over materials were significantly lighter, that is, they had less atomic mass than uranium. "Meitner used Einstein's theory to show the lost mass changed to energy," proving that fission occurred (U.S. Department of Energy5).

Niels Bohr, the winner of the Nobel Prize in physics in 1922, came to America in 1939 for “a conference on theoretical physics in Washington D.C., where he met Fermi” (U.S. Department of Energy 5). They began discussing the possibility of creating a self-sustaining chain reaction, and in 1941 they, along with Leo Szilard, “suggested a possible design for a uranium chain reactor” (U.S. Department of Energy6). On December 2, 1942, the team was ready to present a demonstration of the world’s first nuclear reactor that they named *Chicago Pile-1*, for the university in which they were conducting the experiment. It was a success: “the nuclear reaction became self-sustaining, and Fermi and his group had successfully transformed scientific theory into technological reality” (U.S. Department of Energy7).

Perhaps timing doomed what nuclear energy could have been and/or its future connotations, but research for applications of nuclear energy at the time was largely focused on weapons development, such as the *Manhattan Project* (U.S. Department of Energy 7). After the world wars, the focus moved towards commercial development. Scientists worked on breeder reactors (reactors that would create more fissionable material than they would use) so nuclear energy could be used to create electricity for “peaceful civilian purposes”. A major goal for nuclear energy in the 1950s was to be able to produce nuclear energy on an industrial scale; the first “electricity-generating plant powered by nuclear energy was located in Shippingport, Pennsylvania, came online in 1957” (U.S. Department of Energy 8). The 1960s saw rapid growth for the nuclear power industry as “utility companies saw this new form of electricity production as economical, environmentally clean, and safe” (U.S. Department of Energy 9). Demand decline and worries over nuclear waste disposal and reactor safety stemmed growth of the industry during the 70s and 80s

Despite this down turn, the U.S. has more operating nuclear power plants than any other country, nuclear energy currently accounts for roughly 20% of electricity produced in the U.S. (a nod towards the Energy Policy Act of 1992 which aimed to reduce dependence on petroleum and improve air quality) (Energy policy act of 1992). As the call for clean energy increases, the nuclear energy industry is again being evaluated; is it worth moving forward with nuclear energy or do the costs outweigh the benefits?

**Industry Analysis:**

The U.S. holds a fairly favorable view of nuclear energy, according to the previous Energy Secretary Ernest Moniz, who claimed "Nuclear power is our nation's largest source of low-carbon electricity and is a vital component in our efforts to both provide affordable and reliable electricity and to combat climate change" ("Energy Department"). Throughout the U.S. there are 61 nuclear power plants and a total of 99 reactors, all of which account for about 20% of total electricity generated in the U.S (63% of its carbon-free electricity) ("Nuclear Power in America"). Four more nuclear plants are currently under construction. The largest concentration of nuclear power plants is in the eastern half of the United States. The fuel for these power plants is Uranium, U-235, and it is mined in the western half of the United States; Utah has a big piece of the uranium mining business. The U.S. is the largest producer of nuclear energy; it generates 30% of worldwide nuclear based electricity ("Nuclear Power in America").

As with any industry, nuclear energy comes with its own set of pros and cons. Some cons associated with nuclear energy are high initial development costs, regulatory issues, and concerns with safety and reliability, as well as issues of waste disposal. Nuclear power plants have high upfront costs, which is one of the reasons why companies are hesitant to invest in the industry; between 2002 and 2008 "cost estimates for new nuclear plant construction rose from between $2 billion and $4 billion per unit to $9 billion per unit" according to a 2009 Union of Concerned Scientists report ("The Cost of Nuclear Power"). Then there are the regulations to comply with, and regulations equate to more costs. These regulations are necessary, of course, to promote safety for workers and the surrounding areas. A big con for nuclear energy is also its potentially negative connotations. People who are not used to having a power plant near them, and even some who just do not like the idea of being close to anything remotely "nuclear"; it brings up ideas of radiation and disaster. Due to these fears, potential contractors have difficulty gathering local support for nuclear energy project. The issue of waste management is also one of great concern. No one likes the idea of toxic nuclear waste in his or her backyard; the debate over where to dispose of nuclear waste therefore becomes a political issue.

The pros of nuclear energy are just as noteworthy as the cons. Nuclear energy has competitive operating costs once on line, a high capacity factor making it a base load provider, and newer technologies are improving the safety, efficiency, and reliability for both the power plants themselves and waste disposal management. It is also great for the environment. According to the NEI the capacity factor of an operating nuclear plant is above 90%. Capacity factor is the "ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full capacity"; the next closest capacity factor is that of natural gas, which is around 56% (Bhattacharyya). Once operating, costs of electricity are comparable to that of natural gas.

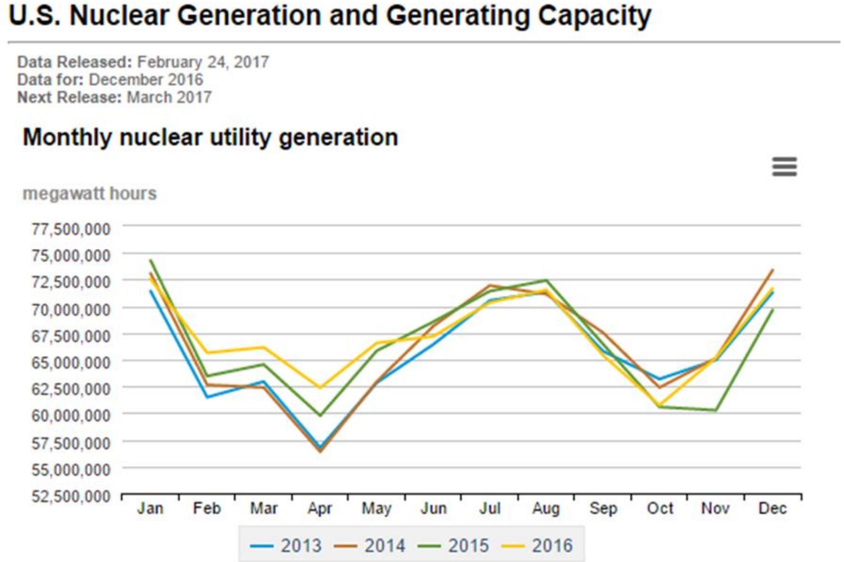



Figure 1: U.S. Generation and Generating Capacity
Generation data shows peak use in the summer months and winter months, associated with spikes in electricity usage for heaters and AC units. (EIA[6])

In addition, the economic benefits are multiplied through the community with approximately every $1 spent at a plant reflecting an added $1.04 in the local economy (Lake). There are also advancements in reactor types, cooling processes, and toxic wastes recycling. These advancements are leading to increased safety for workers and communities who operate closely with the nuclear power plants. New designs for reactors take into account natural disasters and include shock absorption, automatic shutdowns, increased training for workers, and new technologies. With more research, these advancements could bring down some of those upfront costs that make nuclear power plants so hard to start up, and some already are (Martin).

Nuclear is great for the environment. The only emissions associated with nuclear power plants are the mining of uranium and the emissions from transportation during construction and maintenance of the plants; the plants themselves emit essentially zero $CO_2$ emissions (not to be confused with zero pollution; the plant does not produce any $CO_2$ when converting the nuclear fuel into electricity, but it does create the pollutants associated with the mining and transportation mentioned above). Because of the nuclear power plants we have now, experts estimate that 175 million metric tons of $CO_2$ are eliminated each year in the U.S ("Nuclear Power in America").

**Case Study: What is going on in California?**

California, the "Golden State," is making plans to shut down its remaining nuclear power plant, Diablo Canyon, and "replace much of the electricity it generates with power from renewable resources" (Shellenberger). For years the Diablo Canyon plant has been a topic of debate in the state; some saw Diablo Canyon as a way to achieve reliable energy while still making emissions goals, while others continued to have concerns over safety and costs. When Pacific Gas and Electric announced in mid-2016 its plans for the nuclear power plant, both sides of the debate came out to voice their concerns and approval, respectively.

Though California "is a leader in many energy- intensive industries, the state has one of the lowest per capita total energy consumption levels in the country" (EIA [4]). Its electricity profile is made up of a combination of fuel sources: natural gas coal, renewables, and nuclear (See Figure 2 for percentages). Right now Diablo Canyon produces over 1.6 million Mega watthours a month during peak electricity seasons, and 11% of the state's electricity needs year round (EIA[4]).

| Utility-Scale Net Electricity Generation (share of total) | California | U.S. Average | Period |
|---|---|---|---|
| Petroleum-Fired | * | 0.3 % | Dec-16 |
| Natural Gas-Fired | 51.1 % | 27.9 % | Dec-16 |
| Coal-Fired | 0.2 % | 34.4 % | Dec-16 |
| Nuclear | 11.0 % | 20.8 % | Dec-16 |
| Renewables | 37.6 % | 15.9 % | Dec-16 |

Figure 2: California State Energy Profile, Share of Total Electricity Generation (EIA[4])

The decision to roll back nuclear energy in California stems mostly from the state's desire to ramp up renewable energy sources and meet its demanding emissions limits. Electricity generation emissions are second only to transportation emissions in California. By 2020 the state has set a total CO2 emissions goal cap at 431 metric tons of CO2 ("2020 Business-as-Usual (BAU) Emissions Projection2014 Edition."). Based on current projections, this goal will be difficult to realize unless some changes are made; therefore, by 2030, California wants its electricity profile to be mostly supported by renewables- they are shooting for 50% (Daniels). Other issues have also been pointed out: its water usage and proximity to major fault lines. Whatever the reasons, there are costs and benefits to any decision, and this one is no different. Since no single cost-benefit analysis is definitive, it's worth considering both the costs and benefits of this decision.

**Potential costs of rolling back nuclear energy in California:**

There are the obvious costs of lost jobs and economic activity. According to the Nuclear Energy Institute, a nuclear reactor employs "between 400 and 700 highly skilled workers, has a payroll of about $40 million and contributes $470 million to the local economy"; Diablo Canyon has two reactors (Perry). It is understood that these particular losses would not be as drastic as they sound; other energy sources would pick up the slack in contributions to the local economy and workers would be able to find jobs, but to what degree is uncertain. Many people who work for nuclear power plants have specific training that is not always applicable to other fields. If they find employment in other fields, it may be at a lower salary, at least temporarily, which could affect how they participate in their own local economies.

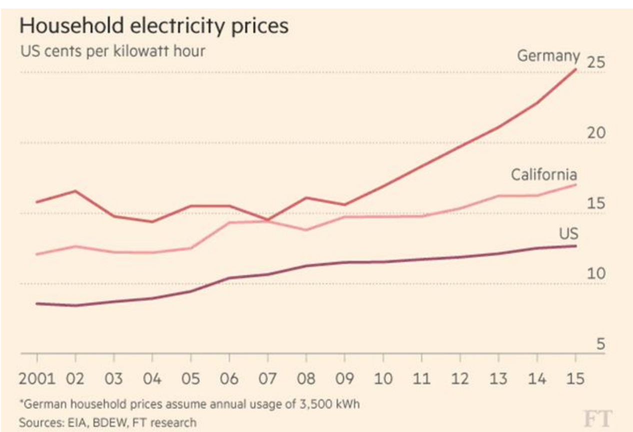
Another potential cost is higher utility bills for residents. In a study conducted by two economists, Lucas Davis and Catherine Hausman of the University of California-Berkley and the University of Michigan respectively, they found that when the San Onofre nuclear plant (located near San Diego in southern California with twin reactors like in Diablo Canyon) was shut down in 2012 "electricity generating costs rose by $350 million during the following year" (Davis). As of December 2016, the cost for electricity in the residential sector of California of18.15 cents/kWh while the U.S. average was12.21 cents/kWh. California continues to have higher prices in the commercial and industrial sectors as well with 13.90 to 10.08 cents/kWh in commercial and 11.05 to 6.63 cents/kWh in industrial (EIA[4]). The two most "costly" forms of energy are renewables and nuclear energy, and because California wants to replace its nuclear capacity with that of renewables, it could be facing another rise in electricity prices (see figure 3).

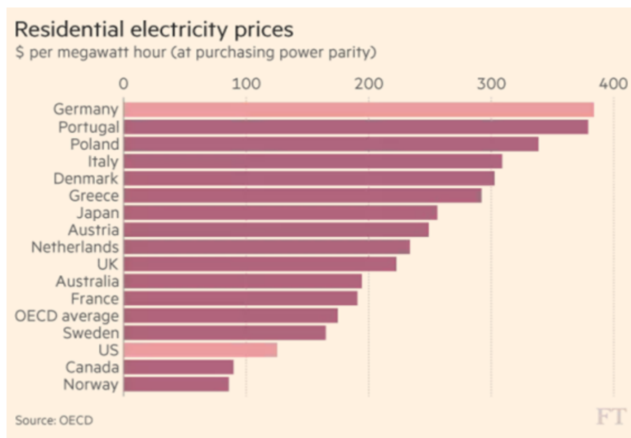
| | Fuel | | | | Total | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Nuclear | Fossil Steam | Hydro-electric | Gas Turbine and Small Scale | Nuclear | Fossil Steam | Hydro-electric | Gas Turbine and Small Scale |
| 2005 | 4.63 | 21.69 | -- | 55.52 | 18.15 | 27.88 | 6.68 | 61.10 |
| 2006 | 4.85 | 23.09 | -- | 53.89 | 19.57 | 29.85 | 6.46 | 59.56 |
| 2007 | 4.99 | 23.88 | -- | 58.75 | 20.32 | 30.88 | 9.32 | 64.43 |
| 2008 | 5.29 | 28.43 | -- | 64.23 | 21.37 | 35.75 | 9.67 | 70.72 |
| 2009 | 5.35 | 32.30 | -- | 51.93 | 21.69 | 40.48 | 8.38 | 57.55 |
| 2010 | 6.68 | 27.73 | -- | 43.21 | 23.98 | 35.76 | 9.15 | 48.74 |
| 2011 | 7.01 | 27.08 | -- | 38.80 | 24.70 | 35.09 | 8.88 | 44.54 |
| 2012 | 7.61 | 28.34 | -- | 30.45 | 27.42 | 37.20 | 11.34 | 35.67 |
| 2013 | 8.14 | 28.94 | -- | 32.56 | 27.29 | 37.92 | 10.88 | 37.92 |
| 2014 | 7.71 | 29.39 | -- | 37.06 | 26.79 | 39.04 | 11.90 | 42.60 |
| 2015 | 7.48 | 26.70 | -- | 28.22 | 25.71 | 37.26 | 13.42 | 33.24 |

Hydroelectric category consists of both conventional hydroelectric and pumped storage.
Gas Turbine and Small Scale category consists of gas turbine, internal combustion, photovoltaic, and wind plants.
Notes: Expenses are average expenses weighted by net generation. A mill is a monetary cost and billing unit equal to 1/1000 of the U.S. dollar (equivalent to 1/10 of one cent).
Total may not equal sum of components due to independent rounding.
Sources: Federal Energy Regulatory Commission, FERC Form 1, "Annual Report of Major Electric Utilities, Licensees and Others via Ventyx Global Energy Velocity Suite.

Figure 3: Average Power Plant Operating Expenses for Major U.S. Investor-Owned electric Utilities, 2005 through 2015 (Mills per Kilowatt-hour
Note that "Gas Turbine and Small Scale includes the renewables wind and solar. The total costs are a combination of operation, maintenance, and fuel costs. (EIA[5])

An example of this happening in real life is in Germany. California is about 1.19 times as big as the European nation with a different climate and about half the population (Bureau), but they both are trendsetters when it comes to environmental conscientiousness and both are determined to replace nuclear with renewables. However, Germany has already done it, while California is still in the process. Germany has incredibly high energy bills, some of the highest in Europe. Germany has had success in switching over to renewables, but the monetary cost is high: "charges for residential customers to cover the cost of renewable power have been set for 2017 at more than double the wholesale price of the power itself" (Hook). These costs come from setting up the renewable energy generation plants and updating the electricity grid.




Figures 4 and 5: Household electricity prices and Residential electricity prices, respectively
California's household electricity prices are above the U.S. average, but note the sharp incline in Germany's prices. In Figure 5 it is shown that the U.S. has fairly low residential electricity prices compared to many other developed countries, but Germany has the highest.

The issue of the electricity grid brings up another possible "cost" in this cost-benefit analysis. California's main goal for adding renewables by cutting nuclear is to further decrease its carbon footprint further. Variable load energy sources, though, interact with the grid differently; they can under and overwhelm it depending on current generation. Ideally, the load on a power station from the "standpoint of equipment needed and operating routine, would be one of constant magnitude and steady duration," which is why there are base load energy sources (natural gas, coal, and nuclear for example) (Mehta). Having a grid completely (mostly) dependent on renewables is going to lead to the need for additional equipment and an increase in production cost as well as possible additional connections to neighboring states (Mehta) in order to maintain reliability. These things take time and money, and while they are being implemented, natural gas will pick up the slack. An article in the New York Times discusses how PIRA, an energy market research organization, “found that natural gas use could rise by 34% in northern California from 2023 to2026, the year after Diablo Canyon would be completely closed,” even considering the state’s goal for renewable energy (Cardwell).

Lastly, another potential cost facing the most populous state in the union is the issue of space. Nuclear power plants take up a relatively small swath of land, but creating more wind and solar farms would take up a lot of available space in the densely populated state. This brings up the issues of scalability and efficiency. As seen in Figure 6, the space needed for a nuclear plant is considerably less than that of either a wind or solar installation. According to a study by the Nuclear Energy Institute, wind requires 260-360 square miles to produce 1000 Mega-watthours, solar needs 45-75 square miles to produce 1000 mega-watthours, and nuclear requires 1.3 square miles to produce the same output (“Land Needs”). If California turns to solar and wind energy as a way of meeting its renewables goals, it could create some land use inefficiency due to the large and distributed footprint required for solar and wind technologies as compared with nuclear.

As defined in Tietenberg’s Environmental and Natural Resource Economics textbook, bid rent functions express “the maximum net benefit per acre that could be achieved by land use as a function of the distance” from the city center (Tietenbeurg). Under the assumption of increasing transportation costs from the city center, the land with the highest use value and net benefits per acre are located around the “center” of a city and further out the value and net benefits decrease. The land further out has lower net benefits and therefore the willingness to pay for it is much lower. Disruption of these land markets, such as the placement of a collection of wind or solar installations around population centers, can lead to inefficiencies such as sprawl and leapfrogging (Tietenberg)[1]. If California chooses to place these installations near population centers in order to minimize electricity grid expansions, this could lead to land allocation inefficiencies.

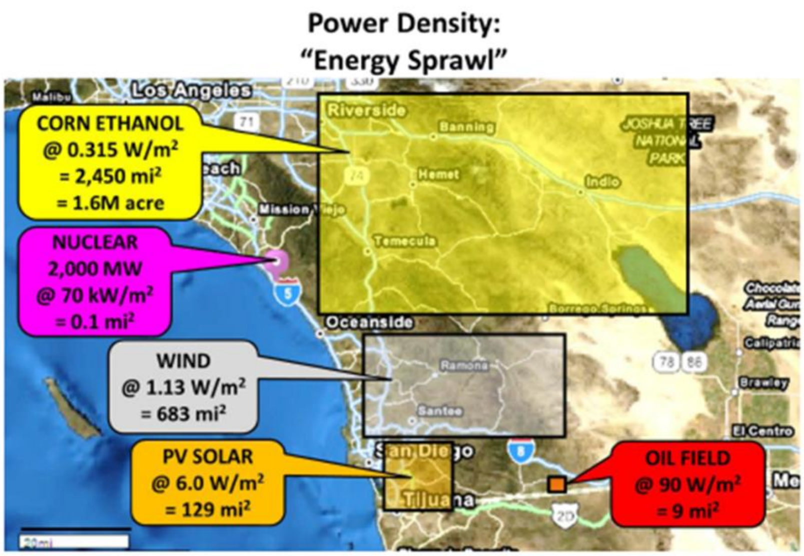



Figure 6: Power Density "Energy Sprawl"
A comparison between different energy sources and the amount of land they require to produce it. (Dale)

**Potential benefits of rolling back nuclear energy in California:**

A cost benefit analysis is not complete without the benefits. One is simply no more worry about an active nuclear plant disaster. Nuclear power plants worldwide pose a threat for disaster, and this threat does concern people who live nearby. Decommissioning Diablo Canyon will set citizens' minds at ease, and though it is hard to put a dollar value on peace of mind, it is still

[1] Leapfrogging "refers to a situation in which new development continues not on the very edge of current development, but further out", randomly leaping from site to site. Sprawl "occurs when land uses in a particular area are inefficiently dispersed" (Tietenberg).

important (and if politicians publicly support their constituents, they will reap the benefits of that peace of mind).

Another possible benefit of shutting down Diablo Canyon and focusing on more renewables such as wind and solar, is water conservation. California often faces droughts and the need for more water. As discussed previously, nuclear energy is generated by fission causing the isotope chain reactions that release heat; this heat then boils water and creates steam (much like how natural gas is burned to boil water). Nuclear power plants also have to use water for cooling and safety purposes and can process up to 25,000-60,000 gallons per Mega-watthours. Not all the water is consumed; once the water used for the cooling process has cooled it can be returned to its source. Evaporation does occur during this process (a 600-800 gallon per Mega-watthour loss) and some of the water stays permanently at the plant, but at the end of the day "the average nuclear plant withdrew nearly eight times as much freshwater as the average natural gas plants" ("Nuclear Power and Water"). Unlike nuclear power or natural gas, solar and wind do not require water for boiling to operate.

Another big possible benefit of Diablo Canyon ceasing operation is the benefit to the future. Right now this plan has lots of public approval. If peoples' actual willingness to pay to replace nuclear energy with renewables is as high as is the policymakers in California believe it to be, this transition plan faces higher probability of success. Closing Diablo Canyon would show that the people of California are willing to invest in a renewable energy future by working to set up an electricity grid that is capable of dealing with variable loads, and in making an effort to reduce greenhouse gas emissions even further, hopefully creating a better environment for future generations.

**Discussion**

Personally I think it is interesting to look at how this case will affect all U.S. nuclear energy moving forward, as well as how other outside influences will affect the industry. If California completely gets rid of nuclear that could spell the end of an era.

“California’s attempt to use only renewable sources is being watched closely by energy executives and policymakers, both because of its size — it is the world’s sixth-largest economy — and because it has long been a pacesetter for environmental policies. Shutting its last nuclear plant, while simultaneously trying to cut greenhouse gas emissions by 60%, is perhaps the state’s boldest energy gambit yet. By 2030, the state aims to draw half of its electricity from renewables such as wind and solar.” (Hook).

U.S. policy also might be changing. The Obama administration and the Trump administration have different views on the role of nuclear energy in America. The Obama administration definitely had a pro-nuclear lean as pointed out in the industry analysis. President Trump might be taking a different approach. One of the president’s campaign platforms was promoting the coal industry and its workers. On March 28, 2017, President Trump signed an executive order “that begins the process of reversing climate change policies put in place by President Obama, including the Clean Power Plan,” which was a piece of legislation that promoted nuclear energy (Radnofsky).

**Conclusion**

I am of the belief that the U.S. should be promoting nuclear energy, but that is not the point of this paper. The purpose here was to explore nuclear energy and look into California’s decision to stop using it, and consequentially to determine whether or not shutting down Diablo Canyon is a good decision. I still think the costs outweigh the benefits, but the answer is it depends. Even with a look into the cost-benefits of the decision, everything ultimately hinges on whether or not California can follow through with its renewables goals. I think though, that if any state can pull this grand scheme off, it will be California. Their past and current actions show that citizens have the willingness to pay for renewables and a commitment to reducing greenhouse gas emissions.

…California is dreaming of a better tomorrow, and time will only tell if its decision to roll back its nuclear energy program will achieve that goal.

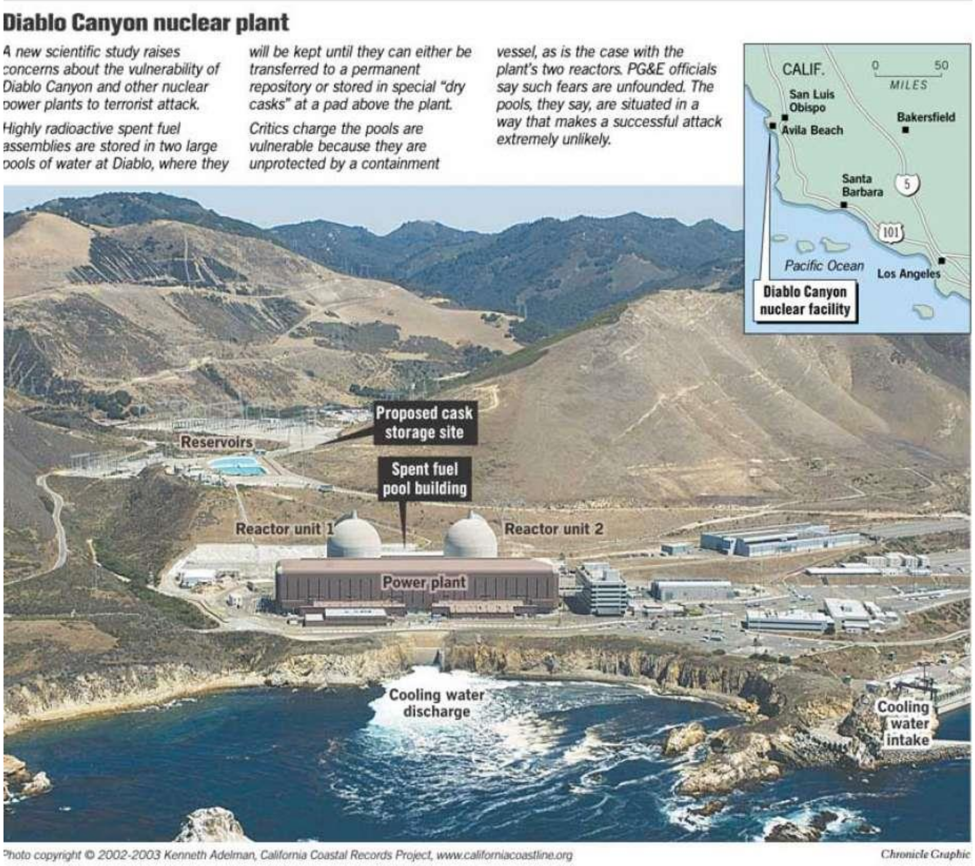



Figure 7: Diablo Canyon Nuclear Plant
A depiction of the nuclear power plant with key components labeled.

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