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The Potential Impact of Small Modular Reactor Introduction on Energy Supply

WILLIAM TATCHER

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Reviewed and approved* by the following:

Dr. Bee-Yan Roberts

Professor of Economics and Asian Studies

Faculty Reader

Dr. Karl Schurter

Assistant Professor of Economics

Thesis Supervisor

Dr. Nima Haghpanah

Associate Professor of Economics

Honors Advisor

* Signatures are on file in the Schreyer Honors College.

Abstract

This paper aims to assess the potential impact of the introduction of small modular reactors on current fuel mixes used to supply energy markets in the near future. This is achieved by analyzing how profit-maximizing energy-providing firms may choose a fuel mix based on cost. This paper examines how much energy capacity SMRs can substitute for in current energy markets in the United States. More specifically this paper will analyze how SMR introduction can change fuel mixtures in the energy supply of the northeastern energy market of the United States that's organized and monitored by the Pennsylvania-New Jersey-Maryland Interconnection. By using a cost minimization function that takes into account current capital stocks of various energy sources in PJM, the amount of capital that will need to be replaced due to depreciation, and their relative costs, this study uses a program to forecast what near-future energy supply composition in the PJM energy market could look like with the introduction of SMRs. Further consideration is also paid to the unique capabilities that SMRs possess that cannot be easily modeled through cost analysis.

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I would also like to thank my mother for supporting me through the process of creating this thesis and throughout my academic career. Without her, I wouldn't be where I am today. Unfortunately, she did not get to live to see my thesis come to fruition. Despite this, I am confident that she is still with me, and will continue to support me throughout my life. I am eternally grateful for the time I had with her and I will continue to honor her memory by being an exemplary student and continuing my education.

Introduction

Considering that Americans spend up to 3% of their income on energy and that energy prices grew by over 6% in 2022 (U.S. EIA, 2023), energy costs heavily affect the financial decisions of firms and consumers alike in the modern world. Our societies depend on electricity and with climate change becoming a major controversial global issue, many nations have demanded efficient clean energy alternatives. For example, both the European Union and the United States have pledged to achieve carbon neutrality by 2050, showing a definite need for an increase in the supply of carbon-neutral energy. Governments and corporations currently rely on renewables to replace fossil fuels but heavily overlook nuclear energy for a variety of reasons. Policymakers and the general public often distrust nuclear power due to disasters such as the Chernobyl and Fukushima meltdowns. Furthermore, nuclear reactors' large upfront costs for construction make them unattainable investments for most private corporations leading to stagnation in the growth of nuclear energy in the West.

Despite the stagnation of nuclear energy in the United States and other developed states, the advent of small modular reactors (SMRs) could potentially pave the way for the future expansion of nuclear energy by giving many more potential firms and governments the ability to invest in nuclear energy. This paper aims to explore the potential effects that SMR introduction may have on energy markets in the United States. Due to the fact that SMRs have largely not been introduced commercially, this paper will attempt to model SMR introduction by projecting how SMRs could fit into an existing energy market. By solving a dynamic cost minimization problem, this study will examine the Pennsylvania-New Jersey-Maryland Interconnection's energy market from the supply side and analyze how its current energy fuel mixture could change with SMR introduction.

To sufficiently understand SMRs and their economic implications it is important to provide background information on important aspects of not only this technology but on the study's method of analysis as a whole. This study is broken up into three main portions. The first is a review of the limited, but important research that has been conducted on the economics of SMRs. The second portion of the study will discuss and explain the chosen data of focus and the methodology used. The third part will summarize the findings of this study.

What are SMRs?

SMRs or small modular reactors, are smaller nuclear reactors assembled from factory-made components or produced as modules to be integrated into a larger system. Whereas conventional nuclear power plants or large reactors (LRs) require on average a square mile of land, SMRs can fit onto a ship or even on the back of a semi-truck (U.S. Department of Energy, 2019). Theoretically, the reactors would be produced in a factory and then its components are transported to a designated site and assembled. If necessary, multiple SMRs can be connected in tandem to produce more power in a conglomerated system. According to Carelli et al. (2007), western LRs can reach up to 1500 megawatts of electric capacity (MWe) and above whereas the World Nuclear Association defines SMRs as typically below 300 MWe and some can even be as low as 50 MWe (World Nuclear Association, 2023). For reference, one MWe provides enough electricity to power 400 to 900 average American homes (Nuclear Regulatory Commission, 2012).

SMRs may just seem like smaller nuclear reactors but in reality, they provide a large body of capabilities that traditional nuclear simply cannot. For one, SMRs typically do not require the same level of upfront investment that LRs require. Traditionally, nuclear energy is limited to governments and government-run monopolies that have the vast resources necessary to construct and operate a nuclear power plant. SMRs have the potential to not only increase the supply of nuclear energy but also make the market for nuclear energy more competitive as their existence lowers the large capital costs that serve as a barrier to entry for most energy companies. Secondly, SMRs are factory-produced like any typical commodity. LRs typically require years of planning due to their size and the geographic difficulties involved with constructing a large power plant. Furthermore, LRs require a large supply chain of construction materials and typically many firms with specialized expertise must coordinate to make a nuclear power plant project successful. LR projects are often plagued with delays and it is not a rare occasion for them to go way over budget. SMRs can increase the efficiency at which nuclear energy is provided by mitigating these obstacles due to their serially-produced nature. Third, SMRs are small and easily transportable. The biggest advantage that this provides is the fact that SMRs can be put in locations that are unsuitable for LRs, giving energy providers much more flexibility in supplying reliable energy in areas with low infrastructure or otherwise difficult geography. SMRs require less infrastructure, further increasing the availability of nuclear energy to a broader group of potential energy suppliers.

When engineers first brought up SMRs as a concept, energy economists criticized the idea with the notion of economies of scale. Economies of scale can be described as a phenomenon where, as a firm's production increases, the average cost to produce each additional unit of output falls. This applies to SMRs in that LRs should be more cost-efficient on a levelized cost-per-watt basis and this notion largely explains the dramatic increase in the size of reactors in the Western world. In the past four or five decades, nuclear reactors have consistently grown larger and this in itself has partly caused nuclear power's stagnation in many developed countries. Modern nuclear power plants are simply too massive for most private investments leading nuclear energy to be exclusively utilized by heavily regulated monopolies. The introduction of SMRs offers an economically competitive energy option that if allowed to prosper, could have massive benefits for the market for nuclear energy and for energy markets as a whole due to its ability to substitute for and complement other existing power sources.

Literature Review

Carelli et al. (2007) created a framework for considering small modular reactors and their use on a large scale by arguing against the notion of economies of scale when applied to SMRs. Furthermore, they explicitly address the various factors that limit nuclear energy in developing countries such as large capital costs and the inefficiency of producing hundreds of megawatts for limited energy grids. Carelli et al. (2007) establish important considerations for future cost analysis rather than attempting to quantify it themselves. The authors find that in most cost factors shared between large reactors and small ones, SMRs are economically competitive if not superior in many instances when comparing designs that would be realistically used. Economies of scale only apply when comparing two technically similar systems and when the authors took newer designs into account, this argument against SMRs largely falls apart. When considering the potential use of SMRs, one must analyze their economic viability compared with other sources of energy production like renewables, but also, with larger reactors (LRs) currently in use today. Cost alone cannot be the sole determining factor when evaluating energy generation as nuclear power has unique safety standards in the sense that accidents like catastrophic meltdowns cannot happen with any other form of power source. Due to the potentially dangerous nature of nuclear energy generation, heavy regulation hinders nuclear power and these regulations need to be adapted to SMRs if they are to be utilized effectively. Special consideration should also be paid to the unique capabilities provided by SMRs such as their low land use, ability to produce energy at full capacity without interruption, and ability to be easily transported.

SMR Cost Compared Against Large Reactors

Khatib and Difiglio (2016) define many of the challenges facing nuclear energy today and contribute to the idea that the commercialization of nuclear power has largely gone nowhere due to massive up-front costs. SMRs can more closely match supply and demand and do not require nearly the same level of investment and risk that LRs require. This aspect could induce investment and create private markets for nuclear energy that currently do not exist with LRs. Khatib and Difiglio (2016) also briefly analyze potential obstacles such as increasing capital and material costs in modern liberalized markets, the potential need for subsidization for nuclear and renewable energy sources, and difficulties regarding their regulation. They also mention the need for the use of discount factors in cost analysis. Discount factors are essentially a multiplier to future costs that put them in terms of present value for analyzing how time could affect the value of power generation in the long term. Nuclear power and even SMRs necessitate the use of discount factors because they require a large amount of time and investment and the value of this sunk capital and time needs to be realized in any effective cost analysis. Khatib and Difiglio (2016) heavily contribute to the discussion by firmly establishing the importance of overlooked cost, discount factors, and regulation considerations. They conclude that SMRs are economically competitive when compared with LRs and later studies that calculate cost more closely and analyze these considerations with more detail come to similar conclusions.

Black et al. (2019) establish a framework that future researchers can use more effectively to compare costs. They use a unique methodology in that they take figures from existing data regarding the PWR-12, a widely used large plant design in the United States and then scale the data by incorporating it into the Economic Modeling Working Group (EMWG) Code of Accounts system (An established system currently in use for estimating costs in large power plants and other energy sources). They then take these figures and compare them to data manipulated by the same system that they have received from NuScale Power LLC, the only company at the time of the study in the development of a light water SMR for commercial use. They find that in most cost categories, both in absolute terms and on a per kilowatt basis, the NuScale SMR significantly saves in costs when compared with LRs. Only in direct costs does the NuScale reactor exceed the PWR-12 due to the integrated nature of the components of the NuScale reactor. This integration and modularity present larger direct equipment costs but at the same time allow for most of the significant savings in other categories. Furthermore, they posit that SMRs have many of the attributes of LRs, but benefit from significantly lower capital costs which grants them an edge in competitiveness when compared to larger plants.

SMR Cost Compared Against Renewable Energy

Khatib and Difiglio (2016) further build on the viability of SMRs through their comparison against renewable power sources. Despite acknowledging that nuclear power faces slow expected future growth, they believe it can compete against existing forms of renewable energy in markets at the time. While renewable energy has consistently made headlines as an alternative to fossil fuels, they are largely associated with high maintenance costs and limited energy production. Furthermore, renewable energy sources suffer from an inherent intermittency problem not only making renewable energy relatively unreliable in terms of consistent power production, but it also complicates efforts to analyze the costs of renewable energy. Renewables are limited in that they typically rely on some intermittent natural force to produce power. For example, wind power relies on weather patterns and wind intensity. This of course causes difficulty in measuring output considering that modern meteorology already has difficulty predicting whether or not a picnic might be rained on. Likewise, solar panels rely on sunlight and the strength of the energy provided by the sun, leading to more upfront costs in storing energy in batteries for nighttime use. Sources of renewable energy all largely suffer from this issue which not only makes it difficult to compare how efficient they are but also severely hinders their performance and reliability.

Khatib and Difiglio (2016) also introduce the levelized cost of electricity (LCOE) metric and effectively compare cost figures between various forms of energy generation. LCOE scales and averages costs between power sources for analysis and their paper supplements it by accounting for the integration costs of energy sources into existing power grids. Khatib and Difiglio (2016) show that integrating renewable power sources into existing power grids will always be associated with higher costs due to the unpredictable nature of renewable energy and their high need for maintenance.

New Capabilities and Other Considerations

Carelli et al. (2007) emphasized the massive potential that SMRs have in developing countries that LRs simply cannot achieve, and this analysis can likewise be applied to energy markets in the United States, as LRs require an unobtainable level of initial investment that most firms simply cannot provide. SMRs also have the potential to be used in remote areas due to their relatively easy setup as compared to the massive construction requirement needed by LRs. SMRs also provide the ability to cogenerate other products more efficiently than LRs. Cogeneration is the ability to create other products or more electricity using the processes that the power plants rely on such as steam production. Distance limits cogenerative products much more than electricity, therefore SMRs can more effectively utilize cogeneration since using a 1000 MWe nuclear reactor to produce desalinated water for urban plumbing may prove to be cumbersome and ineffective.

Vujic et al. (2012) contribute to the discussion the notion of economies of replication; the idea that SMRs can be produced in a more effective manner over time due to the large-scale production of similar components. Economies of replication are further taken into account by studies such as Lovering and McBride (2020) and Shaojie et al. (2023) in their cost analysis. Lovering and McBride (2020) establish the competitiveness of SMRs by building upon the idea of economies of replication, otherwise known as production learning. This study builds on previous research by using scaling factors in their methodology and introduces the idea that SMRs are unique in that they are produced industrially and could potentially be more economically viable than before with the experience that producers will gain by producing them in a streamlined process. SMRs differ from LRs in this regard as they are produced identically on a larger scale whereas LRs must be uniquely constructed to fit the area that they are determined to be built in. This effect largely describes the recent fall in costs for renewable forms of energy as over time they have become more inexpensive due to the advances that manufacturers have made in producing them more cost-effectively. SMRs have yet to benefit from production learning, however, as they have not become widely available commercially yet.

Potential Impact of Regulation

Khatib and Difiglio (2016) established that regulation needs to be further analyzed as it could potentially be a barrier to SMR use. Vegel and Quinn (2017) heavily expand on this idea by discussing the economic viability of SMRs with the introduction of a likely regulatory fee structure surrounding it. They find that much of the work done to analyze cost in SMRs varies too much, overlooks fee structures, and often differs heavily in cost estimates. A lot of this variability stems from the difficulty of analyzing a theoretical cost with some researchers incorporating certain factors that others do not. Vegel and Quinn (2017) also highlight that much of the research surrounding regulation has only focused on licensing costs. Furthermore, they expose the lack of research done on operating costs; an important distinction as most of the economic modeling done so far has relied on capital costs, that is, the costs for building the reactor and starting energy production, not so much the maintenance and cost of operation over time. In that study, the authors set out to address many of the gaps that exist in the research and developed a quantitative analysis based on work done by previous researchers. Their economic modeling takes into account: capital costs, direct and indirect costs, ownership and contingency costs, factory costs, scaling factors, operational expenses, and fee distribution. They model their analysis on nuclear energy markets in the United States and briefly discuss how changes in energy circumstances can pave the way for demand in SMRs. They collectively agreed with Khatib and Difiglio (2016) and Carelli et al. (2007) that SMRs are economically viable and competitive on a cost-per-energy output basis, however, they find that the current regulatory structure in the United States provides major obstacles to SMRs. The system has not yet adapted to such a new technology and the current fee structure has the potential to drown SMRs before they even catch on. Currently, the existing annual fee system for nuclear reactors presents large difficulties for SMRs. The governing body for nuclear power in the United States, the NRC or Nuclear Regulation Committee has created a potential fee structure for SMRs with a sliding scale system but Vegel and Quinn (2017) point out the system's many inherent inconsistencies and unfair fee distribution. They propose their own regulatory fee structure and in their concluding remarks, highly recommend that the regulation of nuclear power in the United States be reevaluated as the current regulation and fee system compromise a large portion of the potential operating expenses of SMRs.

Safety Considerations

One of the greatest obstacles to the proliferation of nuclear energy is public distrust about their safety. Germany for example has completely shut down all of its nuclear power plants over safety concerns that originated from the Chornobyl disaster that were then greatly exacerbated by the Fukushima meltdown. On April 15, 2023, Germany produced its last bit of nuclear energy and in order to prevent similar shutdowns in other countries, nuclear must be proven to be a safe bet. SMRs and nuclear power as a whole face heavy regulation for a good reason. Past blunders have stirred distrust among the general public over nuclear power's safety and this distrust must be overcome to facilitate growth for a future SMR industry. Carelli et al. (2007) highlight that SMRs are intrinsically safer than larger reactors due to their simplicity, reduced size, and lower capacity for destruction should there be a potential meltdown. In the report, they observed reduced maintenance intervals and longer core lifetimes, a reduction in personnel and necessary security, and the fact that SMRs are more difficult to target for hostile agents like terrorists or during wartime. Shaojie et al. (2023) further develop this idea by pointing out the inherent safety in SMR designs. They highlight that current designs feature integrated components, greatly enhancing the potential safety of nuclear energy. Other examples that Shaojie et al. (2023) point to feature new emergency shutdown systems and innovative fuel systems. SMRs are a new technology and as such are built upon many generations of engineering. As novel designs, they feature many modern safety systems that may also be prevalent in future LRs. The inherent integration of systems and simplicity of design of SMRs make them stand out in relative safety. Although little testing has been done so far, Shaojie et al. (2023) and other studies establish SMRs to be theoretically safer than traditional LRs and show little evidence that SMRs should be disregarded over the possibility of a meltdown.

Important Conclusions from the Existing Literature

SMRs have proven to be an extremely promising prospect in energy. Having dismissed the prevailing notion of economies of scale, Carelli et al. (2007) established that new SMR designs provide a cost-effective alternative to other energy options. When compared with larger traditional reactors, SMRs typically produce the same amount of power for a lower cost. Their modularity and factory-style production allows for learning effects to lower costs while their low capital costs and construction time potentially make them a much more viable option for private investors and corporations. These factors also contribute to SMRs being able to match supply and demand for nuclear power much closer. With little to no carbon footprint, SMRs can produce massive amounts of power in remote areas and have other capabilities that simply cannot be matched by other alternatives like renewable power. Other studies have analyzed the potential for use of SMRs in remote areas as their small size and high energy generation allow them to power large facilities in otherwise impossible locations. Their economic implications cannot be understated as their unique capabilities could provide many developing states and private companies with the energy infrastructure needed for economic growth. In terms of safety, SMRs exceed the expectations of conventional reactors. As pointed out by Khatib and Difiglio (2016) and Shaojie et al. (2023), SMRs are inherently safer due to their more integrated designs and smaller size. SMRs also feature modern safety systems and have the potential to take advantage of emerging technologies that allow them to be utilized with confidence. There are many economic benefits if governments and corporations invest more in this promising prospect. However, SMRs have little practical experience behind them making it difficult for potential investors to be confident or for government regulators to be content. This could potentially lead to poor investment decisions, development, and regulation regarding SMRs. Regulation potentially stands as a major obstacle to this nuclear renaissance and without proper research and development, SMRs and their benefits may fall victim to many of the woes that have plagued nuclear energy since its inception.

Despite findings from researchers such as Black et. al (2019), Carelli et. al (2007), and Khatib and Difiglio (2016) as well as others that highlight significant upfront cost savings for SMRs, it seems that the economics of nuclear power, both SMRs, and LRs, suffer from very large initial capital costs. Since the COVID recession construction costs have tremendously increased due to supply chain disruptions and the resulting high levels of inflation. This increase in costs has been recently observed as being the principal reason why NuScale, the leading producer of commercially available SMRs has recently had its deal with the Utah Associated Municipal Power Systems (UAMPS) terminated. NuScale is currently the first and only licensed producer of SMRs in the United States. The NuScale reactor produces 77 MWe for each module, which can be used in tandem in their proposed VOYGR-4, VOYGR-6, and VOYGR-12 series power plants named in accordance to how many of the modules are used by each power plant (NuScale Power, 2023).

As shown by Schlissel (2023) in a recent report published by the Institute of Energy Economics and Financial Analysis, initial NuScale estimates highlighted a relatively low LCOE of $58/MWh for a 6-module 462 MWe power plant that they had planned to deliver to UAMPS. This deal was recently terminated, however, citing increasing costs as the principal reason. New estimates from NuScale put their SMR LCOE at a substantially higher $89/MWh. Both NuScale and UAMPS cited inflationary pressure as a primary driving force for this increase in costs. Most of the increase in costs comes from a 75% increase in construction costs, which was initially valued at $5.3 billion and has since risen to over $9.3 billion for a 6-module power plant. Furthermore, UAMPS noted that a large increase in interest rates (an increase of over 200 basis points since July 2020) also had large consequences for proposed costs. The NuScale reactor was also expected to be heavily subsidized and the LCOE estimates they found take these subsidies into consideration. It was estimated that the Department of Energy would provide a $1.4 billion subsidy to construction costs for the project in addition to a $30/MWh subsidy from the Inflation Reduction Act for a total of over $4 billion in subsidies. According to Schlissel (2023), the 53% increase in total costs put the NuScale SMR at the same cost per kilowatt of electricity as the new large two-reactor Vogtle nuclear power plant currently being built in Georgia. Recent cost figures provided by the U.S Energy Information Administration also back up these findings. According to them the total overnight cost per kilowatt of a standard reactor is $7,030, while for SMRs they cited a figure of $7,547. This tremendous increase in construction costs creates large obstacles for SMRs that will undoubtedly reduce their competitiveness in energy markets.

Based on the existing literature, it can be assumed that SMRs do not seem to face any major limiting factors in their development and introduction. However, more recent studies have shown that SMRs may be too expensive to implement effectively in existing energy markets due to increases in capital costs. Despite this, SMRs are safer than nuclear power plants that are currently in use, and they possess a wider range of unique capabilities that have the potential to have drastic economic effects on existing energy markets despite their large upfront costs. Furthermore, these larger-than-expected upfront costs are due to current economic circumstances which can change over time. Most notably high inflation and high nominal interest rates have been the principal cause of increases in costs and SMRs may become significantly more economically competitive in a different inflationary environment

Methodology

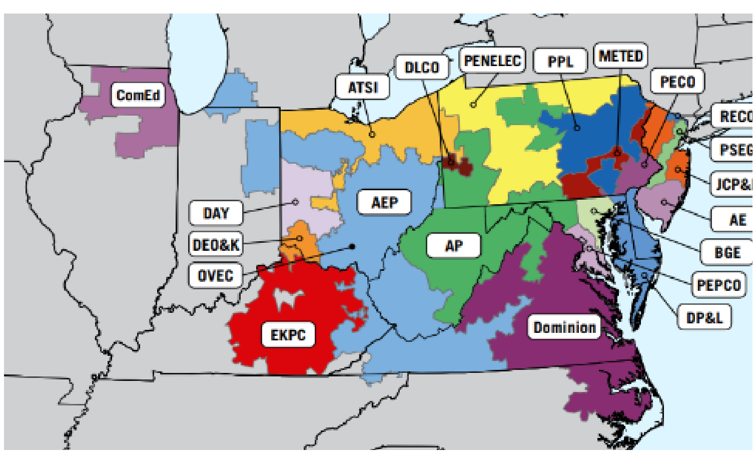
Since effective cost analysis and cost comparisons of SMRs have already been conducted by previous researchers, the goal of this study is to attempt to quantify how SMR introduction can affect real energy markets. We have found the most feasible way to model SMR introduction is to examine how a theoretical cost-minimizing firm would make decisions regarding the composition of energy-producing capital subject to meeting a quantity of output of electricity demanded. The primary instrument of analysis for realizing this model will be a dynamic cost minimization problem.

This study utilizes optimization for its analysis of SMR impact. By optimizing (minimizing) the expected discounted present value of the cost of the most expensive component of energy production, the generation itself, this study can make larger overall conclusions about what SMR introduction could look like in energy markets. Essentially, the solution to the cost minimization problem will provide a capital mix with the smallest possible cost subject to meeting a desired level of output. The function used for the research of this paper will take into account the relative factor costs of currently used energy sources as well as SMRs, the current level of energy-producing capital in the chosen market of study, the amount of capital that will be needed to be replaced over time due to capital depreciation, and a growing energy demand. The results for the cost minimization problem are found through programming the function into Python as the calculations are too complicated to be done by hand. Python is a popular programming language known for its simplicity and ease of use and provides the tools necessary for this kind of analysis. The market of focus for this study is the Pennsylvania-Jersey-Maryland Interconnection.

The Pennsylvania-Jersey-Maryland Interconnection

Originally founded in 1927 and headquartered in Valley Forge Pennsylvania, the Pennsylvania-Jersey-Maryland Interconnection LLC, or PJM, is a regional transmission organization in charge of coordinating the supply of electricity in 13 states and the District of Columbia. It covers over 368,906 square miles of territory and serves over 65 million people in the northeast of the United States. PJM organizes energy supply from over 1,400 different electric generators of various types and currently has close to 1,100 energy firms under its service umbrella and is one of the largest wholesale electricity markets in the world.

Figure 1.1 Map of PJM's Service Territory (PJM, 2024)



The PJM energy market was chosen as the focus of the study for two reasons. The first reason is that their energy mix is relatively diverse and well-balanced compared to other energy markets in the United States. PJM uses a variety of generation methods and has a fairly evenly distributed energy portfolio relative to other studiable energy markets in the United States. As of 2022, PJM had an installed energy production capacity of 183,254 megawatts. Of this generation capacity, 18% consisted of nuclear energy, 26% coal, 44% natural gas, 5% hydroelectric, and 3% other renewables. The last 4% are mostly oil-based energy plants not included in this study (PJM, 2022). While renewables account for a relatively small amount of generation capacity, this trend can largely be observed in most energy markets around the world as renewables are just now finding their mark in terms of economic competitiveness for reasons discussed earlier in this study. Furthermore, it should be noted that according to PJM, coal will likely be completely phased out in the upcoming future due to the emphasis being placed on carbon neutrality and the increase in coal costs due to government interventions such as carbon taxes. What's unique about PJM's fuel mix is that it is very similar to the overall composition of energy production in the United States, and the findings of this paper can be more broadly applied to the United States energy market as a whole. The second and frankly most important reason as to why PJM was chosen is because they provide a wealth of publicly available data just from their website. PJM provides various economic statistics and projections for their energy market and studying PJM has been relatively easy (and cheap). PJM provides forecasts years into the future for variables such as generation capacity, the fuel mix that supplies this generation capacity, peak energy loads (energy demands), and pricing.

Using data from PJM, this study can apply its generation capacity, fuel mix, and average energy load to the cost minimization problem. This provides a suitable framework for analysis that takes into consideration a real, representative, and relevant energy market to constrain the cost minimization problem and ground its findings in reality.

Cost Parameters

Since the cost function relies on the relative costs of the generation sources involved in the market of analysis, finding comparable costs for all of the productive factors involved is essential. Generation sources have only one thing in common, they all produce energy. The difficulty in comparing the costs of energy generation sources stems from the fact that all of the sources are vastly different in their construction, operation, maintenance, variable costs, and total energy produced. Furthermore, different sources of energy can only run at full potential for limited amounts of time. This is the intermittency problem that was discussed earlier in the study. Nuclear power does not suffer from this problem giving it a large advantage in productive capability but other energy sources such as wind or solar are heavily constrained by natural forces outside of our control. With all of this in mind, this study will use 2022 cost estimates provided by the U.S. Energy Information Administration for generation technology expected to enter service in 2024 and beyond. The U.S. Energy Information Administration (EIA) annually publishes long-term energy projections in its annual energy outlook. Their estimations come from a variety of complex methodologies and from a large body of data that they collect. Their cost estimates were chosen for a few reasons. Their estimates are likely to be some of the most accurate that are currently available in the industry. Furthermore, the cost estimates are for new resources entering 2024, as opposed to existing resources. This gives reliable figures for the cost minimization equation because in the hypothetical framework, the firm must find the lowest cost mix of generators to replace existing ones that are subject to depreciation and using figures for the most updated generators for each respective source rather than the ones currently in use provides more accurate results for how the fuel mix will change in the near future. Having one source with all of the cost estimates also avoids issues with needing to level costs in terms of inflation and changing discount factors from different sources and different time periods. Inflation and interest rates change constantly, and attempting to use cost estimates taken from different sources at different times makes empirical analysis more complicated and less accurate. The numbers provided by the EIA are used as parameters in the cost minimization problem. This way the study can determine an optimal mix of energy generation based on the likely costs of near-future energy generators. The variable costs used in this study as well as data pertaining to the regression discussed further in the study are taken directly from the EIA Annual Energy Outlook for 2022 (U.S. EIA, 2022) and 2023 (U.S. EIA, 2023).

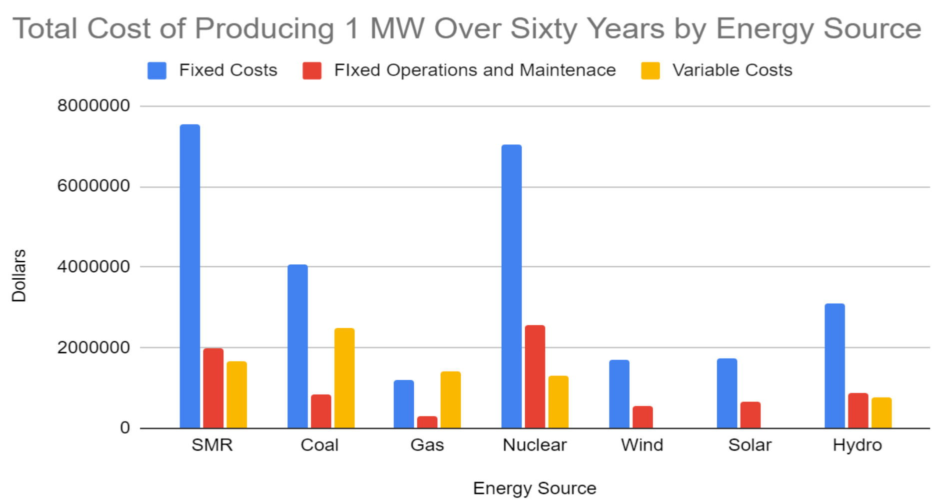


Figure 2.1

As shown in the chart above, nuclear energy's economic competitiveness suffers mostly due to its immense upfront costs. On costs alone, the most economically viable are clearly natural gas, wind, and solar. However, the costs above do not reflect capital depreciation and intermittency (capacity factors) which also heavily impact economic competitiveness and advantage the more expensive power sources such as nuclear power, SMRs, and hydroelectric.

Cost Minimization Problem

The cost minimization problem takes the following form:

$$\text{(1)} \qquad \text{Min} \sum_{i=1}^{I} (FC_i (X_{i,t} - (1 - \boldsymbol{\delta}_i)X_{i,t-1}) + X_i VC_i) / (1 + r)^T$$

where T denotes the amount of yearly periods of depreciation being accounted for. The seven relevant generation types are denoted by i: i = 1 denotes SMR, i = 2 denotes coal, i = 3 denotes combined cycle natural gas, i = 4 denotes wind power, i = 5 denotes solar, i = 6 denotes hydroelectric power. X_i is the new investment amount of a generation type measured in megawatts of energy-producing capacity.

$\boldsymbol{\delta}_i$ is the depreciation rate of a respective energy generator and is calculated by simply taking the reciprocal of the lifespan of a generator in years. The lifespans of the different energy generators are taken from a variety of sources. The lifespan for nuclear power is taken from the U.S. Department of Energy (2020), the lifespan for coal is taken from the U.S. EIA (2021), the lifespan for wind power is provided by the U.S. Environmental Protection Agency (2013), the lifespan for combined cycle natural gas plants is taken from Sargent & Lundy LLC (2017), the depreciation rate for hydroelectric power is taken from the Indiana Office of Energy Development, and the lifespan for solar is provided by Coldwell Solar (2023). These figures give a ballpark estimate as to how often the energy sources must be replaced. This depreciation is then calculated depending on how many periods into the future are being accounted for. The lower the lifespan of an energy source, the more often it must be replaced. This gives energy sources with a longer lifespan an economic advantage as they need to be replaced less regularly. The lifespans of the relevant energy generation methods are depicted below:

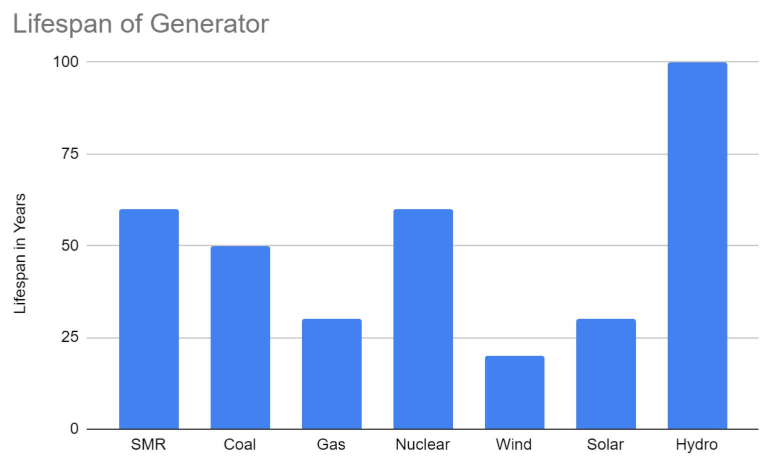


Figure 3.1

After new capacity is invested into, that new capacity will also depreciate, and to reflect this, the term $(X_{i,t} - (1 - \boldsymbol{\delta}_i)X_{i,t-1})$ is included in the cost minimization problem accounting for all of the depreciated capital in use whether it is apart of the initial mix or invested into later. VC_i is the variable cost of one megawatt of capacity measured in cost per output, in this case, cost per megawatt-hour. The prevailing discount rate is represented by r and is arbitrarily set to study the effects of changes in this discount rate. The discount rate r, reflects borrowing costs and puts costs over the lifetime of a given generator into its present value and is set to 0.05.

FC_i is the fixed cost of one megawatt of capacity for a generation type. Fixed costs represent all costs that do not change with output. This includes the initial construction and investment costs required to build an energy generator as well as the lifetime operations and maintenance costs. The fixed costs, FC_i, are calculated by the following equation,

(2) $$FC_i = (OC_i + (O\&M_i(1 + r) / (r + \boldsymbol{\delta}_i)))(1 / CF_i)$$

where OC_i and $O\&M_i$ are the overnight cost of constructing a one-megawatt generator and the yearly operations and maintenance costs of a one-megawatt generator respectively. CF_i is the capacity factor of an energy source. The capacity factor is denoted as the rate at which a generator can run at full capacity. A generator with a .50 capacity factor can only run at full capacity half of the time it's producing energy. $(1 + r) / (r + \boldsymbol{\delta}_i)$ comes from an infinite geometric series where the operations and maintenance cost is calculated at the very start of investment like an upfront sum. The operations and maintenance take into account the number of years that are being projected over, the depreciated units of capital for this period, and are then discounted for this period. This was done to simplify calculations to be used in the cost minimization program.

Constraints

The cost minimization problem is subject to the constraint that it must fill PJM's overall capacity of 173,749 total megawatts after taking into account the depreciation of that capital over time and the growth of energy capacity that will grow at the same rate as energy demand. This is represented by the following constraint:

(3) $$\sum_{i=1}^{I} X_{i,t} = g^T$$

where g^T is the energy capacity that must be met. g^T is represented by the following equation,

(4) $$g^T = 173749 * 1.017^T$$

Where PJM's 2022 capacity of 173,749[1] is growing at a constant energy demand growth rate of 0.017 per year until year T. PJM's current energy-producing capacity of 173,749 megawatts must be increased so that PJM can adequately meet future demand. This capacity is typically much more than what is needed to meet peak electricity loads (energy demand) and this is most likely to add redundancy and reliability to the energy market to avoid brownouts due to the volatility of energy demand which varies heavily between seasons and weather patterns, over different holidays, and even the day and night cycle. We're not sure how PJM determines how much extra energy capacity it wishes to maintain so we decided to model this by simply having energy capacity grow at the same rate as energy demand. This isn't very unrealistic as according to PJM's data, their peak summer demands and overall capacity follow each other fairly closely with a difference of around 30,000 megawatts. According to the 2024 PJM Load Forecast Report, peak summer demand is expected to grow at an annual rate of 1.7% for the next ten years so this is the figure that will be used to model energy demand growth.

Furthermore, the minimization function is also subject to two other important constraints that affect investment behavior. The first constraint is that investment cannot be negative. This essentially means that PJM must refrain from destroying existing energy-producing capital in order to replace it with something cheaper. The second constraint is that coal cannot be invested into. This constraint reflects the carbon neutrality goals of not only PJM but the United States as a whole. This is also shown in the EIA's data as in the last decade coal has largely only seen retirement. The EIA also projects that for the foreseeable future coal will not see any investment in any of the US's major energy markets. Natural gas is still relatively competitive despite its

[1] 9,505 megawatts from PJM's total 183254 are not accounted for in this study as they belong to less utilized energy sources that are not relevant to this analysis.

carbon emissions as it not only produces significantly less carbon dioxide compared to coal but is also significantly cheaper.

Adding Convexity

Because the cost minimization problem takes a linear form, the results are a corner solution that simply assigns all of the new capacity to the cheapest form of energy. This is of course unrealistic considering that the different energy sources cannot make up the entirety of a power grid simply because they are inexpensive. Coal and natural gas plants emit carbon dioxide and directly contradict carbon neutrality goals. Renewable power suffers from intermittency making them unreliable and often associated with steep diminishing marginal returns. Therefore the fixed cost coefficients used are found by regressing total investment in a region by the investment cost for that region. This is reflected in this updated cost function,

$$(5)\ \text{Min} \sum_{i=1}^{I} F_0 + F_1 (X_{i,t} - (1 - \boldsymbol{\delta}_i)X_{i,t-1}) + X_i VC_i) / (1 + r)^T + F_2 X^2_{i,t}$$

Where F_0 is the upfront cost to use a power source before anything is produced, F_1 is a linear coefficient on investment and F_2 is a quadratic coefficient on investment. Both of these cost coefficients allow for the function to take into account how costs change depending on the level of investment of a particular energy generator. The primary purpose of this is to add convexity to what is otherwise a linear cost function. This allows for more realistic results that reflect extraneous cost factors that wouldn't be otherwise accounted for.

These coefficients are found by regressing the initial overnight investment cost of a given generator on the additional investment constructed in a given region or time frame.

$$(6) \qquad C_{it} = F_0 + F_1 i_{it} + F_2 i_{it}^2 + \mathcal{E}$$

Where C_{it} is the overnight capital cost for a one-megawatt investment in a particular energy source, i_{it} is an investment in a region as measured by megawatts of additional capacity, F_0 is the intercept on investment cost, F_1 is the linear investment coefficient, F_2 is the quadratic coefficient on investment, and $\mathcal{E}$ is the residual. Coal wasn't regressed in this study as its investment wouldn't change and the cost coefficients are not relevant to the function. SMRs have no available investment data, so the coefficients for nuclear power scaled proportionately to cost differences provided by the EIA were used instead. For all power sources regressed besides nuclear power, investment changes and average overnight investment costs for national electricity market regions in 2021 are used. This kind of data wasn't available for nuclear power so instead I regressed the total capacities of all nuclear power plants currently in the US by their overnight investment cost. This data was provided by the EIA's state nuclear profiles (U.S. EIA, 2012). Additionally, a time-based coefficient was added to the nuclear power regression to account for drastic changes in cost based on technological advances over time. This coefficient was based on the year in which a power plant was built, and its purpose was to remove cost changes from the coefficients that would have largely been technology-based. This data was also provided by the EIA. The coefficients found through the regression are provided in the table below:

Table 1.1

	Gas	Nuclear	Wind	Solar	Hydro
F0	430061994.2	-8.74734E+11	73163967.24	-53547481.39	-4102406.069
F1	833967.0861	686847.0603	813269.0635	1894583.383	743762.8595
F2	54.85414915	423.6207719	1497.252334	-27.79092697	6817.376318

Unfortunately, the coefficients found through the regression are not as accurate as I would have hoped for. This is largely a consequence of the fact that finding a large amount of data points for the regression proved to be extremely challenging. Besides nuclear power, each of the regressions had less than twenty-five observations to pull from despite my best efforts to find relevant investment information. Some of the above coefficients are negative, meaning that the energy source sees increasing returns to scale or decreasing marginal cost with additional investment.

Results

However, even with unrepresentative cost coefficients, the cost minimization problem produced fairly realistic figures for the hypothetical firm's direction of investment. The quadratic terms that were found in the regression did add some convexity to the cost minimization problem, but not as much as I had hoped for. The consequence of this is that the investment the firm takes is still similar to a corner solution, where most of the new investment occurs in a single energy source. With a T of thirty years, an annual energy demand growth rate of 1.7%, and a discount rate of 5%, the cost minimization problem yielded interesting results. Below is a pie chart indicating PJM's composition of 173,749 megawatts of energy-producing capital for the year 2021, as well as a pie chart for PJM's final composition after thirty years with the introduction of SMRs.

Figure 4.1 PJM Fuel Mix in 2021

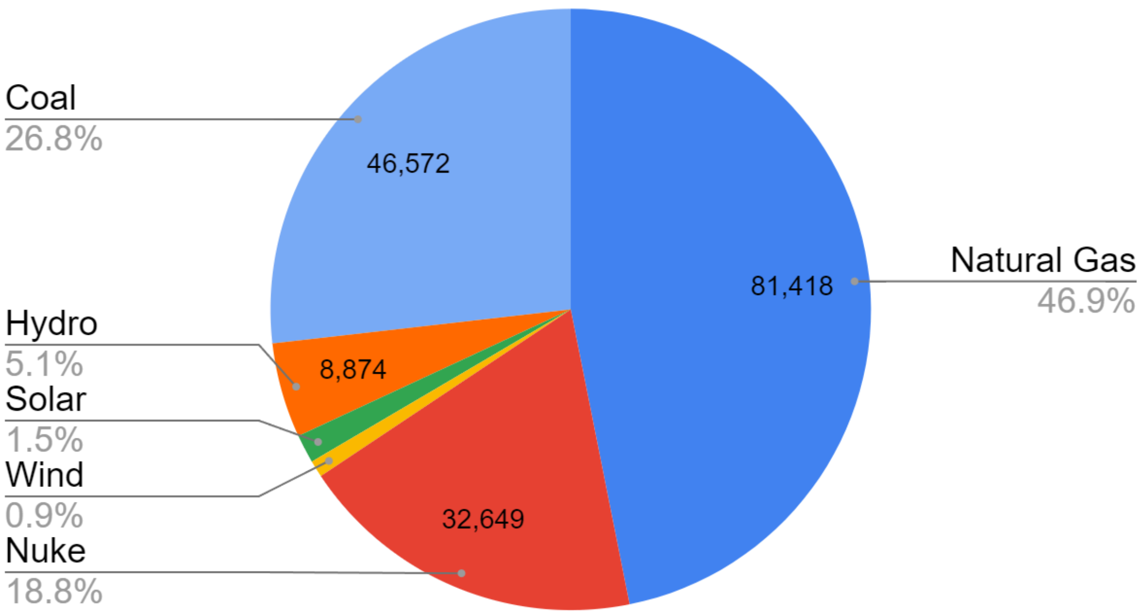
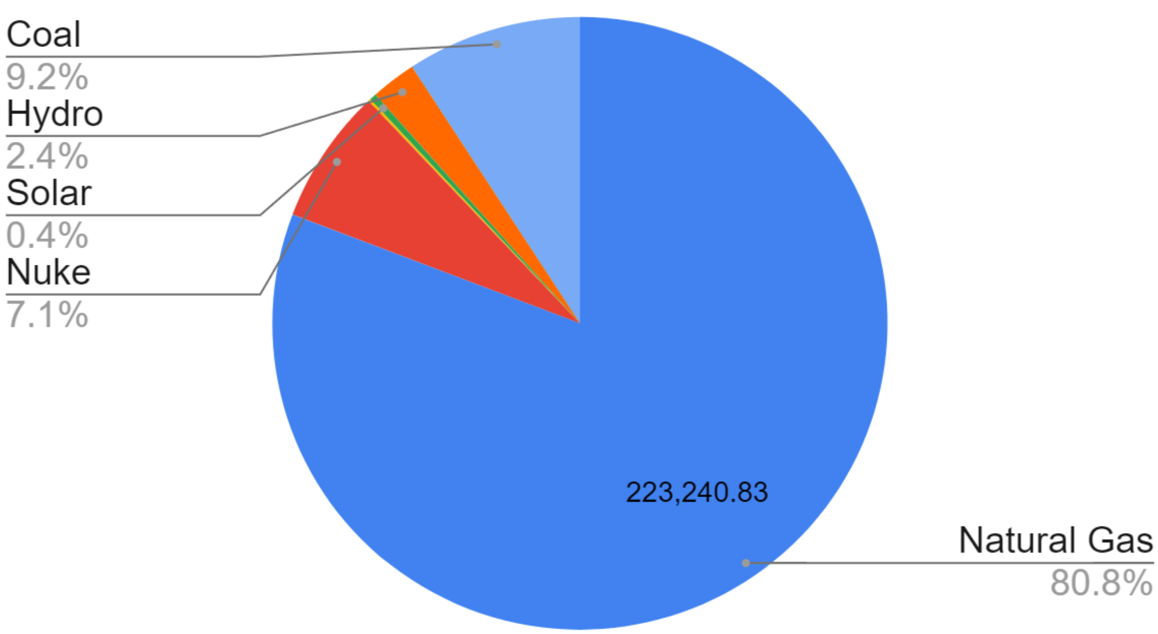


Figure 4.2 PJM Fuel Mix in 2051



Over thirty years, the total capacity needed to fulfill demand went from 173,749 megawatts to 276,335 megawatts. The total cost to replace depreciated capital and to fulfill expanding energy demand over thirty years for PJM was $2.356 trillion. The majority of new investment was in natural gas power as natural gas is not only one of the cheapest, but also one of the most consistent energy-producing sources with a relatively high capacity factor of 0.87 as compared to solar's 0.28, and wind's 0.41. Natural gas's capacity factor is lower than traditional nuclear's .90 and SMR's .96, however. Furthermore, natural gas has a much higher rate of depreciation compared to nuclear, but its low upfront investment costs largely offset these disadvantages. What is most interesting about the results is that the only other energy source that saw investment other than natural gas was SMRs. This can't be seen very well on the pie charts as the portion of the investment that SMRs saw was very small, a mere 21 megawatts, but is nonetheless very important and insightful. Below are line graphs of the trends of investment for each of the relevant power sources, separated into two graphs based on whether or not they made up a significant portion of the power supply.

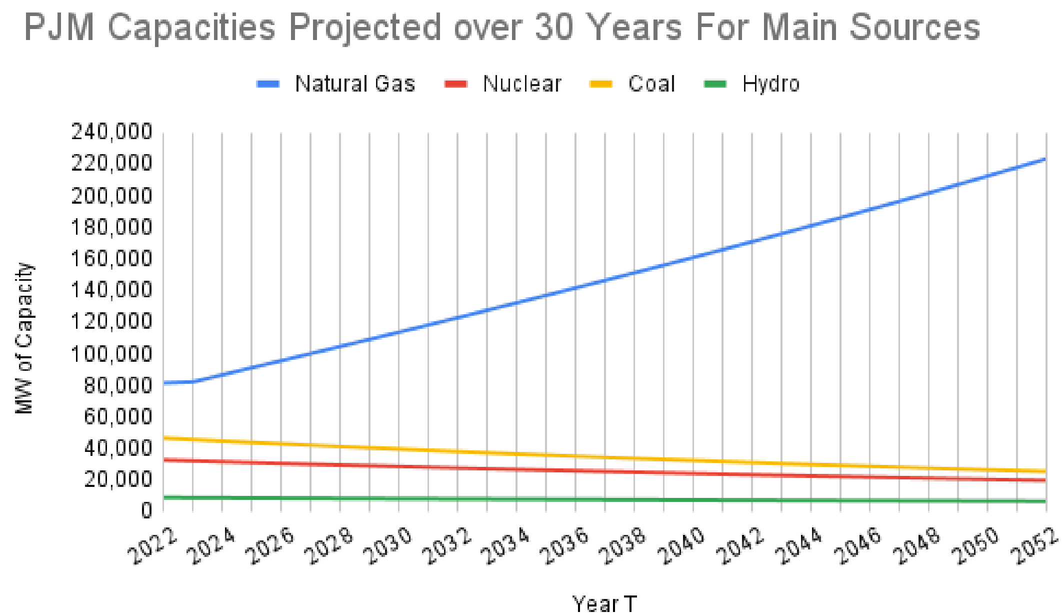


Figure 5.1

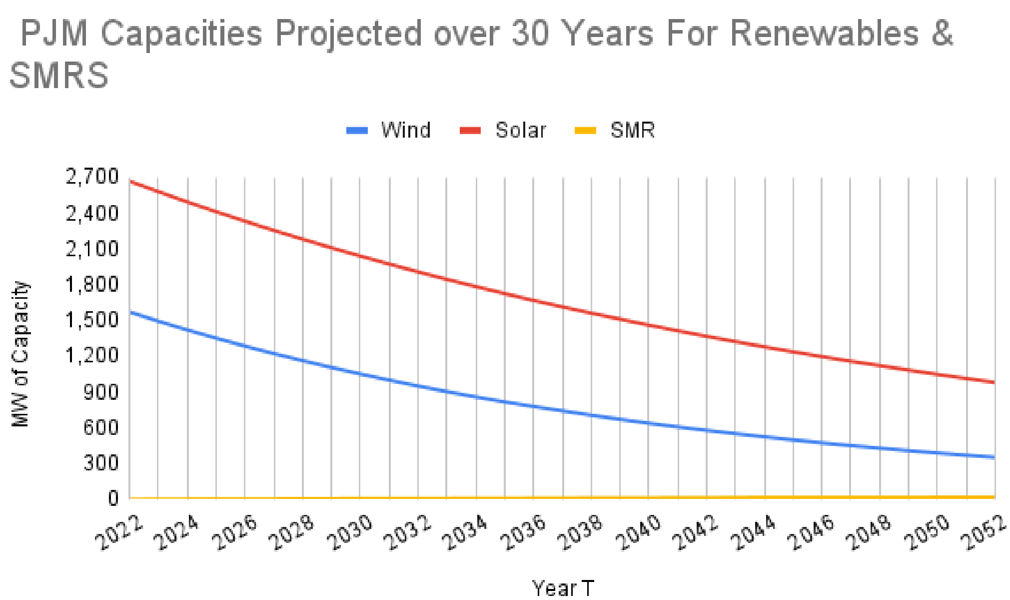


Figure 5.2

For clarity, an individual chart of SMR's investment is provided due to the insignificant portion of power that SMRs provide so that the overall trend can be observed more easily.

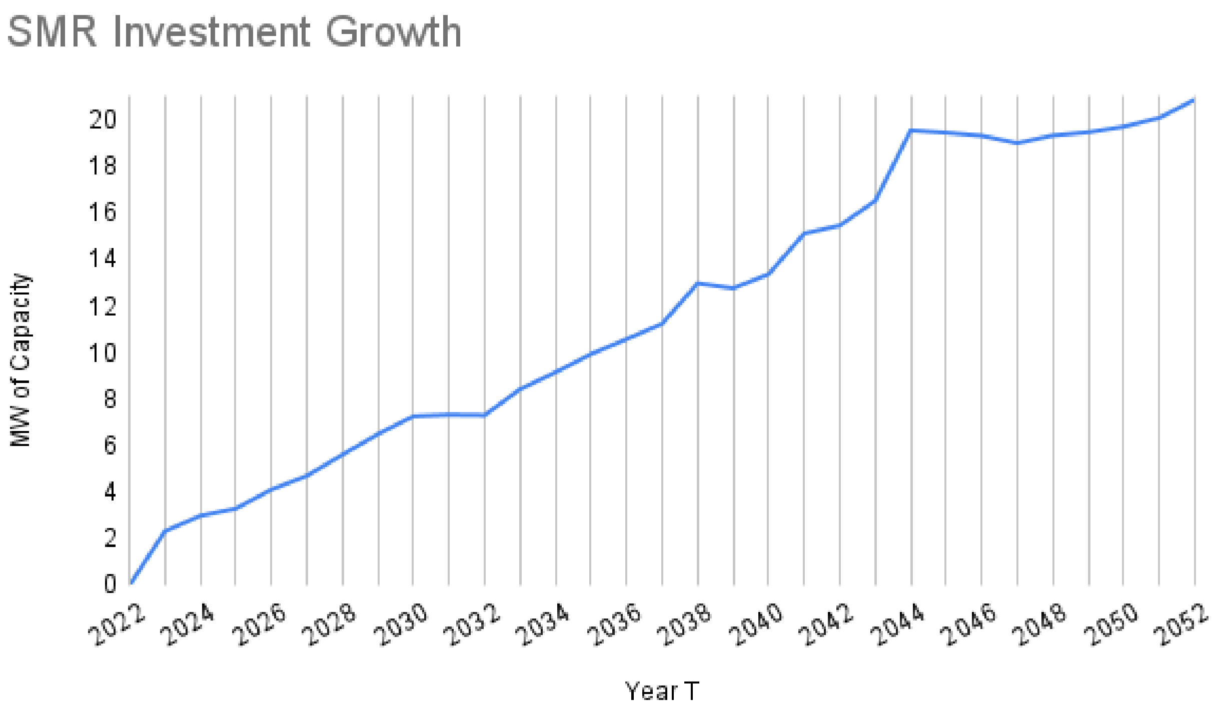


Figure 5.3

Despite SMR's larger upfront costs, its low rate of depreciation, low operations costs, and highest capacity factor of .96, make it somewhat viable on a pure cost basis when compared with the other power sources. What's perhaps even more interesting, is how poorly the renewable power sources did in comparison to natural gas and even SMRs. Despite the large strides in the last decade to make renewable power more economically competitive, its inherent flaws in reliability make it unattractive as the main energy-providing capital in a power grid. This makes sense as energy demand can be unpredictable and relying on a large amount of renewable energy that has volatile output could cause brownouts and even blackouts. This however does not reflect the investment decisions made in reality, as the EIA projected that solar power and wind power will grow by 43% and 6% respectively in the United States in the year 2023 (U.S. EIA, 2023)[2].

Discussion

Unfortunately, the results outputted by the cost minimization program were not as realistic as hoped for. Despite this, the solution to the cost minimization problem did show possible investment in SMRs. While this investment was very insignificant, it speaks volumes about the advantages that SMRs possess over renewables considering there wasn't any new investment in the much cheaper renewable power sources. After spending many hours correcting and tweaking the program, the results seem to mostly follow an unrealistic corner solution. This is largely a result of three main obstacles that were encountered in attempting to quantify SMR's impact on energy markets:

The first obstacle was the weak quadratic terms found by the regression. Similarly, the intercepts and linear coefficients on investment seem inaccurate as well. The goal of these coefficients was to add convexity by simulating diminishing marginal returns for each of the power sources. However, while the quadratic coefficients did create some convexity, it simply was not enough for proper robust results. All of the coefficients were found through a regression that used investment data from various sources. The main problem lies here, as finding specific data on investment and the cost of investment for the power sources proved to be extremely challenging. First of all, there doesn't seem to be much, if any, acceptable data for diminishing marginal returns on investment for generator technologies. If this was more accessible, the regression would have been unnecessary as this is largely what was needed to produce more

[2] The figures used in the study included subsidization from the US federal government as well as taxes and fees. All final dollar amounts used or produced by the study are expressed in 2021 dollars as measured by the U.S. Bureau of Labor Statistics consumer price index.

convex results in the cost minimization program. Secondly, trying to find these values in this study using a regression was also very difficult. A separate regression was done on each relevant generation source. For each power source except traditional nuclear power, there were fewer than twenty or so observations due to the limited data, which made the coefficients fairly unrepresentative.

A second issue in attempting to quantify SMR's impact on future energy markets is the fact that not a single commercial SMR has been fully built. This creates difficulties in quantifying SMR costs because reliable investment data simply does not exist. This made finding a quadratic coefficient for SMRs using this method impossible, so to mitigate this, I simply proportionated the cost terms provided by the nuclear power regression to fit SMRs more closely by using the EIA's cost figures for both traditional nuclear power and SMRs in their Annual Energy Outlook for 2023. While this makes modeling SMR cost coefficients possible for the purpose of this study, it doesn't provide very accurate results. Similarly, production learning couldn't be accounted for and could have a tremendous impact on the costs of SMRs. As more of them are built, producing each individual unit will get cheaper and this factor simply could not be accounted for. In recent years, this trend has been observed with renewables. The cost to produce renewable energy has gone down as firms have gained insight into more cost-effective production by serially manufacturing energy plants. This study also focused on NuScale, the only licensed manufacturer of commercial SMRs in the United States. Other companies are currently in the process of becoming licensed and have already created prototypes. As more firms enter the market, competition would also drive down the construction costs of SMRs.

The third main obstacle for the methodology of this study is inherent in attempting to project SMR introduction in energy markets using an optimization problem. Many of the most important considerations facing policymakers and companies in choosing an optimal energy generator are very difficult to model in terms of cost. While factors like capacity factor, rate of depreciation, fixed, variable, and operations and maintenance costs were accounted for, factors like land usage, carbon footprint, time to build, and other extraneous costs were not. This of course produces inaccuracy in the results and if there were other studies that could more closely quantify these things for energy generators, it would have made a large impact on the findings of this paper.

Conclusion

Despite these difficulties, the solution to the cost minimization problem did show some potential for investment in SMRs. SMRs are much more expensive on not only a fixed cost basis when compared with renewable power sources but also in terms of the levelized cost of electricity which made the results fairly surprising. However, two main factors hinder renewable energy investment: their much higher rate of depreciation and their much lower capacity factors. Hydroelectric power doesn't suffer so much from this problem as solar and wind do, but hydroelectric also has much higher upfront costs.

This study also highlights some of the existing gaps in research regarding energy economics. In general, there is a lack of available energy investment data. Furthermore, there is very little research that shows the changing marginal returns for investment in certain types of energy. This lack of available data severely hindered the accuracy of the projections and these gaps in research should undoubtedly be fulfilled by future researchers hoping to compare the economic competitiveness of different energy sources.

While the results were not what was hoped for, they remain somewhat significant. This study has shown that SMRs have some potential to be considered in decisions regarding energy investment. Furthermore, the cost minimization program and methodology used in this study can be applied to many similar economic problems when attempting to project market supply with the introduction of a different piece of capital or input. While these results are relatively inconclusive, they can somewhat still be applied to the real world. While most of the investment came from natural gas due to low cost and its other attributes, the program showed potential for investment in SMRs. This shows that even with their steep capital costs, SMRs can still produce energy in a relatively cost effective manner. For the near future, SMRs will likely only be used in special circumstances that demand high energy generation in a confined space. As SMRs are made, their costs will go down due to production learning from repeated manufacturing. This, and the appropriate economic conditions and inflationary environment could lead to a wider adoption of SMRs that could have large effects on future energy supply composition.

While SMRs don't seem to be a magic bullet for carbon neutrality today due to high costs, their advantages cannot be overlooked. As SMRs become cheaper in the future, their specific characteristics make them an attractive energy source and a viable competitor to renewable energy currently in use.

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