A COMPARISON OF ZERO CARBON NUCLEAR AND SOLAR ON A NORMALIZED GENERATION EQUIVALENCE BASIS

by

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(Under the Direction of David Gattie)

ABSTRACT

CO_2 emissions and the resulting climate change implications are reorienting the US and parts of the world to a low-carbon energy future. While transitioning from coal to natural gas has made substantial contributions toward decreasing carbon emissions in the electric power sector this transition has its limits. Ultimately, zero-carbon emission energy sources (such as nuclear and renewables) will be needed to further reduce CO_2 emissions from the power sector. The debate between nuclear and renewables usually revolves around issues such as reliability, dispatchability, safety, and construction costs. Commonly, comparisons between solar and nuclear technologies are based on plant capacity, which, due to intermittency and capacity factors differences, isn't a normalized comparison. This research explores the costs associated with building and operating solar and nuclear plants based on a capacity- and generation-equivalence basis under a range of interest rates in order to compare the two technologies on a normalized generation basis.

INDEX WORDS: NUCLEAR, SOLAR, GENERATION, LEVELIZED COST

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INTRODUTION

1.1 Background and Motivation

With a focus being put on the negative impacts of CO_2 emissions and resulting climate change, the US and the rest of the world are reorienting toward a low-carbon future. In the US, this transition can be seen mainly via coal-to-natural gas transitions in the power sector [1]. While this transition has helped reduce CO_2 emissions from the power sector, the transition has its limits because there are only so many coal plants that can be retired and displaced by natural gas. While natural gas CO_2 emissions are about half that of coal on a per MWhr basis, CO_2 emissions will not be zeroed out under a coal-to-gas transition scenario alone [2]. This means zero-carbon resources will be needed in order to sustain the CO_2 reduction trend, meaning renewables, nuclear, or a combination of both.

The debate between renewables and nuclear has revolved around several issues. For renewables, the reliability and intermittency of the technologies are an issue [3]. For nuclear, there is pushback due to the safety concerns of the technology as well as the high construction costs [4]. Oftentimes, there is an either-or decision proposed for the two, when the steady base load supplied by nuclear would be a good complement to the intermittency of renewables.

With many of the comparisons between nuclear and renewables, the construction cost of the technologies of comparable generating capacity are generally put forward as the sole rationale for choosing one over the other. For example, the construction cost of a 1000 MW nuclear plant being compared to the construction cost of a 1000 MW solar plant. However, this comparison is insufficient in that it does not account for the differences in dispatchability, intermittency, capacity factors, lifespan, decommissioning, waste disposal, or spent fuel storage for nuclear and solar.

1.2 Research Objective

This paper will analyze and compare five power plant technologies: 1) nuclear power (light water reactors), 2) fixed tilt solar PV, 3) single axis tracking solar PV, 4) fixed tilt solar PV with battery storage and 5) single axis tracking solar PV with battery storage. Each technology will be analyzed for total construction costs and levelized cost of electricity ($/kWhr). Since these technologies have fundamentally different operating characteristics, particularly capacity factors, intermittency and plant lifetimes, this research will include analyses that normalize the comparisons on a generation-equivalence basis in order to account for intermittency and capacity factor differences across the technologies. Also, in order to account for lifecycle differences between a nuclear plant, which has a lifetime of 60-years, and a utility-scale solar plant, which has a lifetime of 25-30 years, the capacity-equivalent and generation-equivalent analyses will be normalized on a 60-year lifetime basis.

Moreover, since interest rates are a key factor in determining long-term costs, particularly for high capital cost projects such as large capacity nuclear, the plant technologies will be analyzed across a range of interest rates.

1.3 Thesis Structure

This thesis begins with a literature review of the costs associated with building and operating nuclear and solar plants (capital costs, plant operating costs, and other costs) as well as decommissioning of nuclear plants. First the nuclear costs are addressed. The nuclear fuel cycle is also fully explained as well as the licensing process for new nuclear projects. Finally, an example of a timeline for a new nuclear project is outlined. Following nuclear costs, the solar costs are addressed. The third section outlines the methodology of the research conducted. A full explanation of the Excel spreadsheet design, formulas and use is included. The fourth section presents the results of the analyses along with tables and graphs summarizing the levelized costs of electricity (LCOE) for solar and nuclear power across varying interest rates. Finally, the fifth section discusses the results and raises points that need to be addressed in subsequent analyses comparing nuclear and solar.

LITERATURE REVIEW

2.1 Economics of Nuclear Power

While the upfront cost of a nuclear power plant is rather extensive, on a levelized (lifetime) basis, nuclear power is an electricity generation resource with advantages in security [5], reliability, and very low greenhouse gas emissions [6]. When assessing the actual cost of nuclear power, there are three main categories. These are:

- Capital Costs
- Plant Operating Costs
- Other Costs

2.1.1 Capital Costs

Capital costs are incurred while the plant is under construction. Expenditure on the necessary equipment, engineering and labor, and the cost of financing the investment are all included under these costs. In a report published by the World Nuclear Association it is said that the economics of new nuclear plants are heavily influenced by the capital cost, which accounts for approximately 60% of the levelized cost of electricity (LCOE). Interest charges and the construction period are variables that must be taken into consideration for determining the overall capital cost [6]. Capital costs can be further broken down into overnight cost, construction/investment cost, and financing cost [6].

Overnight cost generally includes engineering, procurement, and construction (EPC) cost, the cost of land, cooling infrastructure, any associated buildings, or licenses, and possible other various cost [6]. Overnight cost varies based on the region the plant is being built in, its size, and the type of technology that is being utilized [7] .

Construction/investment cost includes all aspects of the capital cost, meaning the overnight cost, cost escalation, and financing charges [6]. This cost is necessary for identifying the total cost of construction and determining the effects of construction delays [6]. The construction cost for nuclear is overall much greater than coal or natural gas plants because of the need for special materials needed for the construction of the plant and the special safety features that must be incorporated into the design. About 80% of the overnight cost relates to EPC costs, with about 70% of these costs being direct cost, meaning that they are plant equipment, labor, and materials, while 30% are indirect costs, or supervising engineering and support labor [6]. The final 20% is for the cost of testing the system and training for plant workers [6].

The financing cost will be greatly influenced and determined by the construction time and the interest charges put in place. The discount rate, or interest rate, is also critical as it reflects risk. It is generally higher for nuclear than other technologies because of the difficulties in completing the project on time and within budget [7]. The construction period is usually defined as the time between pouring the first concrete to grid connection. Long construction periods will increase financing cost. The World Nuclear Association states that for plants today, four to four and a half years is a typical time projection for completion, as seen in Figure 1. Other sources, such as the Nuclear Energy Agency, state that it could take five to seven years to complete a large nuclear plant, excluding time for licensing [6]. The loans taken to finance the construction accrue interest during construction (IDC) and must be paid at agreed-upon intervals to the lenders by the owners of the project. IDC is capitalized because the plant is not yet generating any income, thus increasing overall capital cost [8].

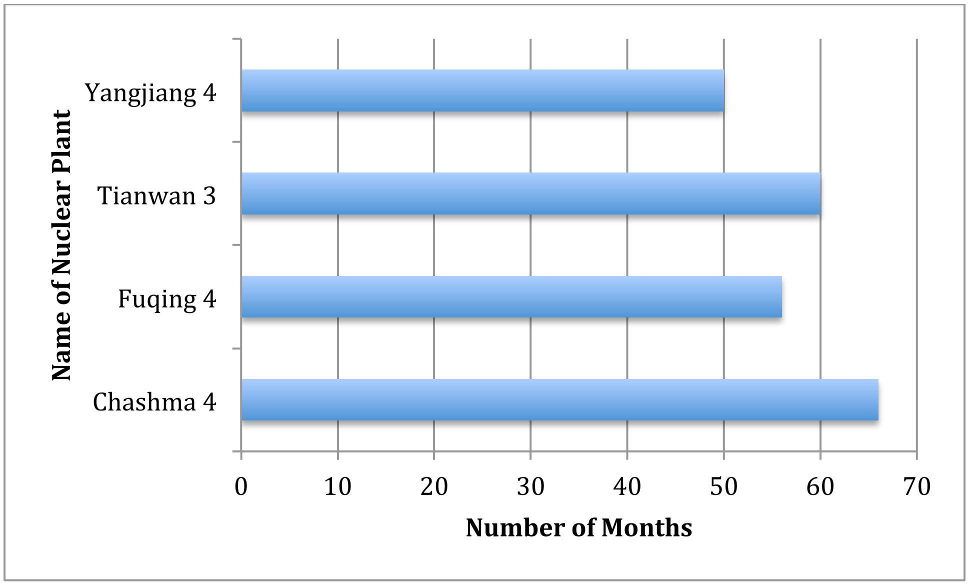

Figure 1: Construction times of four new units connected to the grid in 2017 **[9]**

2.1.2 Challenges to Financing Nuclear Power Plants

There are many financial risks for investors with respect to nuclear power plants. These risks can be divided into two categories: factors that could delay the construction of the plant and increase the capital cost and factors that could affect the plant's operation and its ability to earn a return on investment [8].

There have also been issues with nuclear licensing and other regulatory processes. Difficulties in the licensing process for new plants lead to delays in the plants becoming operational, increasing cost greatly. For example, a newly completed plant in Long Island, New York didn't enter into operation after being refused an operating license. It cost approximately 6 billion dollars to build and bankrupted the owner [8].

Nuclear power plants are subject to legal arrangements to cover the liability for damages caused by a nuclear accident. The federal government covers a portion of the liability, but the plant owners are also required to have specialized insurance [8]. These insurance policies can be expensive, again presenting a risk to investors.

As previously stated, construction delays will significantly increase cost and therefore are a source of risk for investors. There are many instances of nuclear projects taking years longer to complete than initially thought. Today the global approach for nuclear projects is to use a proven design and make minimal changes to adapt to the construction site [8]. This will help reduce the risk of potential delays, but it also limits technological developments. Financing first-of-a-kind projects is much more difficult [8].

2.1.3 Nuclear Power Plant Licensing Process

"The Nuclear Regulatory Commission licenses and regulates the operation of commercial nuclear power plants in the United States" [10]. The plants currently operating were licensed under a two-step process that requires both a construction permit and an operating license. To improve efficiency and predictability of the process, in 1989 the Nuclear Regulatory Commission (NRC) introduced the combined license, which as the name suggests, combines the construction permit and operating license. There is also an Early Site Permit that "allows an applicant to obtain approval for a reactor site without specifying the design of the reactors that could be built there, and certified standard plant designs which can be used as pre-approved designs," [10]. Ultimately the NRC approval is required before a nuclear plant can be built and put into operation. The NRC maintains a level of oversight during the construction phase as well as the entire lifetime of the operating plant. This is to ensure compliance with the regulations set by the agency for safety, the protection of public health, security, and the environment.

2.1.3.1 Two-Step Licensing Process

"All nuclear power plant applicants must undergo a safety review, an environmental review, and antitrust review by the NRC," [10]. The applicant must also submit a Safety Analysis Report. This contains the design information and criteria for the proposed reactor as well as comprehensive data on the proposed site. It also discusses different hypothetical accident situations the plant could possibly encounter and the safety features in the plant that could prevent the accidents or lessen their effects. The application must also have an assessment of the impact the proposed plant will have on the environment. Finally, the applicant must submit information for antitrust reviews of the plant [10].

Once the application to construct a nuclear plant is received by the NRC, the staff then determines if it contains all the material needed to accept it and begin a detailed review. If the application is accepted, the NRC then holds a public meeting close to the proximity of the proposed site to familiarize the public with the safety and environmental aspects of the plant that has been proposed. This information includes the planned location, type of plant, the regulatory process, and the terms of public participation in the licensing process. There are several meetings like this held throughout the licensing process [10].

All of the documents and any correspondence related to the application are put into the Agencywide Documents Access and Management System (ADAMS) and also in the NRC Public Document Room, which is located in Rockville, Md. The NRC then issues a press release to media located near the proposed site announcing receipt of the application and then sends copies of this announcement to federal, state, and local officials. This is also published in the Federal Register, [10].

The NRC staff reviews the application to determine if the plant design meets all applicable regulations. This review includes:

- Characteristics of the site, including surrounding population, seismology, meteorology, geology, and hydrology
- Design of the nuclear plant
- Anticipated response of the plant to hypothetical accidents
- Plant operations, including the applicant's technical qualifications to operate the plant
- Discharges from the plant into the environment (such as radiological effluents)
- Emergency plans
- (all from U.S.NRC site [10])

Once the NRC review is complete, it issues a Safety Evaluation Report summarizing the anticipated effect of the proposed plant on public health and safety. "The Advisory Committee on Reactor Safeguards (ACRS), an independent group that provides advice on reactor safety to the five-member Commission, reviews each application to construct or operate a nuclear power plant," [10]. This review begins early in the licensing process and is accompanied by a series of meetings with the applicant and the NRC staff at appropriate times throughout. Once the ACRS has completed the review, it submits the results to the Commission by sending a letter to the Chairman of the NRC, [10].

To comply with the National Environmental Policy Act (NEPA), the NRC staff preforms an environmental review to evaluate the potential environmental impacts or benefits of the proposed plant. Once this review is complete, the NRC issues a Draft Environmental Impact Statement for comment by the appropriate federal, sate, and local agencies, as well as the public.

The agency then issues a Final Environmental Impact Statement that addresses all the comments and concerns received [10].

The Atomic Energy Act requires that a public hearing be held before the construction permit is issued for a nuclear power plant. This meeting is conducted by a three-member Atomic Safety and Licensing Board that is composed of one lawyer, who will act as chairperson, and two technically qualified persons [10]. The public may submit written or oral statements to the licensing board that will be entered into the hearing record, they may also petition to intervene as full parties in the hearing.

It is possible for the NRC to authorize the applicant to do some construction before the actual construction permit is issued. This is known as a Limited Work Authorization and it is done at the risk of the licensee. This will only happen after the licensing board acknowledges all of the NEPA findings required by the Commission's regulations for authorizing construction [10]. The board must ultimately determine if there is reasonable assurance that the proposed site is a suitable location in terms of radiological health and safety as well as for a nuclear power reactor of the size and type proposed.

Before the construction permit is issued, the applicant must have submitted a Final Safety Analysis Report to support its application for an operating license. The final design and operation and emergency procedures will be outlined in this report. "The NRC prepares a Final Safety Evaluation report for the operating license and the ACRS makes an independent evaluation and presents its advice to the Commission," [10].

Unlike the construction permit, a public hearing is not mandatory for operating license applications. The NRC does publish a notice in the Federal Register that it received an application for an operating license, has accepted it for review, and is considering issuance of the license [10].

2.1.3.2 Combined License

When applying for a combined license, the NRC authorizes construction of the facility in a similar manner to the construction permit under the two-step process. It must also contain much of the same information required in an application for an operating license issued in the two-part process and specify the inspections, tests, and analyses that the applicant must perform. There must be specified criteria “that are necessary to provide reasonable assurance that the facility has been constructed and will be operated in agreement with the license and applicable regulations,” [10]. If there is no early site permit or design certification in the application, then the NRC reviews the technical and environmental information as described in the two-step process. The combined license process also requires a mandatory hearing. After the combined license is issued, the Commission authorizes operation of the facility once it has been verified the applicant has completed the required inspections, test, analyses, and the acceptance criteria has been met. The NRC publishes notice of these completions in the Federal Register, and at least 180 days prior to the date scheduled for initial loading of the uranium fuel the NRC will publish a notice of intended operation of the facility in the Federal Register [10].

2.1.3.3 Early Site Permits

“An early site permit resolves site safety, environmental protection, and emergency preparedness issues independent of a specific nuclear plate design,” [10]. The application must contain:

- Site boundaries
- Seismic, meteorological, hydraulic, and geologic data

- Existing and projected future population of the surrounding area
- Evaluation of alternative sites
- Proposed general location of each plant planned to be on the site
- Number, type, and power level of the plants planned for the site
- Maximum discharges form the plant
- Type of plant cooling system that will be used
- Radiation dose consequences of hypothetical accidents
- Plans for coping with emergencies
- (all from U.S. NRC site [10])

The NRC reports its findings on the site safety characteristics and emergency planning in a Safety Evaluation Report and then reports on environmental issues in Draft and Final Environmental Impact Statements. The early site permit allows for limited work authorization to perform non-safety site preparation activities before a combined license is issued. The early site permit is valid for no less than 10 years and no more than 20 years and can be renewed for 10 to 20 years [10].

2.1.3.4 Design Certification

There is also the possibility that the NRC could approve and certify a standard nuclear plant design that is independent of a specific site. The design certification is then valid for 15 years once issued. This application must include proposed inspections, tests, analyses, acceptance criteria for the standard design, and also demonstrate how the applicant will comply with the Commission's relevant regulations [10].

The safety review for this application is based mainly on the information submitted by the applicant under oath [10]. Therefore, it is essential that the application submitted contain a level of design information that is sufficient to allow the Commission to draw a final conclusion on all safety aspects associated with the design. This would include a complete design of the plant with the exception of some features that would change based on the site chosen for construction.

Once submitted, the NRC staff "prepares a Safety Evaluation Report that describes its review of the plant design and how the design meets applicable regulations," [10]. The ACRS then reviews each application for a standard design certification as well as the safety evaluation report in a public meeting. If the application is determined to meet the requirements of the Atomic Energy Act and the Commission's regulations, the Commission then drafts a rule to issue the design certification. This certification is subject to a more restrictive change process than other licensing processes that have been discussed. "The NRC cannot modify a certified design unless it finds that the design does not meet the applicable regulations in effect at the time of the design certification, or it is necessary to modify the design to assure adequate protection of the public health and safety," [10].

There is the option for an application for a combined license to include by reference a design certification and/or an early site permit. This means that the issues resolved in the rulemaking of the design certification and early site hearings cannot be reconsidered later during the combined license stage [10].

2.1.4 Financing Structure of Nuclear Power Plants

"Most nuclear power plant projects involve a mixture of debt and equity financing" [8]. With debt financing, a bank or other lender, makes a loan for a proportion of the project and some security or collateral is provided. The loan will be repaid with interest in accordance with the loan agreement [8]. In equity financing, an investor provides funding in exchange for a share in ownership of the project. The investor would then receive returns from the sale of electricity once the plant is operating [8].

A nuclear power plant is generally in operation for roughly 60 years before it is decommissioned. Financing of the project will be spread thought the lifetime of plant. The long lifetime of a nuclear power plant is an advantage for this technology.

2.1.5 Plant Operating Costs

Operating costs typically include the cost of fuel and operation and maintenance (O&M). However, funding the cost of decommissioning the plant and treating and disposing used fuel (nuclear waste) must also be accounted for. It is generally expressed relative to a unit of electricity in order to provide a consistent comparison with other energy technologies. To calculate the operating cost of a plant for its entire lifespan, the levelized cost must be estimated at present value [6].

The low cost of uranium fuel is one of the reasons the operating cost of nuclear is much lower than other forms of electricity. This fuel must be processed, enriched and fabricated into fuel elements, and this accounts for about half of the total fuel cost [6]. Even with the included cost of waste management and disposal of nuclear waste included in the fuel cost, it is still about one-third to one-half of coal plants and one-quarter to one-fifth of natural gas plants [6]. The price of uranium per pound is roughly $38.00 [11]. With the heat content of uranium per pound at about 180,000,000 Btu [12], the price of uranium can be calculated to be about $0.216 per mmBtu. The average price of natural gas and coal for the U.S. power sector in 2018 was about $3.50 per mmBtu [13]. The effect of the price of uranium on the overall fuel cost can be seen in Figure 2.

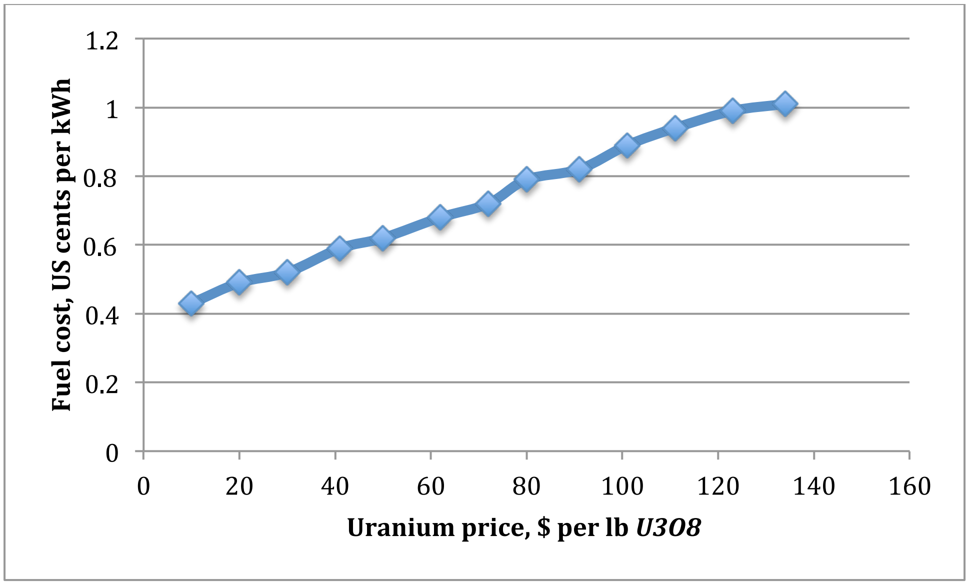

Figure 2: Effect of uranium price on fuel cost **[6]**

Uranium is a highly concentrated source of energy and is easily and inexpensively transported [6]. The amount of uranium fuel needed is also much less than the amount of coal it would take to produce the same amount of electricity (one kilogram of natural uranium will yield roughly 20,000 times as much energy as the same amount of coal) [6]. There are also possibilities of savings in the future when it comes to nuclear fuel. Reprocessing the spent fuel offers the possibility of extracting more energy from the uranium while also decreasing the amount of nuclear waste.

Operation and maintenance (O&M) costs are accounted for in the plant operating cost. They account for about 66% of total operating cost [6].

2.1.6 Nuclear Fuel Cycle

"The various activities associated with the production of electricity from nuclear reactions are referred to collectively as the nuclear fuel cycle, [14]. This cycle consists of front-end steps that prepare the fuel (uranium) for use in nuclear reactors as well as back end steps to safely manage, prepare, and dispose of the radioactive spent nuclear fuel [15]. The entire process is outlined in Figure 3.

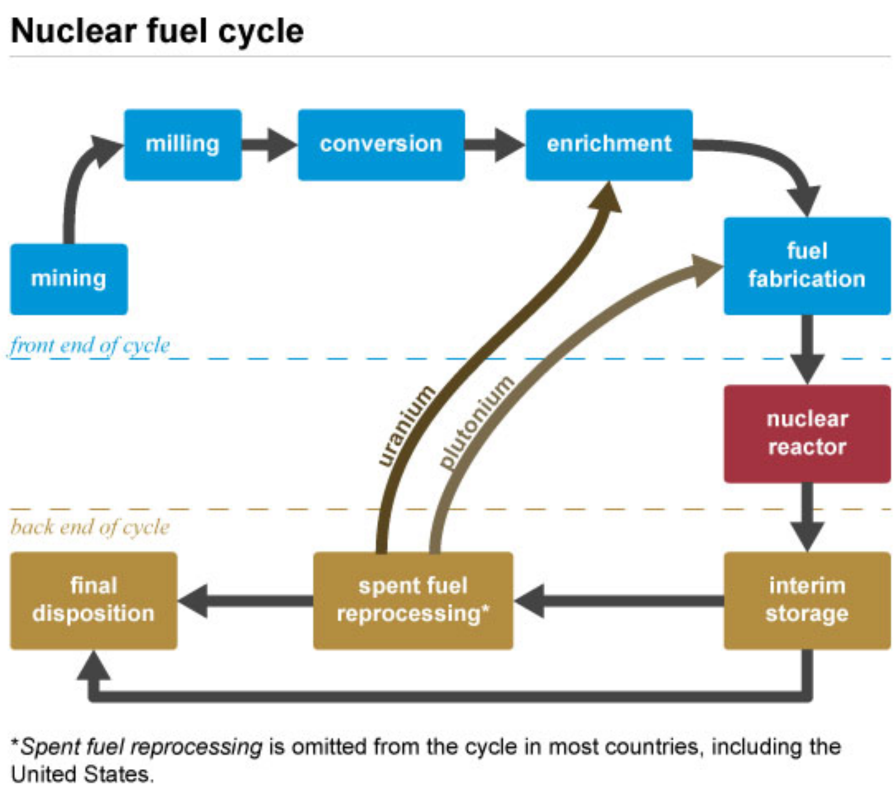

Figure 3: Outline of Nuclear Fuel Cycle **[15]**

2.1.6.1 Uranium

Uranium is a radioactive metal available throughout Earth's crust and for that reason is rather abundant. It is roughly 500 times more abundant than gold and is said to be about as common as tin. It is present in most rocks, soils, many rivers and seawater. "It is found in concentrations of about four parts per million (ppm) in granite, which makes up 60% of the Earth's crust," [14]. Most of the radioactivity that is associated with uranium in nature is due to other minerals derived from it by radioactive decay processes, and they are left behind in the mining and milling processes [14].

2.1.6.2 Exploration

The process starts with actually locating uranium and then developing mines to extract the ore. Techniques used to find the mineral include:

- Airborne radiometric surveys
- Chemical sampling of groundwater and soils
- Exploratory drilling to understand the underlying geology [15]

Once discovered, development drilling is then used to determine how much uranium is present and what it might cost to extract [15].

2.1.6.3 Uranium Mining

Once it is deemed economically feasible to recover the ore deposits, mining begins. The techniques used include:

- Underground mining
- Open pit mining
- In-situ-leach mining
- Heap leaching [15]

Underground mining is used more frequently when the deposits are located deep beneath the surface, typically greater than 120 meters deep [14]. These mines have relatively small surface disturbance and the material that needs to be removed to access the ore is kept to a minimum. However, there are special precautions that must be taken, mostly consisting of increased ventilation to protect against airborne radiation exposure [14].

Open pit mining is generally used where deposits are close to the surface. They require large holes on the surface, much larger than the size of the ore deposit because the walls of the pit must be sloped to prevent collapse [14]. This results in a large quantity of material that must be removed to access the ore.

Today in the United States, uranium is being mined using a solution mining technique called in-situ-leach (ISL) or in-situ-recovery (ISR) [15]. This process uses "oxygenated groundwater that is circulated through a very porous orebody to dissolve the uranium oxide and bring it to the surface," [14]. "ISL may be with slightly acid or with alkaline solutions to keep the uranium in solution," [14]. The uranium dioxide is recovered from the solution in a conventional mill.

Heap leaching is a process in which an acidic liquid is sprayed onto piles of crushed uranium ore. "The solution drains down through the crushed ore and leaches uranium out of the rock, which is recovered from underneath the pile," [15]. This process is no longer used in the United States [15].

In order to choose which method of mining will be used for a certain deposit of uranium, the "nature of the orebody, safety, and economic considerations" [14] are used to make the decision.

2.1.6.4 Uranium Milling

Milling is carried out close to the uranium mine. Most mining facilities include a mill, but if there are several mines located close together, one mill may process the ore from several mines [14]. Milling extracts the uranium from the ore or ISL leachate [14]. "The ore is crushed, pulverized, and ground into a fine powder," [15]. Chemicals are then added to the powder, which causes a reaction that separates the uranium from the other minerals. "Groundwater from solution mining operations is circulated through a resin bed to extract and concentrate the uranium," [15]. What is recovered is a uranium oxide (U_3O_8) concentrate. After drying and usually heating, it is packed in 200 liter drums as a concentrate commonly referred to as 'yellowcake'[14].

The remaining ore, which contains most of the radioactivity and almost all of the rock materials, is referred to as mill tailings. The tailings are placed in an engineered facility near the mine, often in a mined out pit [14]. These tailings need to be isolated form the surrounding environment because they "contain long-lived radioactive materials in low concentrations and maybe also toxic materials such as heavy metals," [14]. The total quantity of radioactive elements is less than that found in the original ore, leading to their collective radioactivity to be shorter lived [14].

2.1.6.5 Conversion and Enrichment

The product that leaves the mill is not directly usable as fuel for a nuclear reactor; therefore, additional processing is required. Only 0.7% of natural uranium is fissile (or capable of undergoing fission). Fission is the process by which energy is produced in a nuclear reactor [14]. There are three forms of uranium that occur in nature. These include U-234, U-235, and U-238 [15]. The fissile isotope is U-235; therefore, current light-water nuclear reactors need a higher concentration of this isotope to operate efficiently. During the conversion phase, the yellowcake is converted into uranium hexafluoride (UF_6) gas. This conversion is necessary because the enrichment process requires the uranium to be in a gaseous form [14]. The United States has used gaseous diffusion and gas centrifuge techniques for the enrichment process.

Currently in the US there is one operating enrichment plant, which uses the gas centrifuge process [15]. This involves thousands of rapidly spinning vertical tubes. "As they spin, the physical properties of molecules, specifically the 1% mass difference between the two uranium isotopes, separates them," [14]. The gaseous uranium hexafluoride is separated into two different streams. One is the enriched UF_6 and has a 4% to 6% concentration of U-235 [15]. The other stream is essentially depleted uranium. "The enriched UF_6 is sealed in canisters and allowed to cool and solidify before it is transported to a nuclear reactor fuel assembly plant by train, truck, or barge," [15].

There are new enrichment technologies under development. These include atomic vapor laser isotope separation (AVLIS) and molecular laser isotope separation (MLIS) [15]. "These laser-based enrichment processes can achieve higher initial enrichment (isotope separation) factors than the diffusion or centrifuge processes and can produce enriched uranium more quickly than other techniques," [15].

2.1.6.6 Fuel Fabrication

After enrichment, the uranium must be converted into nuclear fuel. At a nuclear fuel fabrication facility, the UF_6 that was transported there in solid form is heated to a gaseous form again. It is then chemically processed to form uranium dioxide (UO_2) powder [15]. This powder is pressed to form ceramic pellets. "The pellets are encased in metal tubes to form fuel rods, which are arranged into a fuel assembly ready for introduction into a reactor," [14]. A fuel assembly can contain anywhere from 179 to 264 fuel rods, depending on the reactor, and a typical reactor core holds roughly 121 to 193 fuel assemblies [15].

2.1.6.7 Power Generation

After fabrication, trucks transport the fuel assemblies to the reactor sites. They are stored onsite in fresh fuel storage bins until the reactor operators need them [15]. The uranium is still only mildly radioactive at this point, and all the radiation is contained within the metal tubes [15]. In the reactor core, the U-235 isotope fissions, producing heat in a continuous process called a chain reaction [14]. The reaction is fully controlled by control rods inserted into the reactor. Some of the U-238 is transformed into plutonium by radioactive decay and roughly half of that is fissioned, providing about one third of the reactor's energy output [14]. Reactor operators change out one-third of the reactor core (40 to 90 fuel assemblies) every one to two years [15].

"The reactor core is a cylindrical arrangement of the fuel bundles that is about 12 feet in diameter and 14 feet tall and encased in a steel pressure vessel with walls that are several inches thick," [15]. The control rods are essentially the only moving part in the core, again to regulate the nuclear fission reaction. "Placing the fuel assemblies next to each other and adding water initiates the nuclear reaction," [15].

About 44 million kilowatt-hours of electricity are produced from one tonne of natural uranium [14]. To put this in comparison with a fossil fuel burning plant, to produce the same amount of electrical power, it would require over 20,000 tonnes of black coal or 8.5 million cubic meters of natural gas [14].

2.1.6.8 Used Fuel

After time, the concentration of fission fragments and heavy elements that are formed from the reaction increase to the point where using that fuel is no longer practical [14]. The used fuel must be removed from the reactor after 18-36 months [14]. "Even though the fission reaction has stopped, the spent fuel continues to give off heat from the decay of the radioactive elements that were created when the uranium atoms were split apart," [15]. Because of this, the used fuel is placed in a storage pond after being removed. The water "shields the radiation and absorbs the heat, which is removed by circulating the water to external heat exchangers," [14]. The used fuel is kept in the storage ponds for several months, possibly even years. "From 1968 through June 2013, 241,468 fuel assemblies had been discharged and stored at 118 commercial nuclear reactors in the United States," [15]. After the spent fuel cools, it can be transferred to dry cask storage containers on site before it is moved to the final destination at a permanent site.

2.1.6.9 Storage and Disposal of Nuclear Waste

Nuclear waste can be put into three different categories: low-level radioactive waste (LLW), intermediate-level radioactive waste (ILW), and high-level radioactive waste (HLW). All radioactive waste is stored to avoid radiation exposure to people and to prevent pollution. LLW is sent to land-based disposal immediately for long-term management. HLW is stored in either dry cask or ponds to allow decay of radioactivity and heat. After storage, it is taken for deep geological disposal. As of right now, this is the most favored way of disposing high-level nuclear waste. There is difficultly in dealing with this aspect of nuclear power because the solution must be safe, environmentally stable, and perceived well by the public. ILW can be handled two different ways. ILW that contains long-lived radioisotopes is stored before disposal in a geological repository. ILW containing short-lived isotopes is disposed of like LLW [6] [16].

2.1.6.9.1 Near-Surface Disposal

The International Atomic Energy Agency (IAEA) separates this option of disposal into two categories: at ground level or in caverns below ground level.

- “Near-surface disposal facilities at ground level. These facilities are on or below the surface where the protective covering is of the order of a few meters thick. Waste containers are placed in constructed vaults and when full the vaults are backfilled. Eventually they will be covered and capped with an impermeable membrane and topsoil. These facilities may incorporate some form of drainage and possibly a gas venting system.” [16].
- “Near-surface disposal facilities in caverns below ground level. Unlike ground level, where the excavations are conducted from the surface, shallow disposal requires underground excavation of caverns. The facility is at a depth of tens of meters below the Earth’s surface and accessed through a drift.” [16]. There is the possibility that these facilities could be affected by climate change (glaciation) and needs to be taken into account. Therefore, they are generally used for LLW and short-lived ILW [16].

Ground level facilities can be found in the UK at the LLW Repository at Drigg in Cumbria, in Spain at the El Cabril LLW and ILW disposal facility, in France at the Centre de I’Aube, in Japan at the LLW Disposal Center at Rokkasho-Mura, and in the United States at Texas Compact facility, Barnell, South Carolina, Clive, Utah, Oak Ridge, Tennessee, and Richland Washington [16].

Cavern facilities are located in Sweden at the SFR final repository for short-lived radioactive waste at Forsmark. This facility is located 50 meters under the Baltic seabed [16]. There are also two in Finland, with one located at Olkiluoto for LLW and ILW and then one in Loviisa. Both are about 100 meters deep [16].

2.1.6.9.2 Deep Geological Disposal

Due to the half-life of HLW, disposal of the waste is stored in underground repositories in stable geological formations. “Isolation is provided by a combination of engineered and natural barriers (rock, salt, clay) and no obligation to actively maintain the facility is passed on to future generations.” [16].

An example of a current project of this type of disposal site is Yucca Mountain, located in the remote Nevada Desert. This repository would exist 300 meters underground in an unsaturated layer of welded volcanic tuff rock [16] The nuclear fuel waste would also be stored in highly corrosion-resistant double-shelled metal containers, with the outer layer being made of a highly corrosion resistant metal alloy and then the inner layer being made of stainless steel for structural strength [16] This site would not be backfilled, but instead left open for air circulation. The containment of the waste relies on the low water table and the long-term durability of the engineered barriers [16].

Fuel storage and disposal in a waste repository contributes up to 10% of the overall cost per kWh [6]. The $26 billion US spent fuel program is funded by a 0.1 cent/kWh levy [6].

2.1.6.10 Reprocessing Spent Fuel

Another possibility besides disposal for spent fuel is reprocessing. Used fuel still contains 96% of its original uranium, but the fissionable U-235 content has been reduced to less than 1% [14]. Roughly 3% of the used fuel is made up of waste products and the remaining 1% is plutonium [14]. Reprocessing separates the uranium and the plutonium form the waste products by “chopping up the fuel rods and dissolving them in acid to separate the various materials,” [14,17]. This allows the uranium and plutonium to be recycled into fresh fuel. This reduces the amount of waste that needs to be dealt with.

During reprocessing, some separated liquid HLW is produced. This is then vitrified in glass and stored before final disposal [16].

2.1.7 Decommissioning Nuclear Power Plants

Decommissioning is the process in which nuclear power plants are retired from service and the operating licenses is terminated. The process includes: decontaminating the facility to reduce residual radioactivity, dismantling the structures, removing contaminated materials to disposal facilities, storing used nuclear fuel until it can be removed from the site for disposal, and releasing property for other uses [18]. The owner is held accountable until the entire decommissioning process has been completed and the license is terminated.

The company that owns the plant must assure that funds will be available for decommissioning. Decommissioning costs can be broken down into three different components: labor, energy, and the transportation and disposal of waste materials. These costs are about 9-15% of the initial capital cost of a nuclear plant [6]. When this cost is discounted over the lifetime of the plant, it contributes only a few percent to the investment cost and even less to the generation cost. In the United States, decommissioning cost accounts for 0.1-0.2 cent/kWh, which is less than 5% of the cost of the electricity produced [6].

2.1.8 Other Costs

There must be provisions for backup generation for when the generating power plant is not operating. Electricity must be able to be transmitted from where it is generated to where it is needed and the cost of the transmissions and distribution of the backup facilities are known as system costs. These costs are external to the cosntruction and operation of the power plant, but must be paid by the electricity consumer, usually as a part of the transmission and distribution cost [6].

2.1.9 Example of Current Construction - Plant Vogtle 3 and 4

To meet the rising demand for low- and zero-carbon electricity, Georgia Power and Southern Nuclear are building two additional nuclear reactors at Plant Vogtle, located near Waynesboro, GA. This is the first new nuclear generation to be built in the United States in more than 30 years [19].

In 2005, Southern Nuclear announced its intent to file for an Early Site Permit and then filed in 2006. Southern Nuclear also selected Westinghouse AP1000 technology for the new units [20]. Following this, there were different organizations that filed a petition to intervene in this permit. These groups included Atlanta Women's Action for New Direction, Blue Ridge Environmental Defense League, Center for a Sustainable Coast, Savannah Riverkeeper, and Southern Alliance for Clean Energy [20].

In 2007, the NRC's Atomic Safety and Licensing Board (ASLB) announced that it would allow the petition to intervene in the Early Site Permit, but the following year Southern Nuclear filed for a Combined Construction and Operating License application. The same groups filed a petition to intervene with this as well [20].

"Georgia Power submitted a nuclear self-build option to the Georgia Public Service Commission to meet the demand in the 2016-2017 timeframe," [20]. The Georgia PSC requires market bids to be compared with self-build proposals; however, there were no market bids received for the baseload capacity request [20].

In 2009, the NRC's ASLB held the hearings to review the Early Site Permit. Georgia Governor, Sonny Perdue, signed into law Senate Bill 31, which allowed Georgia Power to recover financing costs during the construction of nuclear units while under construction, therefore, reducing interest charges, thus costs to customers [20]. In June, the ESP was ruled in favor of and then evacuation of the area for the new units began.

In 2010, safety-related construction began. “Southern Company and the Department of Energy (DOE) announced that the company’s Georgia Power subsidiary had reached an agreement with the DOE to accept terms for a conditional commitment for loan guarantees for Vogtle units 3 and 4,” [20].

In 2011, the final supplemental environmental impact statement for a Limited Work Authorization (LWA) and the Combined Construction and Operating Licenses (COL) was completed for units 3 and 4 [20]. The design was certified and construction began. In 2012, the NRC issued Construction and Operation Licenses for units 3 and 4 [20].

Through 2014 and 2015, various parts of the reactors were delivered and constructed. 2016 was the year that the last major permit was obtained, while construction continued [20]. The Georgia PSC unanimously approved an agreement between Georgia PSC staff and Georgia Power, confirming an investment of $5.68 billion by the company in the Vogtle nuclear expansion [20]. “Under the agreement, all capital costs incurred by the company up to $5.68 billion, including $3.3 billion invested through the end of 2015, and the $350 million settlement agreement with the project’s contractors will be presumed to be reasonable and prudent. The agreement fairly balances the company’s contribution with customer benefits and is expected to deliver approximately $325 million in savings to customers during the construction period, while keeping the project’s overall projected rate impact to customers at 6 to 8 percent,” [20].

In 2017, Georgia Power finalized a new service agreement for the expansion. Southern Nuclear, which is a Southern Company subsidiary that operates the existing units at Plant Vogtle, would oversee construction activities at the site [20].

Units 3 and 4 are scheduled to begin commercial operation in 2020 and 2021. Once completed, these reactors will produce enough electricity to power 500,000 Georgia homes and businesses [19]. Each reactor will be able to generate roughly 1,117 MW of electricity with zero carbon emissions [21]. The co-owners of units 1 and 2 will maintain their current ownership shares in 3 and 4: Oglethorpe Power – 30%, Municipal Electric Authority of Georgia – 22.7%, and Dalton Utilities – 1.6% [19]. "Georgia Power's proportionate share of the estimated in-service cost of the two units, based on its current ownership interest of 45.7, is certified at $6.1 billion," [19].

2.2 Economics of Solar Power

The cost of solar power can fall into the same basic three categories as nuclear:

- Capital costs
- Operating costs
- Other costs

For technologies that do not have any fuel cost and relatively low O&M costs, such as solar, LCOE changes in proportion to the estimated capital cost [22]. Solar may also have the benefit of tax incentives.

2.2.1 Capital Costs

The capital cost of a solar PV system can be broken down into PV module costs, balance of system costs, and land costs. Solar is said to be one of the least expensive technologies on a per MW basis [23]. The risk with solar technology is also considered lower than wind or liquid gas turbines [23].

2.2.1.1 PV Module Cost

The interconnected array of PV cells is mainly determined by raw material cost. Silicon costs, cell processing and manufacturing, and module assembly costs are the most notable cost in this category. The growth in solar technology has led to significant price reductions over recent years, as seen in Figure 4 and Figure 5. The PV module cost has a wide range due to the prices of the market, depending on the cost structure of the manufacturer, market features, market pressures and module efficiency [24].

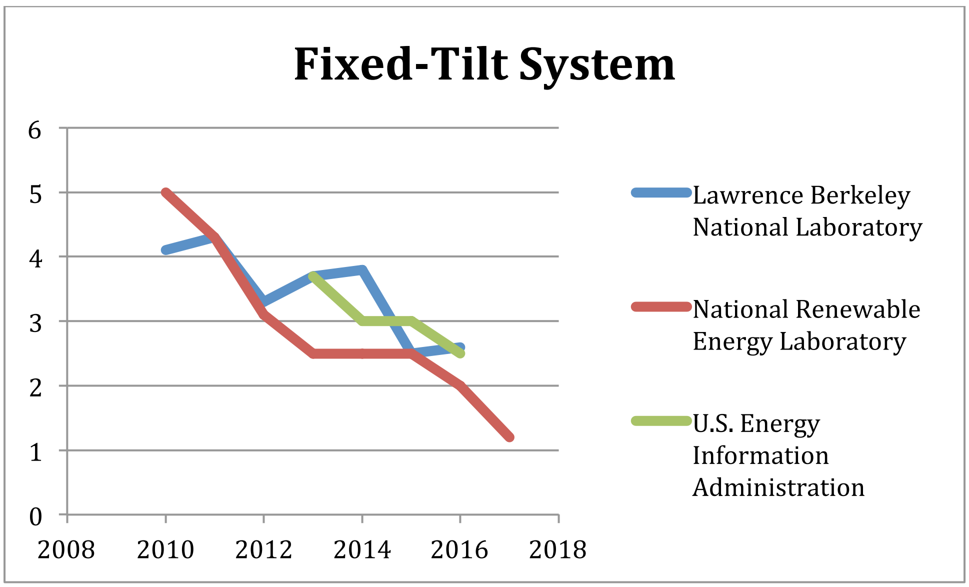

Figure 4: Reported utility-scale solar photovoltaic capital cost (2010-2017) dollars per watt – fixed-tilt systems **[25]**

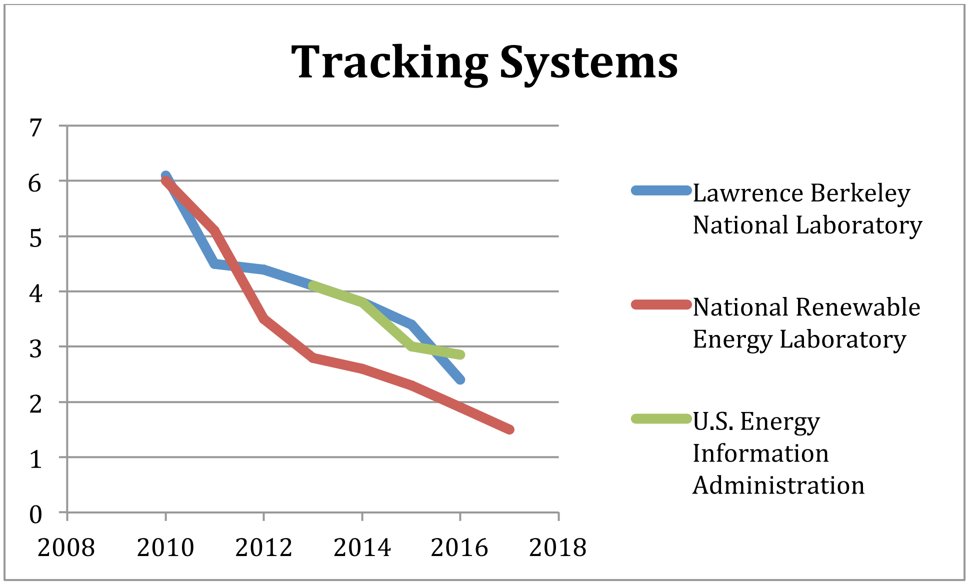

Figure 5: Reported utility-scale solar photovoltaic capital cost (2010-2017) dollars per watt – tracking systems [25]

2.2.1.2 Balance of System Costs

Balance of system (BoS) costs and installation costs make up the remaining capital costs of a PV system. These costs largely depend on the nature of the installation, with large utility scale projects costing less than large ground mounted commercial or residential systems, or rooftop residential systems [24].

BoS and installation cost breakdown:

- The inverter
- Components required for mounting and racking PV systems
- The combiner box and miscellaneous electrical components
- Site preparation and installation, labor, cost for installation and grid connection
- Battery storage for off-grid systems
- System design, management, permit fees, project development costs, and any up-front financing costs [24].

2.2.2 Operating Costs

Operating and maintenance costs generally represent a small fraction of the plant's lifecycle project development and operational costs. The activity generally accounts for between 1% and 5% of a MW-class plant's total $/kW expenditure [26]. Again, the O&M cost ranges based on the size, design, equipment used, and the location of the plant.

There are different approaches taken for O&M for solar plants. These include preventative maintenance (PM), corrective or reactive maintenance, and condition-based maintenance (CBM) [26].

Preventative maintenance requires routine inspections and servicing the equipment. The amount of time between inspections and servicing depends on equipment type, environmental conditions, and warranty terms in O&M agreement. This approach is to prevent breakdowns and unnecessary production losses and, because of this, is a popular approach for O&M. The downside to PM is that the upfront costs are moderate and it can cause more labor cost than needed [26].

Corrective or reactive maintenance addresses equipment repair needs and breakdowns after they happen. The upfront costs of this method are lower, but bring a higher risk of component failure and possible higher backend costs. The more proactive approach of PM is generally preferred over this [26]

Condition-based maintenance uses real-time data to anticipate failures and then prioritizes maintenance activities and resources [26]. Some say CMB leads to greater O&M efficiency, but there is a greater upfront cost for the monitoring needed. It can also lead to more work when there is a malfunction in the monitoring technology.

Utility-scale solar hasn't been applied over sufficient periods of time to evaluate an accurate lifetime of a solar plant. Estimates range from as low as 20-30 [27] years to as high as 30-40 years [28].The old system will either be disposed of or reprocessed.

2.2.3 Other Costs

Solar power will need battery storage to store electricity when the solar resource is not available. The costs for these systems depend on technical characteristics, such as the power and energy capacity of a system [29]. "Total installed system costs for batteries of shorter duration are less expensive than long-duration systems on a per-unit of power capacity basis," [29]. However, in terms of cost per-unit of energy capacity, "the longer duration batteries will typically have lower normalized costs compared with shorter-duration batteries," [29].

METHODOLOGY

This study focuses on the levelized cost of electricity. The LCOE "represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle," [22]. It is useful for comparing different configurations of a technology or comparing the relative costs and benefits across technologies [30]. It is also considered to be a convenient summary measure of the overall competitiveness of differing technologies [22].

3.1 Technologies Compared

To normalize the comparison, the levelized cost of electricity needs to be calculated. In order to do this, the annualized capital cost, annualized operating cost, return on interest, and annual generation is needed. To find the variables needed, the costs were collected and input into an Excel spreadsheet. This process was used to calculate the LCOE for 5 different systems:

- Nuclear
- Solar PV – Tracking
- Solar PV – Fixed Tilt
- Solar PV – Tracking + Battery Storage
- Solar PV – Fixed Tilt + Battery Storage

The analyses were performed in Excel.

3.2 Years

The annual costs are analyzed over a 50- to 60-year span, Where 60 years is the average lifespan of a nuclear plant and 25-30 years is the average lifespan of a solar plant.

3.3 Capacity

For the capacity-equivalent analysis, capacity was held constant at 1000 MW for all systems. For the generation-equivalent analysis, nuclear capacity remained 1000 MW whereas solar varied form 1000 MW to 4650 MW in order to normalize generation output to that of a 1000 MW nuclear plant.

3.4 Capacity Factor

The capacity factor is the ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at a continuous full power operation during the same period [31]. For nuclear the average capacity factor (ACF) is 0.922 [32] [33]. For solar the ACF is 0.2563 [32].

3.5 Efficiency for Solar

A key factor for solar technologies is the efficiency with which sunlight is converted into power and how this relationship changes over time [34]. A 20% decline is considered a failure, but there is no consensus on this [34]. For this study the efficiency decreased 0.05% every year over the lifetime of the plant's operation.

3.6 Annual Generation Calculations

Equation 1: Annual Generation

$$Annual\ Nuclear\ Generation = Capacity * ACF * 8760$$

Equation 2: Annual Solar Generation

$$Annual\ Solar\ Generation = Capacity * ACF * Efficiency * 8760$$

The annual generation for solar changes with each year as the efficiency decreases annually whereas the annual generation for nuclear remains generally consistent absent fuel reloading or unanticipated maintenance. However, ACF is determined over the course of several years of operation. The number 8760 is the number of hours in one non-leap year, giving annual generation units of MWh for a plant capacity given in MW.

Due to its capacity to track sunlight, the annual generation for solar PV-tracking is approximately 7.5% greater than the annual generation for solar PV-fixed tilt [35].

3.7 Land Required

A 1000 MW nuclear power plant requires roughly 1.3 square miles per 1000 megawatts of installed capacity [36] [37]. The land required for solar varies because the capacity changes in this study. On average, 7.4 acres is needed for 1 MW of solar. If capacity increases, the land required also increases.

The cost of the land was taken from the cost of land in Stewart County, Georgia, as it was the location of a recent Georgia Power nuclear feasibility study [38]. The land cost is annualized over a 15-year period for solar and a 30-year period for nuclear..

3.8 Capital Cost Calculations

The capital costs were based on the Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2018 [39]. The "EIA determines the cost of capital using a mix of macro-economic parameters determined through EIA's modeling and an assumed capital structure for the electric power industry," [40].

Table 1: Capital costs ($/MW) for nuclear, solar PV-tracking, and solar PV-fixed tilt

Technology	Capital Cost ($/MW)
Nuclear	$5,946,000
Solar PV – Tracking	$2,105,000
Solar PV – Fixed Tilt	$1,851,000

Equation 3: Annual Costs of Present Value

$$Annual = Present\ Value * \frac{r(1+r)^n}{(1+r)^n - 1}$$

r = interest rate

n = number of years

When the solar plants have to be rebuilt in order to match the lifespan of nuclear, the future value of the capital cost must be calculated using the inflation rate.

Equation 4: Future Value

$$Future\ Value = Present\ Value * (1+r)^n$$

r = inflation rate

n = number of years

The inflation rate is an average of the inflation rates over the last ten years [41]. Once the future capital cost value is found, it is then annualized over 15 years.

Equation 5: Annual Cost of Future Values

$$Annual = Future\ Value * \frac{r}{(1+r)^n - 1}$$

r = interest rate

n = number of years

3.9 Operation and Maintenance Cost

The O&M costs were based on the Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2018 [39].

Nuclear has both a fixed O&M as well as a variable O&M. Fixed costs are costs that incur irrespective of use and can be viewed as long-run maintenance costs [42]. Variable O&M costs are more so maintenance of the capacity that was used in a single year as well as fuel in this study.

Table 2: Operation and maintenance costs ($/MWhr) for nuclear, solar PV-tracking, and solar PV-fixed tilt

Technology	Fixed O&M ($/MWhr)	Variable O&M ($/MWhr)
Nuclear	11.56	2.32
Solar PV - Tracking	2.51	None
Solar PV – Fixed Tilt	2.51	None

Solar does not have any fuel cost; therefore there is no variable maintenance cost.

To find the annual O&M costs, the O&M cost ($/MWhr) was multiplied by the annual generation. These costs are incurred throughout the lifespan of the plant.

3.10 Nuclear Recovery Cost

This is the money set aside by the utilities, as per federal requirements, to pay for the long-term cost of storage and disposal. It is currently set at $0.001/kWhr and does not significantly impact the LCOE [43].

3.11 Decommissioning Cost

The average decommission costs were based on actual costs of decommissioned plants [44]. The average decommissioning cost is $2.826 million per MW. This cost was multiplied by the annual generation and then annualized over the last 30 years of the plant's lifespan.

3.12 Battery Storage

During peak hours of electricity consumption and during times when solar is unavailable or diminished due to weather conditions and regular diurnal changes, electricity must be stored if it is to ramp up and match demand. Therefore, battery storage is needed in this case. Costs were based on the Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2018 [39]. A 600 MW capacity battery storage was used for a 1000 MW solar plant [17]. The capacity for the battery storage increased as the capacity of the plant increased.

Table 3: Capital costs, fixed O&M, and variable O&M values associated with battery storage

Battery Storage Costs	
Capital Cost ($/MW)	2,170,000
Fixed O&M ($/MWhr)	7.12
Variable O&M ($/MWhr)	4.06

The capital costs were annualized over a 15-year span, and added to solar cost. The O&M costs were incurred throughout the lifespan of the solar PV plant.

3.13 Return on Investment

Return on investment (ROI) is highly variable. For this analysis it was indexed to the annualized capital costs and operation and maintenance costs at a 10% rate.

Equation 6: Return on Investment

$$ROI = 0.10(Annual\ Capital\ Cost + O\&M)$$

3.14 Levelizd Cost of Electricity

Levelized cost of electricity is calculated based on capital costs, fuel costs, operation and maintenance costs and return on investment, all on an annualized basis normalized to annual generation. The units are $/kWhr.

Equation 7: Levelized cost of electricity

$$LCOE = \frac{Annual\ Capital\ Cost + Fuel + O\&M + ROI}{Annual\ Generation}$$

After LCOE was calculated, the information was tabulated and put into chart form for comparing the capacity-equivalence and generation-equivalence results across technologies and interest rates.

RESEARCH RESULTS

This section describes the results from this study. In each scenario, the LCOE costs are shown at 3%, 5%, 7%, and 10% interest rates.

Section 4.1 shows a capacity-equivalence based comparison with varying interest rates. Section 4.2 shows a generation based comparison with varying interest rates. Section 4.3 is again a generation-equivalence based comparison, but the lifespan of the solar technologies are reduced to 25 years. Section 4.4 reports the total generation hours, total costs, as well as the average cost per kWhr over the lifetime of each technology.

4.1 Capacity-Equivalence Basis

In the capacity-based comparison, nuclear, solar PV – tracking, and solar PV – fixed tilt all have a capacity of 1000 MW. This is a common comparison between solar and nuclear. However, this comparison does not account for the differences in generation. Because nuclear has a much higher ACF, the total annual generation is 484,603,200 for 60 years. For solar PV – tracking the total annual generation hours is 133,120,845 and for solar PV – fixed tilt it is 123,833,344 over 60 years.

4.1.1 Capacity-Equivalence Baseis – 3% Interest Rate

Table 4 LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 3% interest rate. The capacity for all technologies is 1000 MW and the capacity for battery storage for both solar technologies is 600 MW.

Capacity Basis 3% Interest Rate - 1000 MW				
3% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.0566	0.0566	0.0152	0.0152
Solar PV - Tracking	0.0879	0.0025	0.0936	0.0025
Solar PV - Fixed	0.0835	0.0027	0.0886	0.0027
Solar PV-Tracking + Battery	0.1474	0.00943	0.1567	0.00943
Solar PV-Fixed + Battery	0.1474	0.0101	0.1567	0.0101

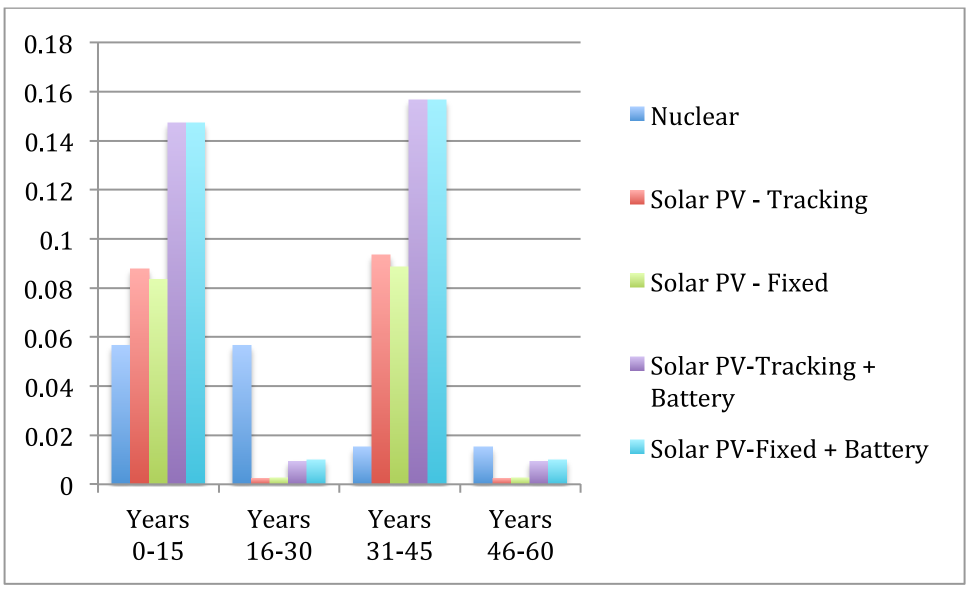

Figure 6 Bar graph comparing LCOE for the listed technologies at a 3% interest rate on a capacity basis. The y-axis is LCOE and x-axis is years of generation.

4.1.2 Capacity-Equivalence Basis – 5% Interest Rate

Table 5 LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 5% interest rate. The capacity for all technologies is 1000 MW and the capacity for battery storage for both solar technologies is 600 MW.

Capacity Basis 5% Interest Rate - 1000 MW				
5% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.06795	0.06795	0.0152	0.0152
Solar PV - Tracking	0.1007	0.00257	0.081	0.00257
Solar PV - Fixed	0.0956	0.00276	0.0767	0.00276
Solar PV-Tracking + Battery	0.1681	0.00943	0.136	0.00943
Solar PV-Fixed + Battery	0.1681	0.0101	0.1364	0.0101

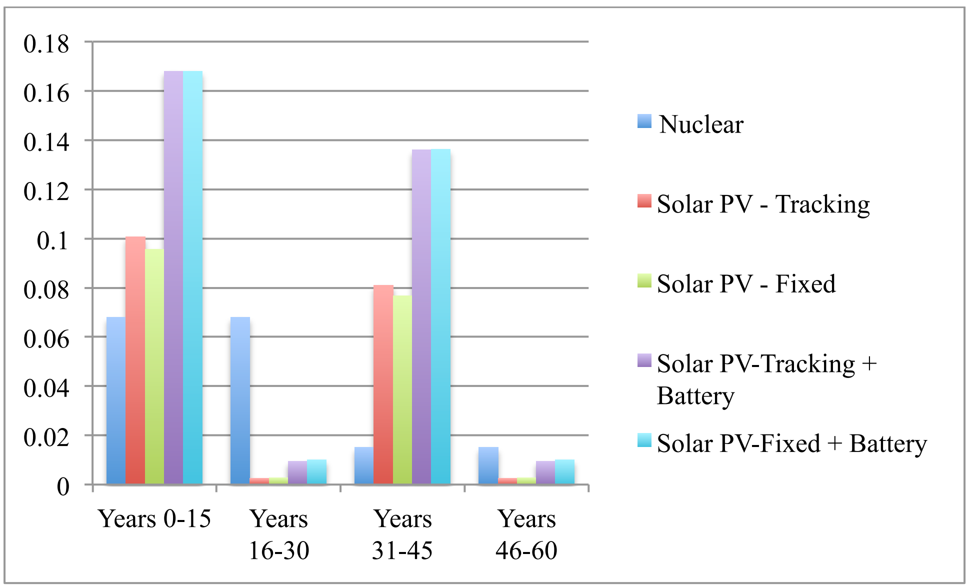

Figure 7 Bar graph comparing LCOE for the listed technologies at a 5% interest rate on a capacity basis. The y-axis is LCOE and x-axis is years of generation.

4.1.3 Capacity-Equivalence Basis – 7% Interest Rate

Table 6: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 7% interest rate. The capacity for all technologies is 1000 MW and the capacity for battery storage for both solar technologies is 600 MW.

Capacity Basis 7% Interest Rate - 1000 MW				
7% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.0805	0.0805	0.0152	0.0152
Solar PV - Tracking	0.1145	0.00257	0.0699	0.00257
Solar PV - Fixed	0.1086	0.00276	0.0663	0.00276
Solar PV-Tracking + Battery	0.1902	0.00943	0.1184	0.00943
Solar PV-Fixed + Battery	0.1901	0.0101	0.1186	0.0101

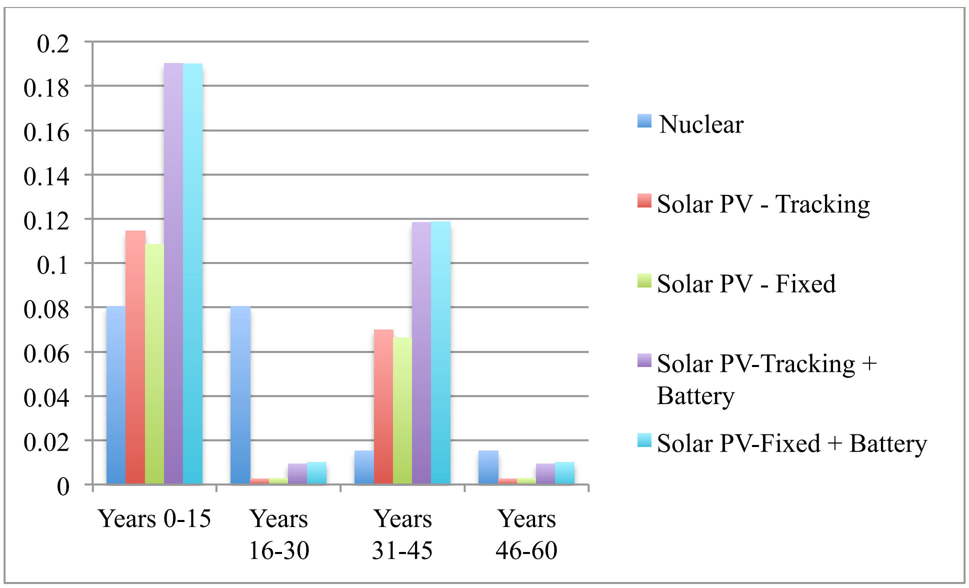

Figure 8: Bar graph comparing LCOE for the listed technologies at a 7% interest rate on a capacity basis. The y-axis is LCOE and x-axis is years of generation.

4.1.4 Capacity-Equivalence Basis – 10% Interest Rate

Table 7: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 10% interest rate. The capacity for all technologies is 1000 MW and the capacity for battery storage for both solar technologies is 600 MW.

Capacity Basis - 1000 MW				
10% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.101	0.101	0.0152	0.0152
Solar PV - Tracking	0.1366	0.00257	0.0558	0.00257
Solar PV - Fixed	0.1295	0.00276	0.053	0.00276
Solar PV-Tracking + Battery	0.2259	0.00943	0.09567	0.00943
Solar PV-Fixed + Battery	0.2256	0.0101	0.09593	0.0101

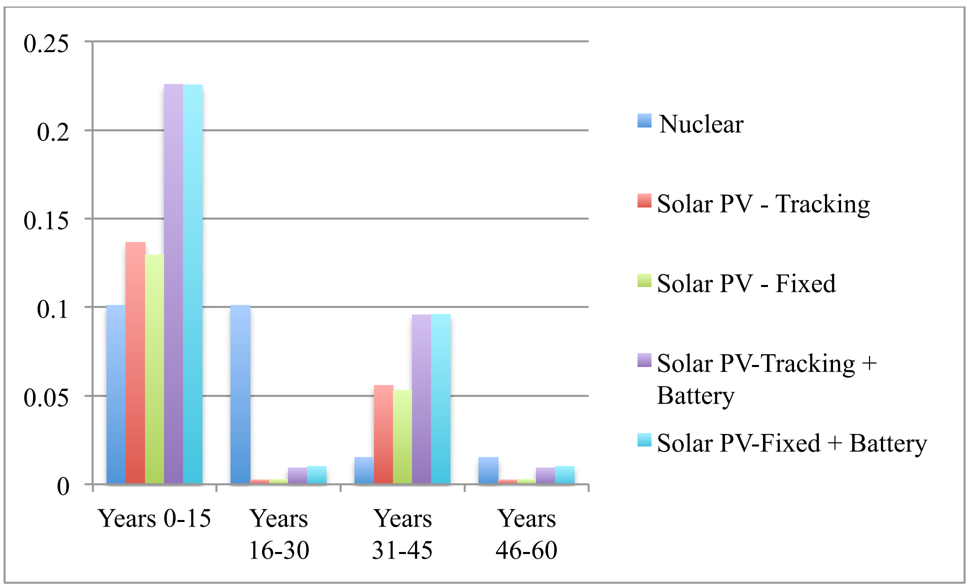

Figure 9: Bar graph comparing LCOE for the listed technologies at a 10% interest rate on a capacity basis. The y-axis is LCOE and x-axis is years of generation.

4.2 Generation-Equivalence Basis

To match the annual generation of a 1000 MW nuclear plant, the capacity of the solar plants had to be increased. Solar PV – tracking was increased to 3650 MW and solar PV – fixed tilt was increased to 3950 MW. This increased the amount of land needed for each solar technology. Instead of 7,400 acres, solar PV-tracking required 27,010 acres. Solar PV-fixed tilt originally required 7,400 acres as well, but increased to 29,230 acres with the capacity increase.

Solar PV-fixed tilt required more capacity because solar PV-tracking annual generation is increased by 7.5 due to this technology receiving more sun because of the ability to track the sunlight. The battery storage capacity for the tracking technology increased to 2610 MW and for fixed-tilt the capacity was increased to 2790 MW.

4.2.1 Generation-Equivalence Basis – 3% interest rate

Table 8: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 3% interest rate. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

Generation Basis				
3% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.0566	0.0566	0.0152	0.0152
Solar PV - Tracking	0.0879	0.00257	0.0936	0.00257
Solar PV - Fixed	0.0835	0.00276	0.0888	0.00276
Solar PV-Tracking + Battery	0.147	0.00943	0.1567	0.00943
Solar PV-Fixed + Battery	0.1474	0.0101	0.1567	0.0101

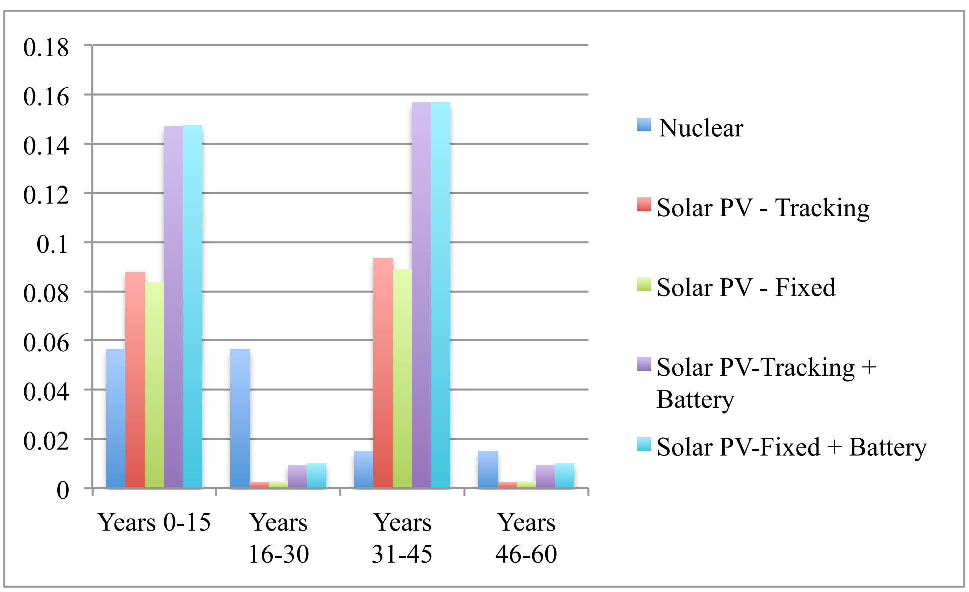

Figure 10: Bar graph comparing LCOE for the listed technologies at a 3% interest rate on a generation basis. The y-axis is LCOE and x-axis is years of generation.

4.2.2 Generation-Equivalence Basis – 5% interest rate

Table 9: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 5% interest rate. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

Generation Basis				
5% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.06795	0.06795	0.0152	0.0152
Solar PV - Tracking	0.10078	0.00257	0.081	0.00257
Solar PV - Fixed	0.09566	0.00276	0.0769	0.00276
Solar PV-Tracking + Battery	0.1677	0.00943	0.136	0.00943
Solar PV-Fixed + Battery	0.1681	0.0101	0.1364	0.0101

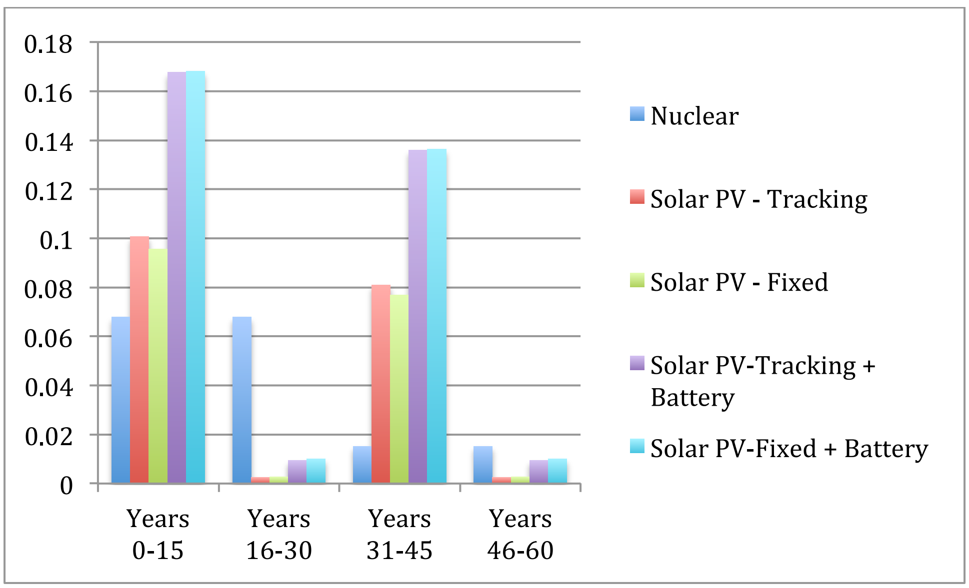

Figure 11: Bar graph comparing LCOE for the listed technologies at a 5% interest rate on a generation basis. The y-axis is LCOE and x-axis is years of generation

4.2.3 Generation-Equivalence Basis – 7% interest rate

Table 10: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 7% interest rate. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

Generation Basis				
7% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.0805	0.0805	0.0152	0.0152
Solar PV - Tracking	0.1145	0.00257	0.0699	0.00257
Solar PV - Fixed	0.1086	0.00276	0.0664	0.00276
Solar PV-Tracking + Battery	0.18986	0.00943	0.1184	0.00943
Solar PV-Fixed + Battery	0.1901	0.0101	0.1186	0.0101

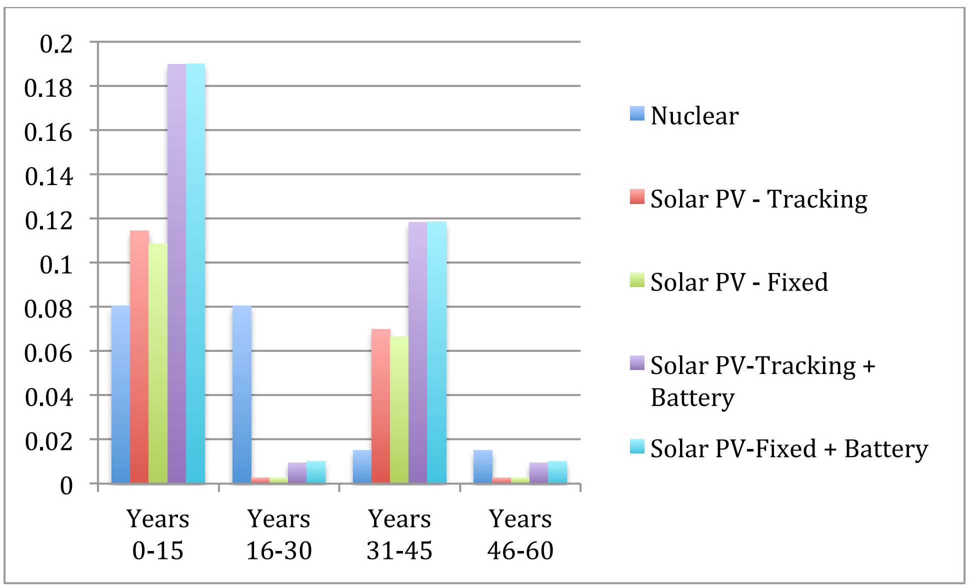

Figure 12: Bar graph comparing LCOE for the listed technologies at a 7% interest rate on a generation basis. The y-axis is LCOE and x-axis is years of generation

4.2.4 Generation-Equivalence Basis – 10% interest rate

Table 11: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 10% interest rate. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

Generation Basis				
10% Interest Rate	LCOE ($/kWh)			
	Years 0-15	Years 16-30	Years 31-45	Years 46-60
Nuclear	0.101	0.101	0.0152	0.0152
Solar PV - Tracking	0.1366	0.00257	0.0558	0.00257
Solar PV - Fixed	0.1295	0.00276	0.0531	0.00276
Solar PV-Tracking + Battery	0.2255	0.00943	0.09567	0.00943
Solar PV-Fixed + Battery	0.2256	0.0101	0.09593	0.0101

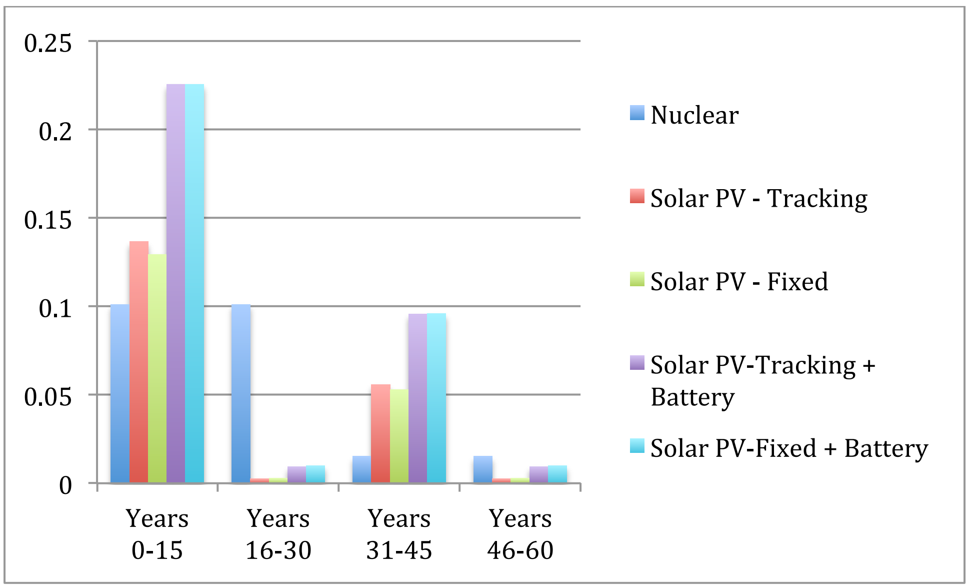

Figure 13: Bar graph comparing LCOE for the listed technologies at a 10% interest rate on a generation basis. The y-axis is LCOE and x-axis is years of generation

4.3 Generation-Equivalence Basis with 25-Year Lifespan for Solar

A 30-year lifespan for a solar plant is possible, but it is more likely to last approximately 25 years. With a 25-year lifespan, rebuilding once after the first 25 years means that the entirety will reach a total of 50 years. To match the annual generation of the 60 years a nuclear plant produces, the capacity of the solar plants needs to be increased even more than it was in section 4.2. Solar PV – tracking is raised to 4350 MW and solar PV-fixed tilt is increased to 4650 MW.

4.3.1 Generation-Equivalence Basis: 25-Year Lifespan for Solar Technologies – 3% interest rate

Table 12: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 3% interest rate. The lifespan for solar technologies has been reduced to 25 years. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

≈ Generation Basis - 25-year lifespan for Solar						
3% Interest Rate	LCOE ($/kWh)					
	Years 0-15	Years 16-25	Years 26-30	Years 31-40	Years 41-50	Years 51-60
Nuclear	0.0566	0.0566	0.0566	0.0152	0.0152	0.0152
Solar PV - Tracking	0.0879	0.00257	0.0936	0.0936	0.00257	0
Solar PV - Fixed	0.0835	0.00276	0.0888	0.0888	0.00276	0
Solar PV-Tracking + Battery	0.1474	0.00943	0.1567	0.1567	0.00956	0
Solar PV-Fixed + Battery	0.1474	0.0101	0.1565	0.1565	0.0102	0

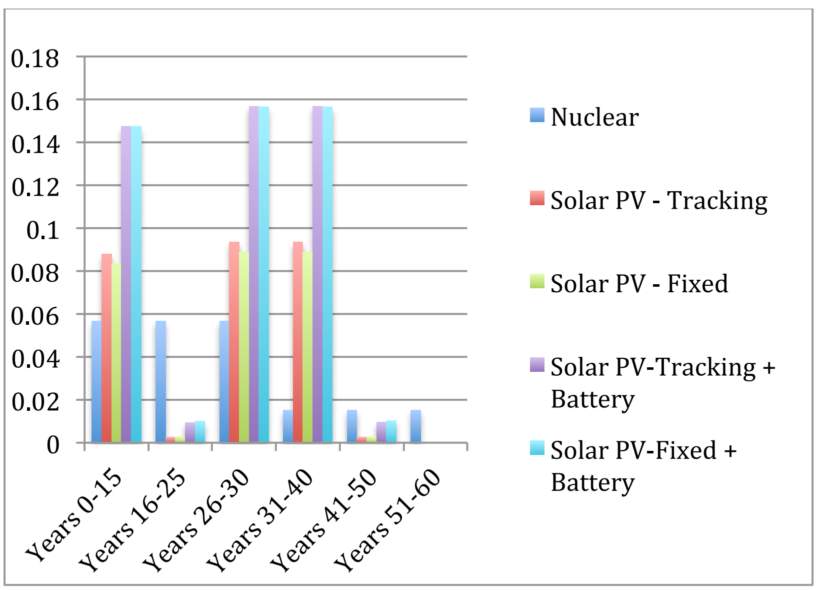

Figure 14: Bar graph comparing LCOE for the listed technologies at a 3% interest rate on a generation basis and a 25-year lifespan for solar. The y-axis is LCOE and x-axis is years of generation

4.3.2 Generation-Equivalence Basis: 25-Year Lifespan for Solar Technologies – 5% interest rate

Table 13: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 5% interest rate. The lifespan for solar technologies has been reduced to 25 years. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

Generation Basis - 25-year lifespan for solar						
5% Interest Rate	LCOE ($/kWh)					
	Years 0-15	Years 16-25	Years 26-30	Years 31-40	Years 41-50	Years 51-60
Nuclear	0.06795	0.06795	0.06795	0.0152	0.0152	0.0152
Solar PV - Tracking	0.1007	0.00257	0.08102	0.08102	0.00257	0
Solar PV - Fixed	0.09566	0.00276	0.0769	0.0769	0.00276	0
Solar PV-Tracking + Battery	0.1681	0.00943	0.136	0.136	0.00956	0
Solar PV-Fixed + Battery	0.16805	0.0101	0.1363	0.1363	0.0102	0

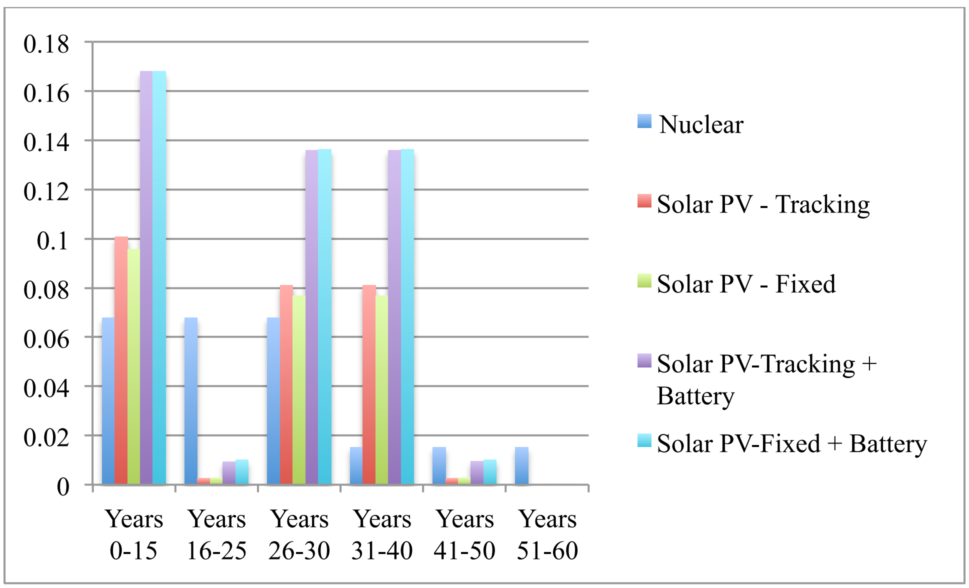

Figure 15: Bar graph comparing LCOE for the listed technologies at a 5% interest rate on a generation basis and a 25-year lifespan for solar. The y-axis is LCOE and x-axis is years of generation

4.3.3 Generation-Equivalence Basis: 25-Year Lifespan for Solar Technologies – 7% interest rate

Table 14: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 7% interest rate. The lifespan for solar technologies has been reduced to 25 years. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

Generation Basis - 25-year lifespan for solar						
7% Interest Rate	LCOE ($/kWh)					
	Years 0-15	Years 16-25	Years 26-30	Years 31-40	Years 41-50	Years 51-60
Nuclear	0.0805	0.0805	0.0805	0.0152	0.0152	0.0152
Solar PV - Tracking	0.1145	0.00257	0.06993	0.06993	0.00257	0
Solar PV - Fixed	0.1086	0.00276	0.0664	0.0664	0.00276	0
Solar PV-Tracking + Battery	0.1902	0.00943	0.1183	0.1183	0.00956	0
Solar PV-Fixed + Battery	0.1901	0.0101	0.1184	0.1184	0.0102	0

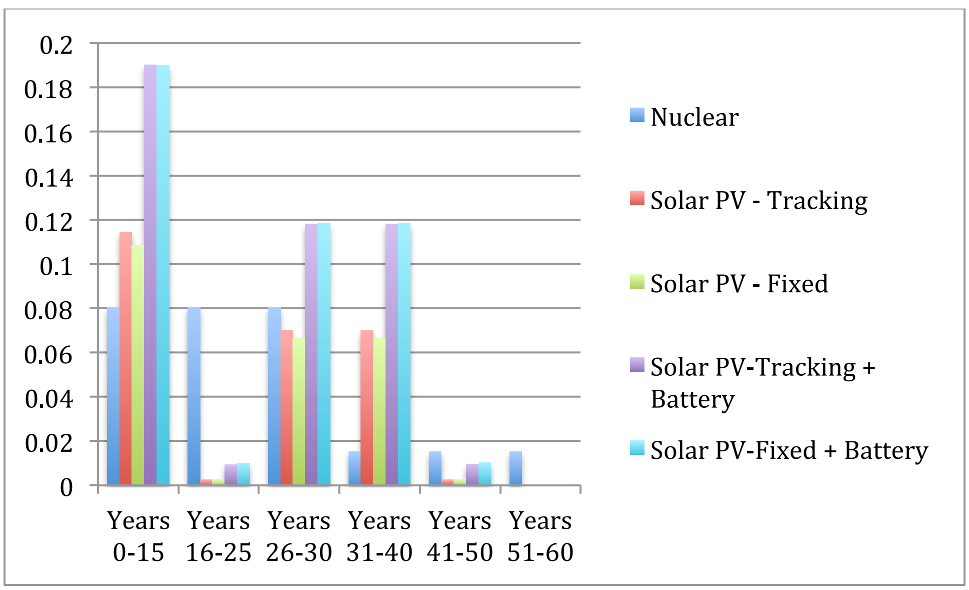

Figure 16: Bar graph comparing LCOE for the listed technologies at a 7% interest rate on a generation basis and a 25-year lifespan for solar. The y-axis is LCOE and x-axis is years of generation

4.3.4 Generation-Equivalence Basis: 25-Year Lifespan for Solar Technologies – 10% interest rate

Table 15: LCOE for Nuclear, Solar PV-tracking, Solar PV-fixed tilt, Solar PV-tracking with battery storage, and Solar PV-fixed tilt with battery storage at a 10% interest rate. The lifespan for solar technologies has been reduced to 25 years. The capacity for nuclear is held at 1000 MW but increased respectively for both solar technologies to match the generation hours for nuclear. Battery storage also increased to account for the increase in capacity for solar.

Generation Basis - 25-year lifespan for solar						
10% Interest Rate	LCOE ($/kWh)					
	Years 0-15	Years 16-25	Years 26-30	Years 31-40	Years 41-50	Years 51-60
Nuclear	0.101	0.101	0.101	0.0152	0.0152	0.0152
Solar PV - Tracking	0.1366	0.00257	0.05585	0.05585	0.00257	0
Solar PV - Fixed	0.1295	0.00276	0.05313	0.05313	0.00276	0
Solar PV-Tracking + Battery	0.22599	0.00943	0.09555	0.09555	0.00956	0
Solar PV-Fixed + Battery	0.2256	0.0101	0.0958	0.0958	0.0102	0

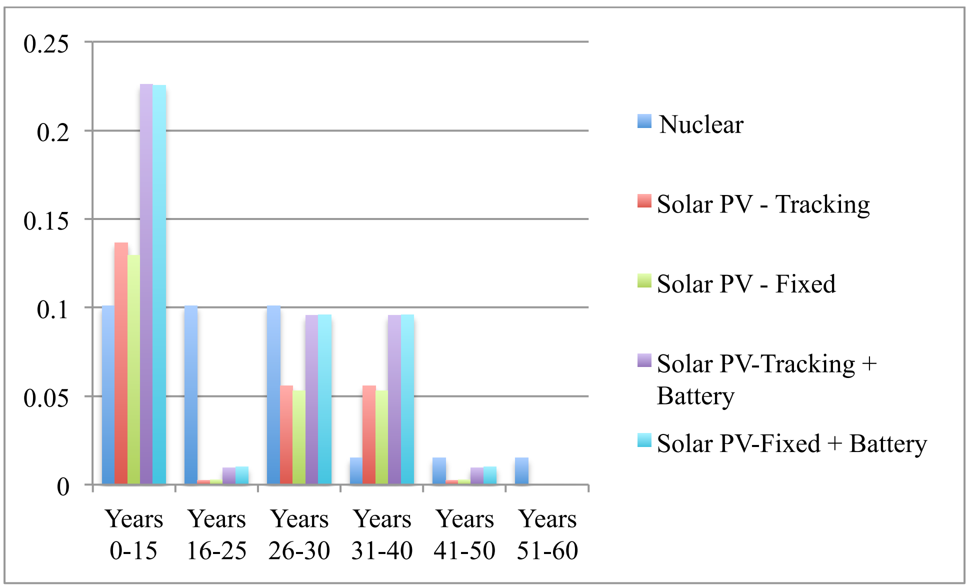

Figure 17: Bar graph comparing LCOE for the listed technologies at a 10% interest rate on a generation basis and a 25-year lifespan for solar. The y-axis is LCOE and x-axis is years of generation

DISCUSSION

The objective of this research is to analyze and compare the five power plant technologies on a capacity basis and a generation basis across a range of interest rates and for a 60-year lifetime equivalent to that of a nuclear plant. The following discussion is separated into the capacity-equivalence analysis and the generation equivalence analysis.

5.1 Capacity-Equivalence Analysis

On a 1000 MW capacity-equivalence basis, it was expected that solar PV would outperform nuclear on a total cost basis. This proved to be the case across all interest rates. However, when normalized to generation hours (LCOE), across all interest rates for the capacity-equivalence analyses, LCOE in the 0-15 year and 31-45 year ranges was lower for nuclear than all four other systems (Figures 5, 6, 7, 8), while for the 16-30 year and 46-60 year ranges, LCOE for the solar technologies are lower than nuclear (Figures 5, 6, 7, 8). During the 16-30 year range, the capital costs of nuclear continue to be amortized resulting in a much lower LCOE for solar. However, at the 30-year mark, when the capital costs for nuclear have been paid in full, and during the 31-45 year range, when the second solar PV system is being constructed, nuclear outperforms all four solar PV systems. This highlights several key issues related to energy resources for power generation.

First, is the value of a zero-cost resource with low O&M, after capital costs have been paid in full. That is, during the 16-30 and 46-60 year ranges, the capital costs of solar have been paid in full, solar fuel costs are zero and O&M costs per MWhr are much lower than those for nuclear. Clearly, during these time ranges in the lifetime of a power plant, and on a capacity-equivalence basis, solar PV has greater economic value than nuclear.

Second, is the importance of an inexpensive baseload fuel resource, such as nuclear, after capital costs have been paid in full. While nuclear LCOE is lower than solar PV LCOE during the 0-15 and 31-45 year ranges, this isn't attributable only to the amortization of capital costs—it's also due to the difference in generation (Table 16). The 1000 MW nuclear plant is generating 8,076,720 MWhrs annually whereas solar PV tracking and solar PV fixed generate 2,282,037 MWhrs and 2,122,825 MWhrs respectively.

Table 16 : Annual generation for each system – capacity-based analysis. Annual generation for solar PV systems is reported as "Average" values due to degradation in PV efficiency, thus a reduction in generation over time.

Technology (1000 MW Capacity)	Annual Generation (MWhrs)
Nuclear	8,076,720
Solar PV-Tracking	2,282,037 (Average)
Solar PV-Fixed	2,122,825 (Average)
Solar PV- Tracking w/Battery Storage	2,282,037 (Average)
Solar PV-Fixed w/Battery Storage	2,122,825 (Average)

Third, is the importance of evaluating and comparing technologies over a common lifecycle of a technology. For this analysis, the 60-year lifetime of a nuclear plant was used. Over that 60-year span, LCOE for solar and nuclear varied depending largely on amortization of capital costs. However, when analyzing the total amortized costs and total power generation for the full 60 years of all four systems, the average cost per kWhr can be used as a key indicator. Tables 17-20 summarize total generation, total costs and average cost per kWhr over the lifetime of each system. For example, at 3% financing, solar tracking, at a total cost of $6,138,687,552 and $0.046/kWhr, and solar fixed, at a total cost of $5,437,756,626 and $0.043/kWhr, are less expensive and provide lower LCOEs than nuclear, with a total cost of $25,652,060,570 and $0.053/kWhr. On a capacity-equivalence basis alone, this would seem to indicate that both solar PV systems are preferred over nuclear on both a total cost and average cost per kWhr basis. However, this doesn't account for the fact that nuclear power is available without respect to weather or daily sunlight availability, which is not the case with the solar resource. When solar's intermittency and nuclear's baseload are accounted for by way of incorporating battery storage, nuclear is the more economical choice based on LCOE as solar PV with storage averages out to $0.079/kWhr for both tracking and fixed systems. It is noted here that solar tracking with storage, at $10,562,322,515, and solar fixed with storage, at $9,861,391,588, have much lower total costs. However, if LCOE is the metric of concern, nuclear is the better economic option provided that availability (i.e., storage capability) is incorporated into the system, thus normalizing both resources on a more equivalent generation and availability basis.

Table 17: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a capacity-based analysis at a 3% interest rate

Capacity Based - 3% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$15,828,719,980.35	$0.03266
Solar PV-Tracking	133,120,844	$5,799,711,537.56	$0.04357
Solar PV-Fixed	123,833,344	$5,138,874,274.00	$0.04150
Solar Tracking + Battery	133,120,844	$10,017,827,016.21	$0.07525
Solar Fixed + Battery	123,833,344	$9,356,989,752.65	$0.07556

Table 18:Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a capacity-based analysis at a 5% interest rate

Capacity Based - 5% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$18,332,222,875.68	$0.03783
Solar PV-Tracking	133,120,844	$5,807,545,585.67	$0.04363
Solar PV-Fixed	123,833,344	$5,145,976,255.25	$0.04156
Solar Tracking + Battery	133,120,844	$10,029,413,627.48	$0.07534
Solar Fixed + Battery	123,833,344	$936,784,429.06	$0.00756

Table 19:Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a capacity-based analysis at a 7% interest rate

Capacity Based - 7% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$21,103,841,412.29	$0.04355
Solar PV-Tracking	133,120,844	$5,889,351,378.91	$0.04424
Solar PV-Fixed	123,833,344	$5,218,139,038.69	$0.04214
Solar Tracking + Battery	133,120,844	$10,160,649,337.13	$0.07633
Solar Fixed + Battery	123,833,344	$9,489,436,996.91	$0.07663

Table 20: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a capacity-based analysis at a 10% interest rate

Capacity Based - 10% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$25,652,060,570.32	$0.05293
Solar PV-Tracking	133,120,844	$6,138,687,552.48	$0.04611
Solar PV-Fixed	123,833,344	$5,437,756,626.12	$0.04391
Solar Tracking + Battery	133,120,844	$10,562,322,515.17	$0.07934
Solar Fixed + Battery	123,833,344	$9,861,391,588.82	$0.07963

5.2 Generation-Equivalence Analysis

On a generation-equivalence basis, the overall costs for solar PV are expected to increase as the capacity is increased to compare with the generation of nuclear. This is seen across all interest rates. Yet again, when normalized, it is seen that across all interest rates for the generation-equivalence analysis, LCOE in the 0-15 year and 31-45 year ranges was lower for nuclear than all four other systems (Figures 9, 10, 11, 12). For the 16-20 year and 46-60 year ranges, LCOE for the solar technologies is lower than nuclear (Figures 9, 10, 11, 12). Again, this is because the capital cost of nuclear is still being amortized during the 16-30 year range. After 30 years, nuclear capital costs have been paid in full. During the 31-45 year range, a second solar PV system is being constructed, leading to nuclear outperforming solar PV.

In this analysis the capacity for solar PV systems was increased so the annual generation would be comparable to nuclear's annual generation. The increase in capacity and annual generation is given in Table 21.

Table 21: Annual generation for each system – generation-equivalence analysis. Annual generation for solar PV systems are reported as "Average" values due to degradation in PV efficiency, thus a reduction in generation over time.

Technology	Capacity	Annual Generation (MWhrs)
Nuclear	1000	8,076,720
Solar PV-Tracking	3650	8,098,184 (Average)
Solar PV-Fixed	3950	8,152,361 (Average)
Solar PV-Tracking w/ Battery Storage	3650	8,098,184 (Average)
Solar PV-Fixed w/ Battery Storage	3950	8,152,361 (Average)

Again, it is important to evaluate and compare technologies over a common lifecycle. In this analysis, nuclear again has a 60-year lifespan. Over this time, the LCOE varied due to the amortization times of the capital costs, just as it did in the capacity-based comparison. Again, by using the total amortized costs and total power generation, the average cost per kWhr is seen. While the average cost per kWhr is the same for both capacity-based and generation-equivalence based, the overall amortized costs for solar PV technologies significantly increased as seen in Tables 22, 23, 24, 25. In this analysis, nuclear has a lower overall total cost than solar at a 3%, 5% and 7% interest rate. At a 10% interest rate, nuclear has a total cost of $25,652,060,570, where solar PV-tracking total cost is $22,406,209,566 and solar PV-fixed total cost is $21,479,138,673. However, with the battery storage added nuclear total cost is less than either solar technology with solar PV-tracking total cost being $38,552,477,180 and solar PV-fixed total cost being $38,952,496,775.

Table 22: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis at a 3% interest rate

Generation Based - 3% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$15,828,719,980.35	$0.03266
Solar PV-Tracking	485,891,084	$21,168,947,112.11	$0.04357
Solar PV-Fixed	489,141,709	$20,298,553,382.28	$0.04150
Solar Tracking + Battery	485,891,084	$36,565,068,609.18	$0.07525
Solar Fixed + Battery	489,141,709	$36,960,109,522.95	$0.07556

Table 23:Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis at a 5% interest rate

Generation Based - 5% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$18,332,222,875.68	$0.03783
Solar PV-Tracking	485,891,084	$21,197,541,387.70	$0.04363
Solar PV-Fixed	489,141,709	$20,326,606,208.23	$0.04156
Solar Tracking + Battery	485,891,084	$36,607,359,740.32	$0.07534
Solar Fixed + Battery	489,141,709	$37,002,984,973.40	$0.07565

Table 24: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis at a 7% interest rate

Generation Based - 7% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$21,103,841,412.29	$0.04355
Solar PV-Tracking	485,891,084	$21,496,132,533.04	$0.04424
Solar PV-Fixed	489,141,709	$20,611,649,202.82	$0.04214
Solar Tracking + Battery	485,891,084	$37,086,370,080.53	$0.07633
Solar Fixed + Battery	489,141,709	$37,483,276,137.78	$0.07663

Table 25: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis at a 10% interest rate

Generation Based - 10% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$25,652,060,570.32	$0.05293
Solar PV-Tracking	485,891,084	$22,406,209,566.54	$0.04611
Solar PV-Fixed	489,141,709	$21,479,138,673.19	$0.04391
Solar Tracking + Battery	485,891,084	$38,552,477,180.38	$0.07934
Solar Fixed + Battery	489,141,709	$38,952,496,775.83	$0.07963

The lifespan of solar PV technologies often vary. In the generation analysis a 30-year lifespan was used as well as a 25-year lifespan. With a 25-year lifespan, after the construction of the second plant, the total span of the plant reaches 50 years. Due to this second plant, the capacity was increased to match the total generation hours of nuclear. This means the average annual generation will be larger than the annual generation of nuclear (Table 26).

Table 26: Annual generation for each system – generation-equivalence analysis: 25-year lifespan for solar technologies. Annual generation for solar PV systems are reported as "Average" values due to degradation in PV efficiency, thus a reduction in generation over time.

Technology	Capacity	Annual Generation (MWhrs)
Nuclear	1000	8,076,720
Solar PV-Tracking	4350	9,743,128 (Average)
Solar PV-Fixed	4650	9,688,435 (Average)
Solar PV-Tracking w/ Battery Storage	4350	9,743,128 (Average)
Solar PV-Fixed w/ Battery Storage	4650	9,688,435 (Average)

This increase in capacity again increases the overall cost of the solar PV systems. By reducing the number of years and increasing the capacity, this increased the average cost per kWhr over the lifetime for solar PV systems. This is seen in Tables 27, 28, 29, and 30. At a 3%, 5% and 7% interest rate, nuclear outperforms the solar technologies in both overall cost and average cost per kWhr over the lifetime. At a 10% interest rate, solar PV-fixed is lower in both categories. However, as noted previously, once battery storage is included, accounting for the intermittency issues, the average cost per kWhr over the lifetime is much lower for nuclear.

Table 27: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis with solar having a 25-year lifespan at a 3% interest rate

Generation Based 25-year lifespan for solar - 3% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$15,828,719,980.35	$0.03266
Solar PV-Tracking	487,156,402	$25,013,782,347.46	$0.05135
Solar PV-Fixed	484,421,763	$23,665,977,509.63	$0.04885
Solar Tracking + Battery	487,156,402	$42,783,275,924.92	$0.08782
Solar Fixed + Battery	484,421,763	$42,660,953,402.77	$0.08807

Table 28: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis with solar having a 25-year lifespan at a 5% interest rate

Generation Based 25-year lifespan for solar - 5% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$18,332,222,875.68	$0.03783
Solar PV-Tracking	487,156,402	$25,047,860,456.73	$0.05142
Solar PV-Fixed	484,421,763	$23,699,001,722.46	$0.04892
Solar Tracking + Battery	487,156,402	$42,833,677,683.95	$0.08793
Solar Fixed + Battery	484,421,763	$42,711,427,034.31	$0.08817

Table 29: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis with solar having a 25-year lifespan at a 7% interest rate

Generation Based 25-year lifespan for solar - 7% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$21,103,841,412.29	$0.04355
Solar PV-Tracking	487,156,402	$25,403,715,657.34	$0.05215
Solar PV-Fixed	484,421,763	$24,034,558,665.45	$0.04961
Solar Tracking + Battery	487,156,402	$43,404,553,020.91	$0.08910
Solar Fixed + Battery	484,421,763	$43,276,833,088.58	$0.08934

Table 30: Total Costs, total generation and average cost per kWhr over system lifetime for nuclear, solar PV-tracking, solar PV-fixed tilt, solar PV-tracking with storage, and solar PV-fixed tilt with battery storage on a generation-equivalence based analysis with solar having a 25-year lifespan at a 10% interest rate

Generation Based 25-year lifespan for solar - 10% Interest Rate			
System	Generation (MWhrs)	Total Costs ($)	Average Cost per kWhr Over Lifetime
Nuclear	484,603,200	$25,652,060,570.32	$0.05293
Solar PV-Tracking	487,156,402	$26,488,328,012.33	$0.05437
Solar PV-Fixed	484,421,763	$25,055,780,447.02	$0.05172
Solar Tracking + Battery	487,156,402	$45,151,831,345.39	$0.09268
Solar Fixed + Battery	484,421,763	$45,006,421,940.97	$0.09291

5.3 Overall Trends in the Analysis

Throughout all comparisons, a lower interest rate is beneficial to all five technologies in keeping the LCOEs lower. Nuclear LCOE remains constant the first 30 years and then decreases and remains constant for years 31-60. This is due to the plant being paid off after the first 30 years and then only incurring O&M costs the remaining 30 years. The capacity of the nuclear plant also does not change; therefore it remains the same throughout the entire study. A common trend for solar is higher prices for years 1-15, then very low costs in years 16-30, followed by higher rates during years 31-45, and then finishing with again very low rates in years 46-60. During years 1-15, the capital cost of the solar plants is being paid off, in years 16-30, only O&M cost are being paid annually. After 25-30 years, a solar plant must be rebuilt, and the capital cost must be paid again, which is when the LCOE increases again.

The capacity-based comparison does not take into account the greater ACF for nuclear. The generation hours for solar technologies at 1000 MW do not compare to nuclear at 1000 MW. Therefore, when comparing overall costs, a capacity-based comparison is an insufficient metric for comparison.

Nuclear power provides a baseload for electricity. The same cannot be said for solar. Solar power is available only when the sun is shining, and often times not available during peak hours when electricity is needed. This is not evident in many comparisons when it simply comes down to the cost of each technology. Solar costs do not take into account that battery storage may also be needed; it is often a separate cost not shown in the comparisons. This increases the overall cost of solar, which can be seen in the capacity-based analysis as well as the generation-equivalence analysis.

A benefit for both of these technologies is there are no external costs because they do not produce CO_2 when generating electricity. The external cost on the environment for fossil fuel burning plants can be expensive.

Because a nuclear power plant's upfront costs are so high, there is a need for political and policy support for new nuclear projects. It would be very difficult to find investors for a plant with such high capital costs. Nuclear investment is also unlikely to take place when the government takes a neutral or uncommitted stance [8]. Nuclear power is still a very controversial topic and is the subject of many debates. Also because the timeline of the construction phase of nuclear plants are so long, there will be one, if not more, elections in this time. Support for these programs shifts when new parties come into power, which could lead to policy changes making it difficult for investors to get on board.

The market conditions and regulations must also be taken into account. The way a market is designed and regulated will have an impact on the investors of the nuclear power plant. A deregulated energy market gives the consumer the ability to choose their energy provider. This means that prices of electricity are competitive and the energy source with the lowest near-term marginal costs generally wins out. This market type makes it difficult for nuclear to compete as its benefits are returned over a longer period of time, as indicated in this analysis. A regulated market of vertically integrated utilities, meaning a single utility controls the flow of electricity from generation to meter. In a regulated market, utility companies often have a natural monopoly for a set area and are responsible for providing power to customers at an affordable rate as determined by a regulatory authority. However, this enables a more diverse energy portfolio, which could include nuclear.

5.4 Issues that need to be addressed in Further Studies

There were several issues that were not incorporated into this analysis that will need to be accounted for in subsequent analyses.

First, for the generation-equivalence analysis, the lifetime of the utility-scale solar PV facilities was based on 25 and 30 years with subsequent replacement in order to match the lifetime of the nuclear plant. What isn't clear are the logistics for this replacement. That is, in order for a new facility to be constructed, the old facility must be taken down if the replacement facility is to be constructed on the same footprint. This will result in a 2-3 year period [45] of time when the plant isn't generation power. In order to circumvent the lag time loss in power generation, an alternative site could be purchased and the new facility constructed on that site during the final either another site will be. However, this would increase the total capital costs for the facility.

Second, the costs associated with after-lifetime handling, disposal and management of the solar PV panels and battery storage technologies haven't been fully realized, yet. Since both solar panels and batteries are comprised of a host of critical materials (e.g., indium, gallium, selenium, tellurium, dysprosium, neodymium, lanthanum, nickel, lithium, cerium) that will need to be processed, disposed of or recycled, the eventual costs haven't been realized. This, too, will be incorporated into the LCOE calculations in much the same way as decommissioning costs for a nuclear plant, just not on the same scale and timeline.

Third, this analysis is based on current light water nuclear reactor technologies. Just as solar PV costs have declined over the past 10-15 years, Generation-IV nuclear reactor technologies are expected to decline as well, particularly for small modular reactors. Whereas overnight costs were set at $5,946/kW for nuclear, those costs are predicted to be much lower for small modular reactors and molten salt reactors [46].

Fourth, these analyses did not include subsidies for any of the technologies, which can have a significant impact on total costs and LCOE.

Fifth, no monetary value (i.e., price signals) was assigned to any of the technologies in compensation for such characteristics as baseload or dispatchability. This remains part of the ongoing debate where nuclear and solar PV are approached as an either-or decision.

Sixth, although all technologies are zero-carbon, if a price on carbon is implemented as part of a broader policy impacting all economic sectors, this will impact LCOE depending on carbon emissions in the respective supply chains for nuclear, solar PV and batteries.

CONCLUSION

In conclusion, with the focus being placed on a low-carbon future to continue the reduction of CO_2 emissions, zero-carbon technologies such as renewables or nuclear power are needed. There are intermittency and dispatchabillity issues for renewable sources and safety and cost concerns when dealing with nuclear. A normalized comparison is needed when looking at different technologies in order to see the whole picture. When comparing nuclear and solar on a capacity-equivalence based analysis the overall costs of solar look much more appealing than the overall costs of nuclear. However, when compared on a generation-equivalence basis, nuclear outperforms solar over the long-term. Furthermore, to compensate for intermittency, battery storage is needed for solar PV systems, which increases the overall cost and the LCOE. A generation-equivalence based analysis makes the overall generation more comparable. To match the generation of a nuclear plant, the capacity for solar PV systems must be increased. The normalized LCOE remains the same, but it increases the overall costs of solar PV system.

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