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Title:	**Michigan Nuclear Feasibility Study Report**	**PROJECT REPORT NO.**	**ESEPC-MPSC-00001-REPT-001**
		REV.	**0**
Client:	**Michigan Public Service Commission**	**Project Identifier:**	**ESEPC-MPSC-00001**

Item	Cover Sheet Items	Yes	No
1	Does this Project Report contain any open assumptions, including preliminary information, that require confirmation? (If **YES**, identify the assumptions.)	☐	☒
2	Does this Project Report supersede an existing Project Report? (If **YES**, identify the approved Project Report.) **Superseded Project Report No.**	☐	☒

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Preparer: See Signature Sheet	**Date:**
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Approver: See Signature Sheet	**Date:**

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PROJECT REPORT REVISION STATUS

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APPENDIX/ATTACHMENT REVISION STATUS

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Acronym List

ABWR	Advanced Boiling Water Reactor
AEC	Atomic Energy Commission
AEP	American Electric Power
AMP	Aging Management Program
ARDP	Advanced Reactor Demonstration Program
AREOR	Annual Radiological Environmental Operating Report
BANR	BWXT Advanced Nuclear Reactor
BWR	Boiling Water Reactor
BWXT	BWX Technologies
CANDU	Canada Deuterium Uranium
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Sequestration
CFR	Code of Federal Regulations
CFPP	Carbon Free Power Project
COL	Combined Operating License
COLA	Combined Operating License Application
C2N	Coal to Nuclear
DOE	U.S. Department of Energy
DTE	DTE Electric Company
EBR-1	Experimental Breeder Reactor I
EIA	Energy Information Administration (part of DOE)
EIS	Environmental Impact Statement
EGLE	Michigan Department of Environment, Great Lakes, and Energy
eGRID	Emissions & Generation Resource Integrated Database (maintained by EPA)
EMF	Electromagnetic Field
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institution
EPSM	Electric Power System Modeling (software created by Veritas Economics)
EPZ	Emergency Planning Zones
ESBWR	Economically Simplified Boiling Water Reactor
ESP	Early Site Permit
FOAK	First of a Kind
GEIS	Generic Environmental Impact Statement
GE-H	GE-Hitachi Nuclear Energy
GHG	Greenhouse Gas
GIF	Gen IV International Forum
HALEU	High Assay Low Enriched Uranium
HDI	Holtec Decommissioning International
HTGR	High Temperature Gas Reactor
IAEA	International Atomic Energy Agency
IMPLAN	IMpactPLANning (a software program)
INL	Idaho National Laboratory
ISFSI	Independent Spent Fuel Storage Installation
I/O	Input-output
ISG	Interim Staff Guidance
I-196	Interstate-196

I-75	Interstate 75
I&M	Indiana Michigan Power Company
IRA	Inflation Reduction Act
IRP	Integrated Resource Plan
ISFSI	Independent Spent Fuel Storage Installation
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MCV	Midland Cogeneration Venture
MISO	Midcontinent Independent System Operator
MPSC	Michigan Public Service Commission
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NEIL	Nuclear Electric Insurance Limited
NEPA	National Environmental Policy Act
NPDES	National Pollutant Discharge Elimination System
NOAK	N^{th} of a Kind
NOx	Nitrogen Oxides
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
PAA	Price-Anderson Act
PJM	PJM Interconnection
PPA	Power Purchase Agreement
Pu-239	Plutonium (Isotope with Atomic Mass 239; Not naturally occurring)
PWR	Pressurized Water Reactor
ROW	Right of Way (for transmission lines)
SFR	Sodium-Cooled Fast Reactor
SDC	Seismic Design Category
SEIS	Supplemental Environmental Impact Statement
SMR	Small Modular Reactor
SOx	Sulfur Oxides
Th-232	Thorium (Naturally Occurring Isotope of Thorium)
TMI	Three Mile Island
TMI-2	Three Mile Island Unit 2
TVA	Tennessee Valley Authority
U-233	Uranium (Isotope with Atomic Mass 233; Not naturally occurring)
U-235	Uranium (Isotope with Atomic Mass 235; ~0.7% of Naturally Occurring Uranium)
U-238	Uranium (Isotope with Atomic Mass 238; ~99.2% of Naturally Occurring Uranium)

Unit List

D/MW_e	Days required to build a reactor per MW_e
ft/yr	Feet per Year
gCO_2e/kWh	Grams of Carbon Dioxide Equivalent per Kilowatt-hour of Electricity Generated
gpm	Gallons per minute
GWh	Giga Watt Hour
kV	kilovolt(s)
kWh	Kilo Watt Hour

kW_e	Kilowatts Electric
mA	milliampere(s)
mT	Metric Tons
MT	1,000,000 Metric Tons
GT	1,000,000,000 Metric Tons
MMTpa	1,000,000 Metric Tons Annually
MW_{th}	Mega Watts Thermal
MW_e	Mega Watts Electric
MWh	Mega Watt Hour
pCi/L	Pico Curies per Liter (concentration of radioactivity)
rem	roentgen equivalent(s) man (unit of radiation dose)
SCF	Standard Cubic Feet
SWU	Separative Work Unit
TWh	Tera Watt Hours
$/MMBTU	USD per 1,000,000 BTU

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Energy is vital to the functioning of the global economy. Goods cannot be produced nor transported without energy. Modern communication networks, which are used ubiquitously through everyday life for the vast majority of the population, cannot operate without energy inputs, either for charging smartphones or operating the networks. Production of energy inevitably results in impacts of various sorts, with particular focus on impacts to the environment. The impacts from increased concentrations of greenhouse gases from human energy-related inputs has become increasingly important for consideration by decision makers. The attributes of nuclear power, being capable of producing substantial quantities of useful energy without associated carbon dioxide emissions from its operation, make it a technology of particular interest as energy mixes of the future are planned. As a result of this interest, Public Act 166 of 2022 [1] passed by the Michigan state legislature directed the Michigan Public Service Commission (MPSC) to engage an outside firm to examine the feasibility of nuclear power generation in the state of Michigan. Parameters for the study were outlined by Public Act 218 of 2022 [2]. This study is the result of those efforts.

A mapping of the study parameters and where the requested items are located within the report is included in Section 1.2, with discussion about the study development process found in Section 1.3. Historical background on nuclear power within Michigan and more generally are included within Sections 1.1 and 1.4 for contextual reference.

Advantages and Disadvantages

Section 1.5 discusses some primary advantages of nuclear power. Some of these advantages to highlight include the emissions-free nature of nuclear power, relatively low land usage for nuclear power facilities, the high reliability and capacity factors that nuclear power plants can achieve, low fuel cost, and the substantial local economic benefits resulting from nuclear power facilities' construction and operation. Section 1.6 discusses primary disadvantages of nuclear power. Key disadvantages to highlight include high upfront capital costs and lengthy project development timelines, lack of clarity on a final disposition plan for used nuclear fuel, concerns relating to radiation from either normal operation or in the event of an accident, and concerns relating to nuclear proliferation. Cost estimates for first of a kind (FOAK) and follow-on nuclear plant installations are summarized within Section 1.6.a, including overnight capital costs and the resulting levelized cost of electricity (LCOE) estimates, both considering the maximum tax credit benefits from the Inflation Reduction Act and presuming no benefit from these tax credits.

Economic Impacts

Section 2 provides a summary of studies conducted to estimate the impacts to Michigan's workforce and economy that would result from a hypothetical new nuclear installation within the state. These studies are detailed within Sections 2 and 4 of Appendix 1. Section 2 of Appendix 1 also includes a table illustrating potential portions of a nuclear project supply chain which could be sourced from Michigan. The estimated lifetime economic impact of building a new nuclear plant within Michigan was estimated to be a value added of $3.6 billion for a hypothetical plant built in Ottawa County in western Michigan with an addition of 719 long-term jobs created for the duration of the plant's operation or $3.7 billion for a hypothetical location in Monroe County in eastern Michigan with an addition of 773 long-term jobs created for the duration of the plant's operation. Substantially more jobs would be created for the estimated 4-year duration of construction for either hypothetical new plant location. These evaluations include direct, indirect, and induced impacts. It must be noted that this report does not endorse or recommend either of these hypothetical locations for a new nuclear build, but these locations were selected to allow illustrative modeling of what the economic impacts of a new nuclear build would be. A further disclaimer applicable to this report as a whole is included in the footnote below[1].

Emissions Reductions

Sections 3 and 5 of Appendix 1 describe detailed power system modeling that has been conducted in support of this study for two different hypothetical locations for nuclear power facilities within Michigan. The associated emissions reduction impacts for these hypothetical new plants as compared to a status quo power system model has been calculated. Inclusion of a hypothetical new nuclear plant within the DTE Electric territory was found to result in annual emissions reductions for the applicable service area of approximately 365,000 tons of CO_2, 62 tons of SO_2, and 140 tons of NO_X as compared to a baseline power system model without the new nuclear plant. The reductions for a hypothetical new nuclear plant within the Consumers Energy territory was found to reduce annual emissions by approximately 1.2 million tons of CO2, 6.2 tons of SO2, and 197 tons as compared to a baseline power system model.

Existing Nuclear

Section 3 of this report describes the existing and historic nuclear power plants within Michigan. Section 3.3 provides an overview of the environmental aspects of these plants. Section 3.2 provides a brief description of nuclear plant decommissioning processes, while Section 3.4 describes the process of obtaining NRC license extensions.

New Nuclear

Section 4 describes new nuclear technologies and siting considerations for new plants. Section 4.1 describes new nuclear technologies, with explanations of some commonly-used terminology such as Small Modular Reactors (SMRs), Advanced Reactors, and microreactors, while also providing descriptions of the progress of some of the developments of these technologies. Section 4.2 includes detailed information regarding siting considerations for new nuclear plants. Section 4.3 includes brief notes about relevant recent announcements for new nuclear development

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[1] Disclaimer

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activities to provide a snapshot as these technologies develop. New information continues evolving in real-time.

Nuclear Development Timeline
Section 5 provides a look at the timelines that would be expected for a new nuclear development project to aid energy planning decision-makers.

Nuclear Technology Integration
Section 6 summarizes how nuclear energy can coordinate with other technologies. Section 6.1 focuses on the possibility of re-purposing retiring coal-fired power plant sites with nuclear power plants as a replacement heat source. Section 6.2 explores the potential for nuclear power beyond solely electricity generation. Nuclear-generated hydrogen is a significant focus in this regard, as hydrogen is being considered as an option to be utilized for a number of purposes.

Nuclear Policies
Section 7 explores nuclear power-related policies. These include a look at historical national policies in Section 7.1, a summary of recent policy actions in Section 7.2, a look at federal incentives for nuclear power in Section 7.3, and a look at proposed updates to nuclear regulation in Section 7.4. Section 7.5 summarizes some state policies relating to nuclear, both for Michigan specifically with the recently passed Michigan Clean Energy Future Bill and for a quick look at some policy actions from other U.S. states. Section 7.6 provides a quick description of Declaration to Triple Nuclear Energy by 2050, signed by a number of countries in conjunction wtih COP28. Section 7.7 provides a policy summary and some recommendations for policies that the State of Michigan could consider regarding nuclear power.

Section 8 provides summaries of various studies relating to nuclear power. Input from some of these studies is also included throughout other areas of the report. The overall conclusion is that nuclear power is feasible within the State of Michigan, though siting and cost considerations will play a significant factor in any decision-making regarding future new nuclear plants within Michigan.

1. INTRODUCTION

1.1 Overview of Nuclear Power Generation in Michigan

In the state of Michigan, commercial nuclear power reactors have operated at four different sites since the first of these began operating in 1962: Enrico Fermi Nuclear Generating Station, Donald C. Cook Nuclear Plant (DC Cook), Palisades Nuclear Generating Station, and Big Rock Point Nuclear Power Plant. These sites have included the following individual reactors: Fermi 1 and Fermi 2, DC Cook Units 1 and 2, and single units at Palisades and Big Rock Point. Big Rock Point was shut down in 1997 and is fully decommissioned, though the spent fuel remains stored at the on-site Independent Spent Fuel Storage Installation (ISFSI), while Palisades shut down in 2022 with the intent to decommission but is now seeking to re-enter operation following a process for reinstating its operating license. Additionally, the Midland Cogeneration Venture was originally planned to be a 2-Unit nuclear power plant, until the construction of the nuclear plant was abandoned in 1984 and subsequently converted to a natural gas-fired facility still operating today, providing both electricity and process steam. These nuclear power plants provided approximately 28% of the electricity within the state of Michigan from 2011 to 2021 (averaging ~31 million of ~111 million MW-hrs annually during this period) [3]. A more detailed discussion of current and recent nuclear power in Michigan follows in Section 3 of this report.

1.2 Study Objective and Overview

Public Act 166 of 2022 [1] of the Michigan state legislature directed the Michigan Public Service Commission (MPSC) to engage an outside firm to examine the feasibility of nuclear power generation in the state of Michigan. Parameters for the study were outlined by Public Act 218 of 2022 [2] [4]. This study is the result of those efforts.

Per the Public Acts referenced above, the Nuclear Feasibility Study will consider the following, with verbiage from the Acts themselves **bold** and *italicized* with references to the sections of the study addressing each aspect.

- ***The advantages and disadvantages of nuclear energy generation in Michigan, including, but not limited to, the economic and environmental impact.*** Advantages and disadvantages are discussed within Section 1. Detailed discussions of the economic impacts are included primarily in Section 4 of Appendix 1, with summary information included in Section 2. Environmental discussions are included primarily within Sections 3 & 4.
- ***Ways to maximize the use of workers who reside in Michigan and products made in Michigan in the construction of nuclear energy generation facilities.*** This is addressed within Appendix 1 Sections 2 and 4.
- ***Evaluations, conclusions, and recommendations on all of the following:***
  - ***Design characteristics.*** This information is included within Sections 1, 3, and 4.
  - ***Environmental and ecological impacts.*** This information is included within Sections 1, 3, and 4.
  - ***Land and siting criteria.*** This information is included within Sections 1, 3, and 4.
  - ***Safety criteria.*** This information is included within Sections 1, 3, and 4.
  - ***Engineering and cost-related criteria.*** This information is included within Sections 1 and 4.
  - ***Small cell nuclear reactor capability.*** This information is included within Sections 4 and 6.
- ***Socioeconomic assessment and impact analysis, including, but not limited to, the following:***
  - ***Workforce education, training, and development.*** This information is included in Appendix 1 Section 2.

    - ***Local and state tax base.*** This information is included within Appendix 1 Section 4.
    - ***Supply chains.*** This information is included primarily Appendix 1 Section 2.
    - ***Permanent and temporary job creation.*** This information is included within Appendix 1, with summary information in Section 2.
- ***The timeline for development, including areas of potential acceleration or efficiencies and leveraging existing nuclear energy generation facilities in Michigan.*** This information is included within Section 5 along with some description in Appendix 1.
- ***Additional efficiencies and other benefits that may be gained by coordinating with other advanced, clean energy technologies, including, but not limited to, hydrogen, direct air capture of carbon dioxide, and energy storage.*** This information is included within Section 6.
- ***Literature review of studies that have assessed the potential impact of nuclear energy generation in supporting an energy transition.*** This information is included within Section 8.
- ***Analysis of national and international studies of cases where development of nuclear energy is supported and adopted.*** This information is included within Section 8.
- ***Assessment and recommendation of current and future policies that may be needed to support or accelerate the adoption of nuclear energy generation or may improve its cost-effectiveness.*** This information is included primarily Section 7.

1.3 Stakeholder Engagement

During the development of this study, a series of public meetings were held to provide an opportunity for stakeholders to provide input to the study. All stakeholder input was considered, and when applicable to the legislatively determined scope of the study, the input has been included in the report. An initial stakeholder meeting was held on May 3, 2023, a second stakeholder meeting was held on September 8, 2023, and a third stakeholder meeting will occur after a draft version of this study has been posted to the Study website [4]. As questions and comments fit within the scope of this study, additional detail has been included within the report. Additions as a result of stakeholder feedback includes the following:

- Information from historical nuclear construction projects in the U.S. and around the world has been included. A chart documenting construction durations from historical builds is included in Section 5.
- Efforts have been made to ensure that all acronyms used within the report have been defined, with an acronym list included within the report.
- Information relating to coordination with other technologies has been included within Section 6.
- Reference has been included to ongoing efforts to ensure that the Nuclear Regulatory Commission (NRC) will have sufficient capacity to review upcoming applications. The

question of NRC staffing and capacity for completing reviews was raised during a Stakeholder meeting.

- Environmental impacts relating to nuclear power plants are covered in detail, both relating to the existing nuclear plants in Michigan within Section 3 and considerations that will be necessary for siting any new plants within Section 4.
- To the degree of fidelity possible, information regarding approximate costs as well as projected timelines for new nuclear plants has been included. This information is found within Section 1.6.a as well as within Section 2 of Appendix 1.
- Information regarding repowering coal plants and the cost savings that could be achieved from doing so has been included within Section 6.

1.4 Brief History of Nuclear Power

The power of the atom was initially demonstrated with the assembly of the Chicago Pile-1 reactor under the viewing stands of Stagg Field at the University of Chicago. This first human-made self-sustaining nuclear chain reaction occurred on December 2, 1942, as part of the Manhattan Project during World War II. Nuclear energy was first used to produce electricity, on December 20, 1951, with the illumination of four 200-watt lightbulbs near Arco, Idaho, from electricity generated via power from the Experimental Breeder Reactor I (EBR-1) at the National Reactor Testing Station, part of Argonne National Lab's western installation (now Idaho National Lab). The first commercial scale nuclear power plant was the Shippingport Atomic Power Station in Shippingport, Pennsylvania, which achieved criticality (a sustained nuclear chain reaction) on December 2, 1957 (15 years to the day after the first human-made self-sustaining nuclear chain reaction at Chicago Pile-1) and first started supplying power to the Duquesne Light Company grid 16 days later. The Shippingport reactor was developed as part of the Atoms for Peace[2] program and was based on the reactor designs developed for powering the U.S. Navy's nuclear-powered submarines.

Nuclear power is generated by sustained nuclear fission. Fission is the splitting of large atomic nuclei[3] into smaller atomic nuclei, which releases energy as well as neutrons. The neutrons released sustain the process by causing further fission (atom-splitting) events. Due to the need to have neutrons collide with a fissile nucleus to continue a chain reaction, spacing, geometry, and concentration[4] of fissile nuclei is a key factor in nuclear reactor core designs. The concentration of fissile material also plays a substantial role in determining the amount of time a given reactor core can operate without the need for refueling. For example, U.S. naval reactors

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[2] The Atoms for Peace program began in 1953, highlighted by a speech from U.S. President Dwight D. Eisenhower given December 8, 1953. The program included developing nuclear/atomic technologies for purposes such as energy production, rather than solely for development of nuclear arsenals.

[3] Nuclei is the plural form of the word nucleus, which is the inside portion of an atom, containing protons and neutrons.

[4] Concentration of fissile nuclei is generally determined by the enrichment level of a given nuclear fuel form. Enrichment processes increase the percentage of uranium-235 (U-235) in nuclear fuels.

utilize highly enriched uranium (HEU) fuel and are designed to operate for roughly 30 years without the need for refueling[5].

Prior to the Atoms for Peace program, atomic/nuclear[6] technology developments were kept in strict secrecy and were restricted from the private sector. Subsequent to the opening up of opportunities to the private sector, During the era of the Atomic Energy Commission (AEC), the roles of both regulating and promoting nuclear power technologies were shared by a single agency, the AEC. The Energy Reorganization Act of 1974 established the Nuclear Regulatory Commission (NRC) “as an independent agency to ensure the safe use of radioactive materials for beneficial civilian purposes while protecting people and the environment" [5]. The promotional role of the AEC was moved to the Energy Research and Development Administration, which subsequently became the Department of Energy (DOE).

many different reactor designs were built, tested, and demonstrated during the initial nuclear era from the mid-1950s into the mid-1960s, including gas-cooled reactors, metal-cooled reactors (mostly sodium or lead-bismuth, including Fermi Unit 1 in Michigan), and the molten salt reactor experiment (MSRE) at Oak Ridge National Lab. The testing of different reactor types sought to determine the best characteristics for different applications. Many different concepts had been postulated during the earliest days of nuclear development, such as with the New Piles Committee that met in 1944 [6]. Many early designs focused on the capability to breed fissile fuel from fertile[7] materials (natural thorium occurring as almost entirely Th-232 or the predominant uranium isotope, U-238), as the availability of natural uranium and enrichment capabilities were not (and still are not) equally dispersed across the globe. A key aspect of nuclear power plant designs is the choice of coolant, as the heat generated by the reactor must be transferred out of the reactor core to be utilized for electrical power generation. While several designs utilizing different coolants were conceived and developed to varying degrees, ultimately, the boiling water reactor (BWR) and pressurized water reactor (PWR) won out commercially. These two designs, known collectively as light water reactors (LWRs) ended up accounting for the vast majority of commercial nuclear power plants operating around the world from the 1970s through the early 2020s.

BWRs make up 31 of the 93 currently operating commercial nuclear reactors in the U.S. In a BWR, the water coolant is designed to boil in the reactor core and then travel to a steam turbine, where work is extracted to rotate the turbine that is connected to the rotor of an electric generator. The rotor rotates within a stator, generating electricity, which is then transferred to the electric grid as 3-phase alternating current (AC) power through a set of transformers that steps up the voltage

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[5] Detailed information about Naval reactors is not publicly available.

[6] The words “atomic” and “nuclear” are generally used interchangeably in regards to fission-related items, with the word atomic having been used predominantly within the early days after the discovery of fission and nuclear being much more commonly used in more recent years. Definitionally, atomic refers to atoms and nuclear refers specific to the nuclei of atoms, where protons and neutrons reside.

[7] Fertile materials are atoms that can become fissile after capturing neutrons from prior fissions. U-233 and Pu-239 are the predominant fissile isotopes that can conceivably be produced from fertile materials.

to the grid voltage. The low-pressure steam that has passed through the turbine then passes through a condenser, where it is condensed back into a liquid state, and then pumped back to the reactor via a series of condensate and feedwater pumps.

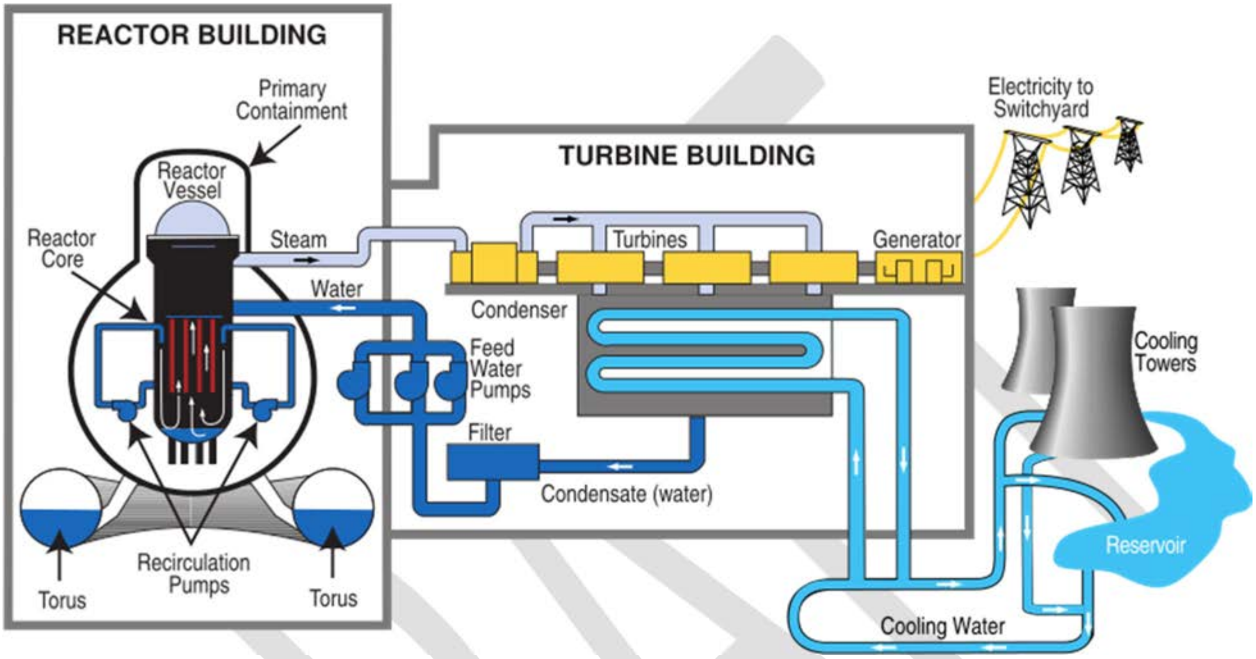

Figure 1 Diagram of a BWR from Wikimedia Commons [7]

PWRs make up 62 of the 93 currently operating commercial nuclear reactors in the U.S. In a PWR, the reactor core is pressurized to maintain the water coolant as a liquid through its entire path through the reactor core and associated reactor coolant system. After flowing through the reactor core and capturing the heat generated, the coolant system water inventory flows into steam generators (specialized heat exchangers which allow for a separation of water loops and for boiling to occur outside of the reactor core), traveling through numerous tubes (while remaining in the liquid phase due to the pressurization of the system), boiling the feedwater on the shell side of the steam generators. The steam then travels to the steam turbine, where it provides the energy to spin the turbine, which is connected to the generator via a shaft. The spinning generator creates electricity and the low-pressure steam exiting the turbine is condensed to a liquid state. The liquid water is returned to the shell side of the steam generators in a similar manner as BWRs. The main difference between PWRs and BWRs is the presence of steam generators in a PWR plant as opposed to boiling of reactor coolant water occurring within the core of a BWR.

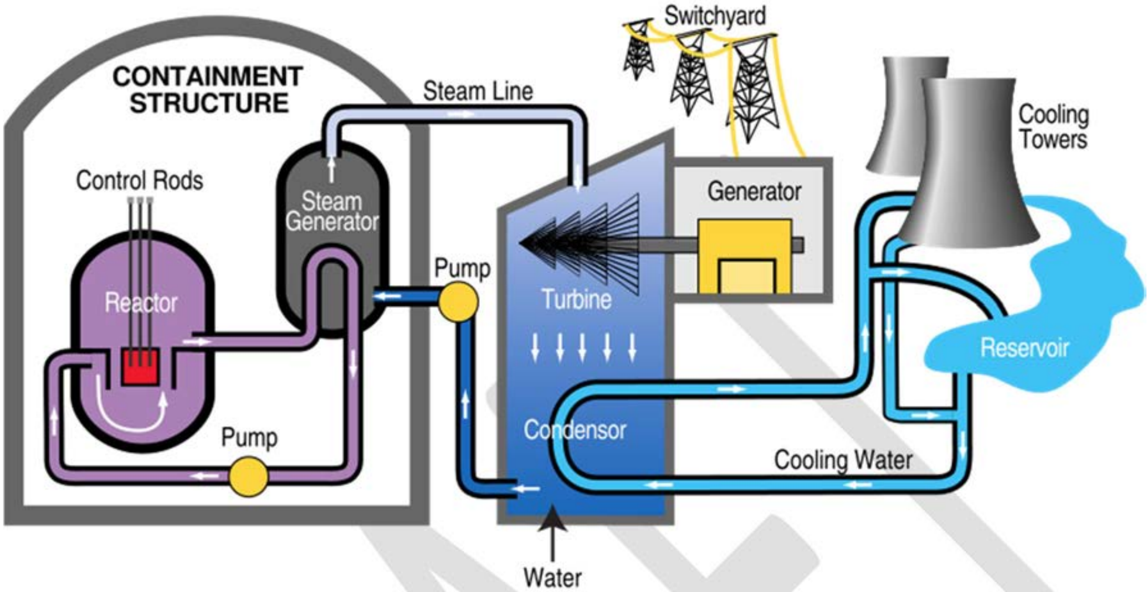

Figure 2 Diagram of a PWR from Wikimedia Commons [8].

BWR and PWR reactors, which have been the world's most prominent commercial power reactor designs, have typically used fuel enriched to 3-5% U-235. Current efforts underway to extend BWR and PWR fuel cycles from 18 to 24 months, for plants that have not already made such extensions, will likely result in use of fuel at enrichment levels greater than 5% [9]. Most operating nuclear reactor designs require the enrichment of the U-235 isotope above the 0.7% level present in natural uranium.

In addition to LWRs, there have also been some commercial-scale gas-cooled reactors, primarily of UK design, Canada Deuterium Uranium (CANDU) pressurized heavy water[8] reactors of Canadian design, and metal-cooled reactors of various national origins. Reactor design selections have been heavily influenced by the capabilities and resources available within the given regions of design origin. As previously discussed, reactor types can contain various amounts of fissile material, U-235, which determine the operational capabilities of a reactor. A primary advantage of CANDU reactors is the lack of necessity of enrichment for the reactor's fuel (enrichment to 3-5% U-235 is required for other LWRs), being able to use natural uranium with 0.7% U-235 due to the moderation characteristics of the heavy water used as their coolant/moderator. Gas-cooled reactors present a higher thermal efficiency than their water-cooled counterparts due to higher operating temperatures.

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[8] "Heavy water" is water made up of hydrogen atoms with both a neutron and proton in the nucleus (known as deuterium), whereas "light water" is made up of hydrogen atoms with no neutrons (hydrogen atoms containing 2 neutrons and 1 proton are known as tritium).

1.5 Primary Advantages of Nuclear Power Generation

1.5.a High Capacity Factors

Nuclear power possesses useful attributes as a primary energy source. For example, nuclear power plants can operate continuously between scheduled refueling outages, resulting in high-capacity factors[9]. In the U.S., the nuclear industry's operating capacity factor has steadily increased since the initial plants began operating. This is due to numerous factors, including knowledge sharing of operational experience, improvements in the reliability of individual components and systems, and decreases in refueling outage durations due to detailed activity scheduling. The combination of many factors (beyond the few mentioned) has led to U.S.-based nuclear power plants averaging over a 90% capacity factor for the past two decades [10, 11]. This increase in capacity has allowed for more electricity generation from nuclear reactors and has increased the resilience of the electricity supply leading to a more stable grid. The resilience of nuclear reactors has served as the backbone of clean electricity generation in the U.S. through both extreme weather events and the pandemic in 2020. Despite the worldwide constraints resulting from both extreme weather and from the pandemic, nuclear power plants continued to operate safely and reliably, experiencing less than 0.1% capacity factor loss due to weather events [12]. As of 2019, only four out of 98 operating reactors within the U.S. were operating at a capacity factor between 60%-80%, while over 60 reactors were all operating above a 90% capacity factor [13]. Amongst U.S. utility-scale generators primarily using non-fossil fuels, 2022 capacity factors were as follows: 69.0% for geothermal, 36.3% for hydroelectric, 92.7% for nuclear, 60.2% for other biomass, 61.6% for other gas, 24.4% for solar photovoltaic generation, 23.1% for solar thermal, 35.9% for wind generation, and 57.9% for wood [14].

1.5.b Small Footprint (High Power Density)

Nuclear power plants require relatively small land areas for generating large amounts of electricity. For a comparison between solar, wind, hydro, and nuclear land usage, as non fossil-fuel based generation sources with substantial installed capacities within the U.S., the selection of three solar power and three wind power installations at advantageous latitudes are used. Three solar power plants located in the southwestern U.S., Topaz Solar Farm, Solar Star Solar Farm 1 & 2, and Crescent Dunes Solar Energy Farms generate on average 3,410 GW-hr annually and take up a land area of 9,506 acres [15, 16, 17, 18, 19] for approximately 0.36 GW-hr/acre. Atla Wind Energy Center, Los Vientos Wind Farm, and Shepherds Flat Wind Farm generate on average 7398 GW-hr [20] annually and take up a land area of 99,084 acres [21] for approximately 0.075 GW-hr/acre. Hydropower varies greatly on the topography and source of water but according to a Landsat estimate, hydropower has a power to land usage ratio of 0.57 GW-hr/acre (using the adjust land occupation value) [22]. Conversely, considering DC Cook, Sequoyah Nuclear Plant, owned by the Tennessee Valley Authority (TVA), and Fermi Unit 2, these three

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[9] Capacity factor is the percentage of electricity generated by a power plant compared to its ability to operate at 100% of nameplate capacity for 24 hrs/day 365 days/year.

plants respectively have averaged 17,249 GW-hr [23], 6,194 GW-hr [24], and 7,966 GW-hr [25] annually of electricity production from sites taking up 650 [26], 432 [27], and 1260 [28] acres, respectively, for approximately 13.4 GW-hr/acre. From this comparison, the production of energy per acre is over 35 times larger for nuclear plants compared to solar plants and over 180 times larger as compared to wind farms (note that this average contains a small sample size). This is a substantial advantage in terms of location management, area of maintenance, and impact on the surrounding environment. Additional global information is also provided within Section 4.4.d. A graph of land use efficiency values for different energy sources was included within the recently-published DOE report “Pathways to Commercial Liftoff: Advanced Nuclear” [29] and has been included here as Figure 3.

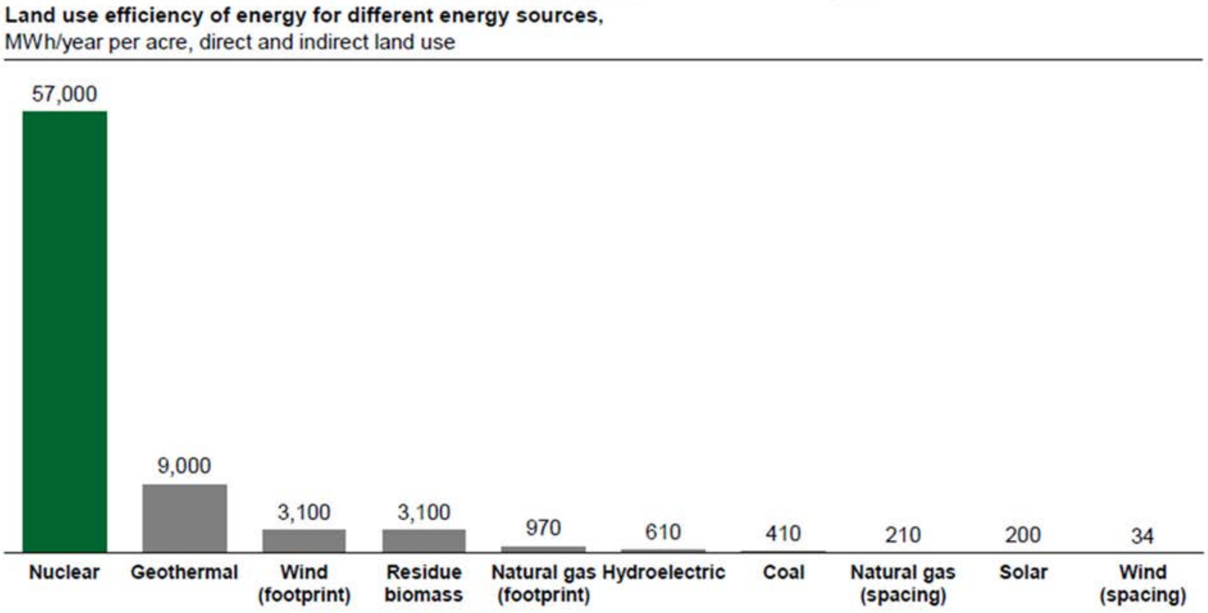

Figure 3 Land-use efficiency of electricity sources as determined by the inverse of total land-use required [29].

An additional land consideration for reactors is the area occupied by the emergency planning zones (EPZ) which vary in shape and size due to the geographic location [30]. The land within the EPZ beyond the specific land used for plant operations can still be used for farming, residential usage, industrial, and other purposes, but plans need to be developed for residents and businesses that reside in this area to take shelter and evacuate during potential extreme events at nuclear facilities. For current reactor systems, the NRC defines two types of EPZs. The first is a ten-mile radius which buffers the exposure of the public to inhaled radioactive contamination through plume exposure pathways. The second is a 50-mile radius which accounts for ingestion of radioactive contamination through food and water [31]. These standards are set for the current fleet of nuclear systems in the U.S. but do not consider the potential enhanced safety or decreased source terms[10] of advanced reactor systems. Studies for advanced reactor systems take into account radiation protection regulation, reactor and plant design, site characteristics, and public behavior to determine the needed EPZs. Through a review of five separate small modular reactor (SMR) technologies and previously approved early site permits by the NRC, their EPZ was reduced to a two to five mile radius, while still ensuring the public's safety [32]. This is a considerable decrease, a quarter of the land required, from the land usage for the current fleet of operating nuclear reactors and should allow for easier land management and siting of these future nuclear power plants.

Many advanced reactor vendors have suggested that they anticipate being able to justify limiting the EPZ for their designs to the site boundary, but this remains to be proven through the NRC's licensing processes. In August 2023, the NRC announced plans to issue a final rule and regulatory guide relating to emergency preparedness requirements for SMR and other new reactor technologies. This new guidance will be risk-informed and performance-based and should be published later in 2023 [33], and should generally allow for EPZs of a size smaller than the previously prescribed, one-size-fits-all ten-mile radius.

1.5.c Greenhouse Gas (GHG) Emission-Free Operation

The operations of nuclear power plants do not emit any carbon dioxide (CO_2) nor require pipeline delivery of natural gas (primarily CH_4) which contribute to the greenhouse effect[11]. The main emissions toll paid by reactors comes from its initial construction and mining of steel, uranium, and concrete resources as well as uranium enrichment and fuel fabrication. However, these emissions are only a fraction of the carbon emissions produced by the lifetime operation of any natural gas, oil, or coal power plant lacking carbon capture technology. As a comparison, the life cycle generation of greenhouse gases for natural gas combined cycle plants produces 486 gCO_2e/kWh[12] while nuclear power plants produce 13 gCO_2e/kWh, a difference of roughly 97% from inception to their respective decommissioning. The production of lifecycle greenhouse gas emissions by solar is more than three times that of nuclear power plants at 42 gCO_2e/kWh, and wind farms have approximately the same 13 gCO_2e/kWh lifecycle emissions footprint as nuclear power plants [34]. Over the past 50 years it is estimated that the operation of nuclear reactors globally has avoided CO_2 emissions by over 60 Gigatons (GT, 1 GT = 1,000,000,000 Metric Tons) [35]. In the U.S. alone, nuclear power generated 772 million MWh in 2022 which would equate to a reduction in emissions of ($\{486\ kgCO_2/MWh - 13\ kgCO_2/MWh\} \times 772 \times 10^6\ MWh$) 365 Megatons (MT, 1 MT = 1,000,000 Metric Tons) of CO_2 when considering the replacement of electricity produced by natural gas combined cycle plants [36]. This has been the average production value for the past two decades, accounting for roughly 7.3 GT of CO_2 emissions prevented from U.S.

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[10] Source term is the amount of radioactivity within a nuclear power reactor's core. Lower power reactors have lower total amounts of radioactivity and thus lower source terms.

[11] The greenhouse effect is a shifting of the balance of solar energy that is absorbed versus what is emitted back out into space. Methane (CH_4) can leak from pipelines and is a greenhouse gas.

[12] gCO_2e/kWh is grams of carbon dioxide equivalent per kilowatt-hour of electricity generated.

reactor operation over the past 20 years [36]. Nuclear reactors typically have emergency diesel generators which operate infrequently either for scheduled periodic testing or under circumstances that the power plant loses power from the grid (loss of offsite power) as a safety measure for powering various plant systems. Since station blackout happens infrequently, with a predicted median frequency of occurrence every 34 years, [37]operation of nuclear power plant emergency diesel generators produce a negligible amount of emissions.

1.5.d Air Pollutant-Free Operation

Operation of nuclear power plants does not emit NOx, SOx, particulate matter, or mercury, in contrast to coal-fired power plants lacking modern emissions control technologies (flue gas desulfurization, selective catalytic reduction, and other technologies that have been retrofitted onto many older coal-fired plants). Modern fossil fuel-combusting plants have undergone substantial efforts to reduce their sulfur- and nitrogen-oxide emissions over the past two decades, mainly resulting from enforcement through the Environmental Protection Agency (EPA) [38]. Substantial reductions in these pollutants have come from the reduction in coal usage and switching over to natural gas, however, natural gas on average emits 0.6 lbs/10^6 SCF[13] of SO_2 when burned [39]. Other harmful emissions such as N_2O and PM[14] are produced at 2.2 lbs/10^6 SCF and 7.6 lbs/10^6 SCF, respectively, when burning natural gas [39]. In Michigan, the industrial and electric power sectors burned a total of 413,733×10^6 SCF of natural gas in 2021 producing 112 metric tons (mT) of SO_2, 412 mT of N_2O, and 1,426 mT of PM [40]. Coal production from the same year shows a worse emissions result than natural gas despite being used less. For 2021, the burning of coal in Michigan produced 57,600 mT of SO_2 and 52,400 mT of NOx its total generation [3, 41]. The replacement or possible retrofitting, as discussed in later sections, of fossil fuel plants with nuclear in Michigan presents a potential for greatly reducing harmful air-pollutants on a yearly basis from the state of Michigan.

1.5.e On-site Fuel Storage & Overall Plant Resilience

Nuclear reactors store enough fuel for 18-24 months of operation within the core. If economics dictated any advantage to doing so, it would be feasible to store decades of new fuel at a site. The design of nuclear power plants allows them to continue operating through substantially adverse weather conditions, including during storms with heavy winds or through very hot or cold temperatures. Per a study from the Electric Power Research Institute (EPRI), from 2011-2020, weather-related events contributed to a less than 0.1% impact on nuclear power plants' capacity factors [42]. Comparable resilience resulting from on-site fuel storage is only achieved by coal-fired power plants, which still present a minor potential for issues with freezing for outdoor coal piles.

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[13] 1 SCF = Standard Cubic Feet, where this ratio generates 0.6 pounds of SO_2 per million square cubic feet of natural gas burned.

[14] PM = particulate matter

1.5.f Low Fuel Cost and Abundance Potential

Relative to fossil fuel-powered generation sources, nuclear fuel is inexpensive. For 2021, the all-in cost for nuclear fuel was approximately \$0.00631/kWh (\$6.31/MWh) as compared to \$0.0246/kWh (\$24.60/MWh) for fossil fuel generated steam plants [43]. These costs for 2022 fell to \$6.12/MWh for nuclear and rose to \$32.04/MWh for fossil fuel generated steam plants. With the low proportion of overall operating costs that fuel represents for nuclear power, the total cost of nuclear generation has low sensitivity to fuel-related costs, which are comprised of the cost of natural uranium, cost of conversion, cost of enrichment services, cost of deconversion, and costs of fuel fabrication. Coupled with that low sensitivity, the low cost of nuclear fuel is advantageous due to the historical volatility of prices for nuclear fuel cost components having been lower than the costs of fossil fuels.

Another advantage that proponents of nuclear energy tout is the relative abundance of fuel resources, particularly given the potential for breeding new fissile fuel from fertile material. As of estimates in 2021, there are over six million tonnes[15] of uranium from reasonably assured resources around the world, as compared to less than 3.2 million tonnes of uranium of cumulative production from 1945 to 2022 [44]. Over one-third [45] of the energy generated in a conventional nuclear power plant is a result of breeding of fissile fuel from the fertile proportion of the fuel loaded into the reactor, primarily from fertile U-238 capturing neutrons from a nearby fission event and being bred into fissile Pu-239 (but also from a mix of other fissile transuranic isotopes). Use of fertile thorium to be bred into fissile U-233 has been demonstrated in the Shippingport reactor (a PWR) as well as during operation of the MSRE [46]. Substantial interest in use of a thorium fuel cycle has resulted from the acknowledgement of thorium's greater abundance within the Earth's crust as compared to uranium[16], particularly for regions which do not have ready access to rich deposits of uranium. Additionally, many studies have focused on the concentration of uranium in seawater, with an eye toward extracting uranium from seawater as a possible future alternative to uranium mining. While the concentration is only about three ppb [47], this could be a viable future option for countries with ready-access to the sea but little terrestrial uranium access (particularly Japan) [48]. While the quantities of potentially useful nuclear fuel show promise, a number of technologies being developed must come to fruition for these fuel sources to be able to be utilized and provide the benefits of having ready access to thousands of years' worth of available fission fuel. A brief listing of the needed developments to further utilize the fuel potential of these resources includes further demonstration and deployment of (1) fast neutron spectrum reactors to more fully utilize fertile U-238 resources, (2) yet-to-be-deployed thermal spectrum neutron reactors to utilize fertile Th-232, and (3) either technologies to enable higher burnup capabilities or reprocessing/recycling capabilities or a combination of both. A key factor that must remain paramount in developing these technologies is ensuring that proliferation concerns are

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[15] A tonne, also known as a metric ton, is a unit of mass equaling 1,000 kilograms or approximately 2,205 pounds.

[16] There are some other purported benefits/advantages of a thorium fuel cycle and the associated thermal energies of reactors that would be utilized for use of a thorium fuel cycle, but exploration of those are outside the scope of this study.

addressed for all the steps along the way to creating new fissile material from fertile material. These developments will not be addressed further in this study but are mentioned here to describe that pathways exist within the bounds of physics and human technological capabilities for nuclear fission to have an essentially inexhaustible fuel supply on Earth.

1.5.g Waste Storage and Accountability

Spent fuel from nuclear power plants is all catalogued, tracked, and stored safely in concrete and steel casks. This is contrasted with the free release of combustion products from fossil fuel-generated electricity sources (with CO_2 as a primary combustion product of interest). There are no known radiation related injuries or impacts from the handling of used commercial fuel since the early 1970s [49]. Spent fuel is in the form of fuel rods that have been used for approximately four to five years within a reactor's core. While typically referred to as spent fuel, there is remaining fissile and fertile material (actinides) within the fuel rods, so it is not entirely spent. After reaching various operational limits (for radiation and temperature exposures[17] and with reductions in fuel reactivity[18]), the spent fuel is transferred from the reactor core to a spent fuel pool, in a contained building with radiological safeguards, to cool as it continues to decay away shorter half-life fission product isotopes and release a majority of its decay heat. Once sufficiently cooled, both thermally and radiologically, these spent fuel rods are sent to dry cask storage where they are sealed up in shielded containers to continue decaying and releasing their ever-decreasing decay heat. Nuclear waste is often thought of as a substantial negative for nuclear power, but the accountability for the waste and manageability of its small volume could be considered an advantage, as the spent fuel is fully accounted for and sequestered from the environmental by being stored in robust casks. Waste storage and accountability is dependent on safe and timely adherence to NRC regulations.

Efforts are underway to site consolidated interim storage facilities for spent fuel. The NRC received construction applications for two different sites for such storage facilities, one in Texas and one in New Mexico [50]. Additional development efforts for other spent fuel solutions are underway, with one potential future option being developed by the company Deep Isolation, to provide deep borehole disposal options. Sweden has completed a geologic repository. France recycles most of their fuel and their waste is contained in a single facility. Recycling nuclear fuel can allow more of the fissile content of the fuel to be utilized and decrease the level of radioactivity that must be disposed of as waste, by removing the longer-lived actinides present in spent fuel.

1.5.h Nuclear Plants are Insured

In 1957, to amend the Atomic Energy Act of 1954, the Price-Anderson Act (PAA) became law. The provisions of this Act provide a backstop to cover liability claims for any personal or property damage caused by commercial nuclear power plants. The law enabled commercial development

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[17] Excessive time at operating temperatures and within the radiation fields of a reactor core brings the fuel cladding closer to its end of life, where fuel leakage would become more likely.

[18] After operating for some amount of time, fission products build up and a portion of the initial U-235 within the solid fuel of current reactor designs is reduced, which decreases the fuel's ability to continue to sustain a chain reaction.

of nuclear power reactors by private companies and to-date has generated an insurance pool of more than $13 billion. Current owners of nuclear power plants in the U.S. collectively pay a premium of approximately $1 million annually for $450 million in private insurance for offsite liability coverage. Any liability amount in excess of that $450 million threshold would be covered by each U.S. nuclear licensee on a pro-rated basis. In 2005, the Energy Policy act extended the PAA until December 31, 2025 [51]. Furthermore, the NRC regulations require any licensee to maintain a minimum of $1.06 billion in onsite property insurance for each reactor site. This act has reimbursed more than 600 individuals for the Three Mile Island accident [51].

Additionally, nuclear power plants in the U.S. are all insured by the mutual insurance company Nuclear Electric Insurance Limited (NEIL). This company covers almost all areas of a reactor from damages to physical property, decontamination expenses, decommissioning cost, and cost associated with long-term interruptions of electricity supply [52]. They have been responsible for providing private insurance to commercial nuclear power plants over the past 45 years and continue to do so with the introduction of many new advanced reactor technologies. This insurance pool helped pay for repairs at DC Cook Unit 1 following an issue with its turbine blades in 2008 [53]. The importance of appropriate insurance in energy infrastructure goes beyond nuclear as evidenced by transmission induced wildfires in California, hydro dam breaches in Michigan, and the potential for grid-scale battery fires.

1.5.i Small Fuel Mining Needs

The mining needs for fuel are relatively small in terms of the energy output from the plants. Uranium can be found in most rocks and precious metals mined from the earth, and once manufactured into a pellet (roughly the size of a gummy bear) it can produce as much energy as one ton of coal or 17,000 SCF of natural gas [54]. Uranium mining occurs through the collection of ore which is milled, converted, and then enriched before being fabricated into a fuel pellet [55].

Opportunities exist to enrich the depleted uranium “tails”[19] from prior enrichment activities to reduce the needs for future uranium mining. There is a proposed project to utilize laser enrichment for this purpose. This allows for an increased concentration of uranium-235 (U-235) within the material which is the necessary fissile material used within almost all nuclear reactor fuel [56]. The concept uses a laser to generate a positive charge on U-235 from a uranium vapor flow and then uses a negatively charged collector plate to extract the negatively charged U-235 out of the stream.

1.5.j Demonstrated Weapons Reduction Capabilities

Since the end of the Cold War, a substantial reduction in nuclear armaments has been seen worldwide, with the number of weapons dropping by almost ten times from the fiscal years of 1967-2020 [57]. Los Alamos Laboratory has been the front runner in research within the U.S. for

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[19] Uranium “tails” are the depleted uranium remnants/leftovers from the enrichment process. While the enriched uranium ends up having more than the naturally-occurring 0.7% U-235 concentration, the tails have less than 0.7%, with the exact enrichment level of the tails being dependent on the overall enrichment process.

non-proliferation of nuclear weaponry and counter proliferation to ensure the safety and accurate detection of nuclear material [58]. For a brief background, nuclear non-proliferation is governed by the Non-Proliferation Treaty[20], which was opened for signatures in 1968. The International Atomic Energy Agency (IAEA) is entrusted with key verification responsibilities under this treaty [59]. As history has progressed, more efforts have been made by converting old warheads into future nuclear fuels. The initial effort toward this occurred in 1993 when the U.S. and Russia signed an agreement for 500 mT of highly enriched uranium to be converted to low-enriched uranium fuel, as part of the “Megatons to Megawatts” program. The program ceased in 2013, but while it was underway it provided about one-third of the required enriched uranium for the fuel for U.S. reactors [60] [61].

1.5.k Substantial Local Economic Benefits

Nuclear power plants provide long-term, stable employment for the workers at the plant, in addition to substantial numbers of jobs for construction. The maintenance, monitoring, and construction of commercial nuclear power plants are critical to local economies and the International Atomic Energy Agency (IAEA) reported that for a LWR at any point in a typical ten year construction period requires 1,200 professional construction staff which is approximately 12,000 labor years, and for 50 years of operation, approximately 600 administrative, operations and maintenance, and permanently contracted staff are employed annually equaling about 30,000 labor years [62]. This topic is discussed in substantial detail in Sections 2 and 4 of Appendix 1, with local economic impacts modeled for hypothetical new nuclear plant builds in Michigan. From this economic modeling, a new nuclear plant built in Michigan is estimated to provide a lifetime economic value added of approximately $3.6 billion.

1.6 Primary Disadvantages of Nuclear Power Generation

1.6.a High Initial Capital Costs and Lengthy Project Timelines

Nuclear power plants have exhibited a wide range of capital costs throughout the years. The initial build-out in the U.S., prior to the mid-1970s, exhibited lower capital costs. However, subsequent to the mid-70s, construction costs began to rapidly rise. These rising costs were exacerbated by high inflation to the point that numerous nuclear construction projects that had been started were abandoned and never finished. This topic has been the subject of numerous studies, going as far back as Bernard Cohen’s 1990 book *The Nuclear Energy Option* [63].

The Three Mile Island (TMI) accident resulted in substantial increases in both construction periods and overnight costs because of additional safety measures being implemented after the start of construction of many plants. These changes, primarily relating to operator interfaces providing information about plants’ operational conditions, along with enhanced sharing of lessons learned

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[20] Also known as the Treaty on the Non-Proliferation of Nuclear Weapons

amongst nuclear operators[21], have led to improved nuclear power plant performance subsequent to the TMI accident. Lovering, et. al. [64] performed a study which captured the cost and construction time of reactors built prior to and after the TMI incident. The research showed reactors that began construction from 1968-1978 had overnight capital costs varying from \$1800/kW$_e$ to \$11,000/kW$_e$ [64]. Reactors that were under construction during and completed after the TMI incident had median costs that were 2.8 times higher than pre-TMI due to issues with licensing, regulatory delays, or retrofitted designs which upheld new safety requirements. Even though the overnight capital costs for several countries had a distinct increase, the U.S. had the largest increase in overnight capital costs of any country that was building nuclear power plants at the time [64]. Table 2.8 within Appendix 1 also includes a summary of some nuclear power plant cost estimates.

In a compilation of data from the Nuclear Energy Institute, reactor operating costs were contextualized over a 20-year period to determine the average generating cost of a plant considering fuel, capital, and operations of each facility. This study showed that costs have decreased from 2000 to 2021. For PWR and BWR plants, the total generating costs (not inclusive of up-front plant construction costs) averaged \$28.98/MWh and \$29.42/MWh, respectively, in 2021 [65]. These generating costs have fluctuated over the years due to other incidents in the nuclear industry and reached a maximum operating cost of \$47.65/MWh in 2012 [65]. However, these relatively low generation costs are a product of long-standing operations, with cost-saving lessons learned as the reactor continues to operate and limited on-going capital costs subsequent to the initial construction cost of a nuclear power plant.

Older reactors were able to take advantage of economies of scale and the operating experience that came from each predecessor reactor that was constructed. New small modular reactors will not be able to count on achieving economies of scale with smaller unit sizes. The strategy for achieving improved capital costs for smaller reactors is to take advantage of the manufacturability and modularity benefits for the advanced reactors. Future new reactor designs, per studies performed by the U.S. Department of Energy (DOE), are expected to start off having First of a Kind (FOAK) overnight capital costs ranging from \$6,000/kW$_e$[22] - \$10,000/kW$_e$[23] [29] [66] [67] with an approximate construction time for a FOAK SMR technology to be four to five years [68]. This lower value would translate to approximately \$87/MWh after the application of the 48E investment tax credit with no adders[24] which is now in place or approximately \$104/MWh with no benefit from the Inflation Reduction Act [29]. The highest anticipated capital cost of \$9,000/kW$_e$ for a FOAK

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[21] In the U.S., this function is primarily maintained by the Institute of Nuclear Power Operators (INPO), which was established directly as a result of the TMI Accident, with the World Association of Nuclear Operators (WANO) serving a similar function internationally. [395].

[22] While these values are not clearly referenced to a year for ease of future cost escalation, 2020 \$USD is a reasonable presumption based on the timing of the sourced value.

[23] This high-end \$10,000/kW$_e$ value was published in the 2020 IAEA “2020 SMR Book” for the Korea Atomic Energy Research Institute’s (KAERI) System-integrated modular advanced reactor (SMART), which listed an expected 30-40% total cost reduction for an NOAK unit.

[24] As low as \$75/MWh with both adders for siting in energy communities and for use of domestic content.

plant postulated in the DOE report would have an LCOE range of as low as \$92/MWh with use of the 48E investment tax credit with both adders or as high as \$133/MWh with no benefit from the Inflation Reduction Act. Nth-of-a-kind (NOAK) SMR deployments are predicted to achieve overnight capital costs as low as \$3600/kW$_e$. Such a capital cost would allow a levelized cost of electricity of approximately \$57/MWh with use of the Section 45Y production tax credit with both adders or as high as \$76/MWh with no benefit from the Inflation Reduction Act after the successive building of 20 sites needed to implement the necessary lessons learned to achieve the suggested reduced overnight capital (Note: this also considers a plant life of 60 years and the inclusion of the 30% tax credit from the Inflation Reduction Act (IRA)) [29]. However, in consideration of the worst-case scenario predicted by the labor environment and construction, a reasonable conservative estimate of cost for FOAK SMR technologies would be \$9,500/kW$_e$ [29]. To expect to achieve the NOAK estimations for the costs of SMR technology would not be appropriate for a FOAK implementation of any given reactor design.

Reactor specific predictions of costs for various companies' advanced reactor technologies from publicly available sources can be seen below

- Versatile, PWR-12 (FOAK): \$5,587/kW$_e$ (subject to inflation from 2011) [69]
- KEPCO, LASR (FOAK): ~\$5,800/kW$_e$ [70]
- MMNC (FOAK): ~\$6,500/kW$_e$ [70]
- Holtec, NC-SMR (FOAK): ~\$7,700/kW$_e$ [70]

One issue to note with these costs is consideration that the producer price per index in every major resource has undergone a substantial increase since 2019 [71]. With the recent inflation seen throughout the economy, information estimating the cost of SMR technology is somewhat unreliable at this time due to fluctuations with material costs and additional construction costs. This is similar to recent events with the cancellation of FOAK offshore wind projects in New Jersey, resulting from substantial increases in interest rates. As reactor designs further mature and component orders are place, cost estimates for various reactor technologies should become more refined and reliable.

1.6.b What About the Waste?

After nuclear fuel has undergone fission within a reactor, it is highly radioactive and generates decay heat. Thus, it is hot from both a thermal and radiological perspective. Due to this, it must be properly managed and handled with care, including ensuring proper shielding. There are technologically-achievable options to ultimately reduce the quantity of this waste if reprocessing/recycling were to become commercially viable in the U.S., which would require some shifts in federal policy. A significant portion of the long lived actinides associated with the spent fuel from conventional BWRs, PWRs, and other operating nuclear reactors can be re-used in fast-spectrum reactors, which would reduce the waste volume from including both actinides and fission products to primarily including only fission products. However, there will still be fission product that will remain and require permanent storage. In addition to needing a final storage location, transportation of the waste must adhere to applicable regulations, as governed by the NRC [72].

Although all nuclear waste is tracked, a permanent solution has yet to be identified to either store or recycle the fuel. The Nuclear Waste Policy Act (NWPA) of 1982 established a procedure and timetable to select sites for a geological repository to house nuclear waste. The DOE was supposed to begin receiving spent fuel from facilities beginning in 1988. Amendments to the act directed the DOE to consider Yucca Mountain as the primary site for a geologic repository and prohibited the DOE from conducting activities for a second site unless authorized by Congress [73].

Yucca Mountain was selected with insufficient local consent and thus never became fully licensed to receive spent fuel from U.S. reactors. The DOE did submit a license application to the NRC for authorization to construct Yucca Mountain in 2008 [74], which the NRC staff has reviewed, issuing five separate volumes of Safety Evaluation Reports [75]. Despite these efforts to establish a national high-level waste geologic repository, no national repository has been constructed or authorized to-date. This lack of a permanent national repository has led to the present situation with spent fuel being stored primarily on-site in casks, with the DOE having not yet started receiving commercial spent nuclear fuel. The on-going storage of this material requires security measures, which have associated costs. Within Michigan, four sites have continuing storage of spent nuclear fuel, Big Rock Point, Palisades, DC Cook, and Fermi. The total projected inventory of spent fuel to be stored at these four sites by the end of their operational lives[25] was estimated to be 58, 869, 2772, and 1372 metric tons respectively, as of the November 2021 DOE Spent Nuclear Fuel and Reprocessing Waste Inventory report [76]. Additionally, increased capacities have been engineered into the existing plants' spent fuel pools. Utilities with nuclear power plants have successfully sued the DOE for reimbursement of expenses incurred due to the DOE not yet being in position to receive spent fuel from nuclear power facilities. The firm HKA has been involved with efforts to recover $1.8 billion for different clients relating to NWPA litigation, though their listing does not mention clients within Michigan [77]. Further information regarding NWPA-related litigation issue can be found in a Congressional Research Service report [78].

1.6.c Lack of Flexible Dispatchability

Nuclear power plants in the U.S. have historically operated at a steady state level of essentially either 100% power when in service or 0% power when undergoing a scheduled refueling outage (with various equipment or environmental issues causing occasional deviations from these two levels). This historic operation of nuclear power plants in most parts of the world has caused many opponents of nuclear power to suggest that nuclear plants are incapable of flexible operation. There are limits to ramping power levels up and down, for both the secondary power generating equipment of plants and particularly for primary reactor power, to ensure that overly rapid

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[25] These estimates will need to be estimated upward in the event of additional operating license extensions being granted to any of Palisades, DC Cook Units 1 or 2, or Fermi Unit 2.

temperature changes are avoided. Additionally, with the fuel cycles of nuclear power plants, there is no economic incentive to operate at lower power levels to save fuel for later. This characteristic of nuclear fuels causes operating cycles to be determined primarily by economics rather than solely on the basis of technological capabilities [79]. In contrast to the typical operation cycles of currently-operating nuclear power plants, some newer advanced reactor technologies such as the Natrium reactor claim that ramping at 40 MW/min from to 0% to 100% capacity is achievable [80] which would imply the reactor could reach full power within less than an hour, compared to most traditional reactors which take at least 12 hours to reach full capacity [81].

1.6.d Radiation Concerns

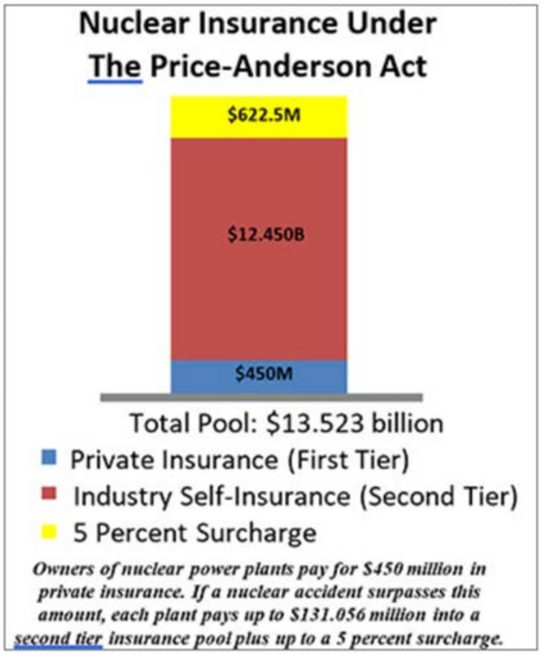
Nuclear fission results in radioactive fission products and actinides, along with the production of radioactive contamination in areas of the plant outside of the nuclear fuel itself. While radiation is well-understood by many experts, the public often does not have a great deal of familiarity with radiation and what hazard it presents. This lack of familiarity or understanding can lead to fear among portions of the population. According to the NRC, an average radiation dose to a person living within 50 miles of a nuclear power plant from the plant is about 0.01 millirem per year, which compares to average exposure of about 300 millirem per year from background sources of radiation [82]. The sources of this background radiation include cosmic radiation, naturally occurring radiation from uranium, thorium, and radium in soil, radon within the air, or internal sources of radiation such as from potassium-40 or carbon-14 [83]. The NRC has established regulations for how much radiation exposure workers at the plant are permitted to receive. These limits are tracked with dosimetry within the plant. The NRC also regulates radiation limits to members of the public from postulated releases from nuclear plants after various accident scenarios, based on rigorous safety analysis methodologies and knowledge of historic wind patterns to calculate potential plumes of releases. Conducting these analyses is a part of the process of obtaining a nuclear power plant license.

Well-known nuclear accidents at Chernobyl in Ukraine and at Fukushima-Dai'ichi in Japan resulted in substantial radioactive releases, which resulted in substantial evacuations. These accidents provide clear examples of why nuclear power plants must be designed and operated with nuclear safety always remaining the paramount consideration.

The most well-known nuclear power accident that occurred in the U.S. was the partial meltdown of the Three Mile Island Unit 2 reactor (TMI-2), in Pennsylvania. Following the meltdown, there was a small release of radioactive gasses. The radiation dose to the public for the approximately two million people around the plant has been estimated to be an average of 1 millirem above background doses, as compared to that region's average background doses. No known adverse health impacts were attributable to the releases from TMI-2 [84].

1.6.e Implied Subsidy from Price-Anderson Act

Critics of nuclear power have suggested that the PAA presents an unfair subsidy for nuclear power, in that it artificially lowers the amount of insurance coverage that a plant must carry along with making capital investment in nuclear power more attractive by limiting the potential liability for a nuclear power plant operator [85]. The PAA was enacted in 1957 establishing a system of financial protection that would serve to benefit both 1) persons who may be liable for a nuclear incident and 2) persons who may be injured by a nuclear incident. Financial protection is in the form of indemnification by the DOE. The indemnification to persons liable for a nuclear incident, coupled with the special administrative and judicial requirements in the PAA, provides assurance that persons who may be injured by a nuclear incident receive prompt compensation for damage to the person or property. The pool of funds for the coverage amount from the PAA that would serve as secondary coverage (second tier pool) for any liability amounts exceeding the maximum from primary coverage (first tier pool) would be collected equally across the U.S. reactor operators [86]. Any liability amounts exceeding the combined primary and secondary coverage amounts from PAA (along with a 5% surcharge) from any hypothetical accident might rightly be classified as a subsidy. Figure 4 below shows an illustration of insurance coverage funded by the commercial nuclear industry from 2022, sourced from the NRC website’s description of nuclear insurance tiers [87].



Owners of nuclear power plants pay for $450 million in private insurance. If a nuclear accident surpasses this amount, each plant pays up to $131.056 million into a second tier insurance pool plus up to a 5 percent surcharge.

Figure 4 Insurance Tiers for Nuclear Power Plants in the U.S. [87].

1.6.f Fermi I Discussion (We Almost Lost Detroit)

Fermi 1 was a fast breeder reactor[26], cooled by liquid sodium located in Monroe County, Michigan. The reactor reached initial criticality in 1963. During a 1966 ramp up of power in the reactor, a

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[26] A fast breeder reactor can create new fissile fuel (primarily Pu-239) from fertile U-238.

zirconium plate blocked flow to some fuel subassemblies, and potential instrument indications at low power levels were ignored, which ultimately resulted in a partial meltdown[27], with two subassemblies starting to melt [88]. Prior to TMI-2's meltdown, the Fermi 1 accident was the worst commercial nuclear power plant accident in the U.S. [89] While there were no injuries or hazardous radioactive releases as a result of this incident, it did cause the reactor to be shut down for repairs for almost four years. The Fermi 1 meltdown was almost identical to the Sodium Reactor Experiment in Santa Susana, CA in 1959 [90] [91]. While lessons learned from the Sodium Reactor Experiment incident did not prevent the incident at Fermi 1, subsequent to the TMI meltdown the industry began to institute a formal process of sharing and implementing lessons learned from operating experience as a regular course of business. These efforts included the creation of the Institute of Nuclear Power Operations. Following repairs, Fermi 1 re-entered operation until 1972, when the decision was made to decommission the plant. The partial meltdown incident inspired a book titled *We Almost Lost Detroit,* along with a song of the same name.

1.6.g The Need for Emergency Planning Zones

Current commercial nuclear power plants safety planning goes beyond the footprint of the power plant. This requires close coordination[28] across stakeholder groups, which does require time and effort expenditures. Two EPZs are required to be approved by the NRC. One is a ten mile EPZ that protects communities in the event of an accident, the other is a 50-mile zone that would monitor food products, livestock, and water to protect the public from radiological exposure [92]. These plans constantly evolve and require a degree of preparedness, which incur opportunity costs by taking away from time for conducting other activities. Current regulations require SMRs to follow the same guidance. However, draft rule 10CFR50.160 would add provisions for SMRs and nonpower production facilities. The updated rule will include the ability to use a performance-based[29] emergency planning framework and a scalable approach for determining the size of plume exposure [93]. While the new rule should greatly shrink the size of a necessary EPZ, it will not eliminate the need for emergency planning. The design goal of current SMR and microreactor vendors is to achieve an EPZ size considerably smaller than the 10-mile radius that existing reactors have use, with the zone preferably being limited to the site boundary. Analyses have not all been completed and made their way through the NRC licensing processes for most SMR and microreactor designs to achieve a site boundary EPZ. The current prospects, however, indicate that many selected SMR and microreactor locations will undergo sufficient analysis to achieve a desired small EPZ size

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[27] A meltdown is when solid nuclear fuel overheats and becomes a liquid. For this occurrence at Fermi 1, only two subassemblies experienced melting..

[28] This coordination also provides benefits by enhancing stakeholder familiarity with nuclear plant sites, so it is not entirely a disadvantage.

[29] In this instance, performance-based refers to being able to complete analyses specific to a design and location to inform the planning zone sizing, rather than being required to adhere to a one-size-fits all planning zone size.

1.6.h Nuclear Weapons and Proliferation Concerns

Fission can produce useful energy, but it can also produce extremely powerful bombs. Due to this, substantial measures are required to ensure that fissile material cannot be diverted from nuclear power plants for use in weapons. These measures add costs to nuclear energy production that cannot be fully eliminated. The nuclear weapons program in India did arise out of what was initially a nuclear power program, which shows that proliferation concerns for not-yet-nuclear nation states are fully legitimate [94]. A point of particular interest relating to the topic of nuclear proliferation are reactor designs that would primarily breed plutonium (Pu) fuel from U-238. While the mix of reactor grade Pu from conventional LWR operation is not entirely fissile material and thus poor quality for making a high-yield nuclear bomb, safeguards must remain in place to ensure the Pu is not diverted to any potential weapons purposes. Additional proliferation concerns arise related to higher enrichment levels of uranium, which get increasingly closer to highly enriched uranium[30] levels which could be useful for making bombs. Reactor types that could extract usable Pu or U-233 following some irradiation of fertile U-238 or Th-232 would require particularly robust safeguards to alleviate proliferation concerns. While these concerns are valid, controls on material accountability[31] could be put in place to alleviate the possibilities of material diversion. The current fleet of solid-fueled PWR and BWR reactors in Michigan and many of the SMR / GEN IV advanced reactors would not be conducive to production of weapons materials due to the combination of having a low fissile content, being highly radioactive following irradiation in a reactor, and being in a solid form with the remaining fissile material being difficult to access.

1.6.i Unfulfilled Promises

In the early stages of nuclear energy development (1954), Lewis Straus, then the Chairman of the Atomic Energy Commission (AEC)[32], was making an address to science writers [95]. Within his address, he uttered the statement “It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter.” While he may have been referring to nuclear fusion, the fuel costs even of nuclear fission plants at times have seemed like the energy could be almost too cheap to meter. Unfortunately, with all the other necessary costs of operating a nuclear fission-powered plant, nuclear power has not yet reached or even approached being “too cheap to meter.” Some of the earlier nuclear plants that were completed in the U.S., the majority of the buildout of the French plants, and many plants in Asia have been constructed at very affordable capital costs. However, many contrary examples of extreme cost overruns also exist, which causes a wide range of uncertainty regarding the true expected cost of future nuclear power plants. Additionally, numerous nuclear construction projects were started but abandoned prior to

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[30] Highly Enriched Uranium is defined internationally as anything enriched to a concentration of 20% U-235 or higher. Weapons grade Highly Enriched Uranium is generally considered to be the >90% enriched range [383].

[31] In the U.S., Materials Control and Accountability is required by NRC regulations [397].

[32] The Atomic Energy Commission existed from 1946 to 1975, serving both promotional and regulatory functions for nuclear/atomic technologies, until being broken apart by the Energy Reorganization Act of 1974 into the separate functions of the Nuclear Regulatory Commission and the Energy Research and Development Administration, which subsequently folded into the Department of Energy with the 1977 Department of Energy Organization Act.

completion within the U.S. The Midland Cogeneration Venture was originally planned to be nuclear-powered prior to the nuclear construction being halted in the mid-1980s, officially announced on July 16, 1984 [96]. This halting was due to the combination of there being issues with the plant foundation and retrofits due to the Three Mile Island incident causing delays and cost overruns for the project. At the time of cancellation, the plant was 13 years behind the original planned schedule. The issuance of interim standards relating to emergency core cooling systems necessitated changes from the design that had been originally planned. Subsequent to the cancellation of being completed as a nuclear-fueled power and steam plant, the plant design was changed to utilize natural gas as its fuel source. Conversion of the plant began in 1986 and the plant entered operation in 1990, remaining in operation to the present [97].

1.6.j Enrichment Requirements and Associated Energy Use

Reactors other than CANDUs require uranium enrichment of their fuel. During the Cold War years, the U.S. maintained an ample uranium enrichment capacity. In more recent years, however, domestic uranium enrichment has been a mostly uneconomic proposition and the domestic enrichment capability has decreased substantially. Due to the economics, an over-reliance on importing enrichment services has developed. Part of this is a result of the success of the "Megatons to Megawatts" program of down-blending highly enriched uranium that had previously been reserved for nuclear warheads. Plans to utilize foreign enrichment services, particularly for procuring high assay low enriched uranium (HALEU[33]) from Russian-based Tenex, have dramatically changed subsequent to the February 2022 Russian invasion of Ukraine. Efforts are now underway and have received a new sense of urgency to develop domestic enrichment capabilities up to HALEU levels. As of 2022, no U.S.-based HALEU production was in place. A small quantity of HALEU (20 kg) has now been produced prior to the end of 2023 as part of a DOE-sponsored HALEU availability program [98]. Substantially greater quantities of HALEU are needed to fuel the initial TerraPower and X-Energy ARDP-funded reactors currently under development. Lack of availability of HALEU has already been cited as a primary reason for a delay for the TerraPower Natrium Demonstration project [99]. Enrichment of uranium does require energy input, but the energy input for enrichment has been substantially decreased by the use of centrifuge technology rather than gaseous diffusion, to only 50-60 kW-hr/SWU[34] from ~2400 kW-hr/SWU for gaseous diffusion [100]. Further improvements in the energy efficiency of enrichment are possible if laser isotope separation develops commercially, but laser isotope separation technology is closely protected due to nuclear weapons proliferation concerns.

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[33] HALEU is uranium enriched to between 10% and ~19.75% U-235, remaining below the internationally-recognized 20% limit above which uranium is classified as "highly" enriched uranium, or HEU. Enrichment levels between 5% and 10% are often referred to as LEU+.

[34] SWU = separative work unit, which is the primary unit of measurement used to quantify uranium enrichment processes. Uranium enrichment services are sold by the SWU.

1.6.k Requires Well-Trained, Local Workforces

To operate and maintain nuclear power plants requires a well-trained staff of operators and maintenance workers of various trades. To maintain an NRC operating license as a reactor operator operator requires federally mandated training on a regular basis as described in 10 CFR 55.53, after an initial training regimen that typically lasts 18-24 months [101]. The costs for such training are not trivial but are a necessary part of operating nuclear power facilities. Additionally, operators must be on-site, limiting any potential savings from extending the potential labor pool to further geographic locations. While many new nuclear development efforts have postulated future use of remote operators/operations, such capabilities have yet to be demonstrated and may be difficult to achieve under present NRC regulations.

2. MICHIGAN RESOURCES, EXPERTISE, AND ECONOMIC IMPACTS

2.1 Use of Michigan Workers, Workforce Education, Training, and Development

Detailed analysis relating to the use of Michigan workers and workforce education, training, and development has been conducted as part of this study and is included in Section 2 of Appendix 1. The high-level results indicate that substantial direct job creation and indirect and induced economic benefits would result from new nuclear being deployed within Michigan. The types and number of jobs for Michigan-based workers and estimated wages from these workers has been included in the analyses for estimating the economic benefit from building a hypothetical new nuclear plant within Michigan. The presence of the University of Michigan’s nuclear engineering program and the Monroe County Community College associate of applied science with specialization in nuclear engineering technology program are highlighted as being positives in regard to meeting the employment training needs for the construction of a hypothetical future nuclear plant within Michigan.

2.2 Use of Michigan Products and Supply Chain Development

A listing of the potential use of Michigan-sourced products as part of a new nuclear power project within the state is included within Section 2 of Appendix 1. A number of component types that would be utilized in a nuclear power plant installation could be sourced from Michigan. A listing of components used as part of the completion of the new AP1000 Vogtle Units 3 and 4 sourced from Michigan companies is included as Table 2.7 within Appendix 1. Nine different components with manufacturing sites in Michigan are included in this table. Further components could also be sourced from Michigan as the supply chains for new reactor designs continue to develop. Considering the timeframes required for nuclear project developments, which are outlined in further detail in Section 5 of the main body and in Section 2 of Appendix 1, there is sufficient time that the use of Michigan-sourced products could be increased beyond current capabilities with further development by companies located within Michigan.

2.3 Economic Impact to the People of Michigan, Businesses of Michigan, and State of Michigan

Detailed economic analyses are included within Appendix 1. Two separate hypothetical new nuclear plant locations were modeled to estimate overall economic impacts if a plant were to be build within either of the modeled locations. The results of the analysis indicate substantial economic benefits to workers within the state of Michigan from direct jobs supporting the plant, indirect spending generated from the direct workers, and induced economic activity resulting from the direct jobs. The total lifetime value added was estimated to be $3.6 billion for the Ottawa County location modeled and $3.7 billion for the Monroe County location modeled. These economic impacts were modeled for both the construction phase of a plant, as well as for the operational phase, with the impacts adjusted to provide an estimate in present dollar amounts. The results of this analysis align with the results from a recent economic study of the impacts of the shutdown of Palisades [102]. For further details of the economic analysis, see Section 4 of Appendix 1.

3. NUCLEAR TECHNOLOGIES EVALUATION

3.1 Evaluation of Current Nuclear Technology and Designs

The goal of this section is to discuss the operating and recently decommissioned nuclear power plants in the state of Michigan while highlighting operational factors of relevant plants. Furthermore, operational capacities and licensing periods for relevant plants will be discussed. Palisades nuclear power plant has been included in this discussion as it shut down to begin the decommissioning process in May of 2022, but is now undergoing evaluations relating to the potential to return to operation [103]. Michigan currently has two operating nuclear power plants. The Enrico Fermi Nuclear Generating Station Unit 2 (Fermi 2) in Monroe County and the two-unit (DC Cook) Plant in Bridgman. These three units are all “gigawatt-scale” and are classified as LWRs, which generally achieve a thermal efficiency of 33%. Thermal efficiency is the electrical power generated divided by core thermal power. Nuclear power plants are regulated by the NRC on the basis of a licensed core thermal power limit, stemming from numerous safety analyses validating the systems’ capabilities under various conditions. LWRs utilize uranium dioxide fuel, enriched to roughly 3-5% U-235, which is classified as low enriched uranium. Fuel enhancements have occurred throughout the operating history of LWR power plants and the accident tolerant fuels programs underway (supported by the DOE and NRC) show promising continued enhancement opportunities for currently-operating plants via lengthened fuel cycles and present potential for increases in plant operating limits (subject to future NRC approval of license amendments) [104] [105]. Accident tolerant fuels, once licensed, would improve plant efficiencies and provide small incremental improvements to electricity output from existing plants, including those in Michigan.

Michigan is also home to three former nuclear power stations; the decommissioned medical isotope facility Big Rock Point Nuclear Power Plant in Charlevoix, the decommissioned fast breeder prototype Fermi 1 in Monroe, and the recently shut down single unit PWR Palisades Nuclear Power Plant in Covert. Big Rock Point and Palisades nuclear power plants were both decommissioned for economic reasons and Fermi 1 was decommissioned due operational issues over the 9-year operational period.

Table 1 The licensed operational conditions of plants that are/were operating in Michigan.

Plant	**Licensed Power (per Operating Licenses)**	**Net Summer Capacity (MW_e)** [106]	**2019-2021 Capacity Factor** [106]	**Fuel Cycle Duration**[35]
Fermi 2	3,486 MW_{th} [107]	1,141 MW_e	84.4%	~24 months
DC Cook 1	3,304 MW_{th} [108]	1,009 MW_e	93.3%	~18 months
DC Cook 2	3,468 MW_{th} [109]	1,168 MW_e	89.9%	~18 months
Palisades[36]	2,565.4 MW_{th} [110]	796 MW_e	97.0%	~18 months

3.1.a Enrico Fermi Nuclear Generating Station

Fermi is owned and operated by DTE Electric Company (DTE), formerly The Detroit Edison Electric Company. DTE is a diversified energy company that develops and manages energy companies nationwide, and with the inclusion of its operating units it serves electricity to approximately 2.3 million Michigan residents. Additionally, they also provide natural gas services to approximately 1.3 million Michigan resident. The original plant operating license was issued on July 15, 1985, for a 40-year operating period. Fermi 2 is a boiling water reactor producing 1,170 MW_e (licensed for 3,486 MW_{th}) [107]. A simplified, general description of a BWR is included in Section 1.4. The reactor was designed by General Electric and is a BWR 4 Class, with a pressure-suppression Mark 1 design. The plant is located in Monroe County, Michigan, on the western shore of Lake Huron, approximately 30 miles southwest of downtown Detroit, Michigan. Fermi applied for and was granted a license renewal by the NRC to operate the plant until March 20, 2045. If a subsequent license renewal is pursued by DTE and granted by the NRC, the license will extend to 2065. Thermal power limits at Fermi have been increased several times during its operating history which has increased the plant‘s electric output to the grid. These thermal limit increases required both physical upgrades to the plant and changes to the plant’s design basis[37]. Further information will be provided in Section 3.3.a.

3.1.b Donald C. Cook Nuclear Plant

Indiana Michigan Power Company (I&M), the licensee for DC Cook, is a wholly-owned subsidiary of American Electric Power (AEP), a public utility holding company. I&M is a public utility engaged in the generation, purchase, sale, transmission, and distribution of electric power to approximately

567,000 retail customers in its service territory in northern and eastern Indiana, and a portion of southwestern Michigan. I&M also sells wholesale power to municipalities and electric cooperatives.

The DC Cook site encompasses approximately 650 acres [26]. The site is located along the eastern shore of Lake Michigan in Lake Charter Township, Berrien County, Michigan; about 11 miles southwest of Benton Harbor, Michigan. The nearest town is Bridgman, Michigan, which is approximately two miles south of the plant site. Each unit is a PWR nuclear steam supply system (NSSS) furnished by Westinghouse Electric Corporation. The Unit 1 reactor produces a power output of 1044 MW_e (licensed for 3304 MW_{th}) [108], and the Unit 2 reactor is licensed for a power output of 1117 MW_e (licensed for 3468 MW_{th}) [109]. Unit 1 was initially licensed to operate on October 25, 1974, with an initial license period of 40 years, allowing operation until October 25, 2014 and has entered a period of extended operation which expires on October 25, 2034. Unit 2 was initially licensed to operate on December 23, 1977, with an initial license period of 40 years, allowing operation until December 23, 2017 and has entered a period of extended operation which on December 23, 2037. Further information will be provided in Section 3.3.b.

3.1.c Palisades Nuclear Plant

Originally, Palisades was owned by CMS Energy Corporation and operated by the Nuclear Management Company until 2007 when Entergy Nuclear became the owner and operator of the facility. Although Palisades received an extended operating license through March 2031, the plant was sold to Holtec Decommissioning International in 2022 with the intention of starting plant decommissioning. Holtec has since changed their plans and is currently pursuing funding to support a restart effort and necessary regulatory approval for re-instatement of an operating license. Palisades Nuclear Plant (Palisades) is located approximately five miles south of South Haven, MI. Palisades began power operations in 1971 and was defueled in 2022. Palisades is a Combustion Engineering design, and produced a power output of 845 MW_e (licensed 2565.4 MW_{th}) [110].

At the time that Palisades was built, the general design criteria for commercial nuclear power plants were in a drafted form. In 1977, the NRC initiated the Systematic Evaluation Program to review the designs of older operating plants. Palisades was one plant selected for the systematic evaluation program reviews. Based on the systematic evaluation program reviews, various topics such as structural integrity of the containment building and steam lines were closed based on the adequacy of the existing system designs or, in some cases, after the licensees made procedural or design changes. Single failure criteria adequacy (electrical and fluid systems) was evaluated in several topics and no requirement to address passive failures on a plantwide system level basis was backfit by the NRC or were committed to by Palisades. Specific issues were addressed on a

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[35] Fuel cycle duration information is not always readily available, due to commercial concerns.

[36] The most recent values of power, during operation.

[37] A nuclear plant's design basis includes analyses that demonstrate the margins of safety for the plant.

case-by-case basis. The systematic evaluation program topic evaluations and integrated plant safety assessment documents confirmed that the level of safety provided by the Palisades design was adequate even though the design differed from later design requirements embodied in the general design criteria and other documents. Further information will be provided in Section 3.3.c.

3.2 Decommissioning

The decommissioning costs for nuclear power plants can vary depending on factors such as plant size, design, condition, and the specific decommissioning strategy chosen. Decommissioning funding estimates are required to be evaluated and reported in accordance with 10 CFR 50.75, *Reporting and recordkeeping for decommissioning planning* [111]. These sections establish requirements for how a licensee will provide reasonable assurance that funds will be available for the decommissioning process as well as address the establishment of funds or other financial mechanisms to ensure adequate resources are available. It should be noted that the only reactor undergoing decommissioning currently is Palisades. The licensee is required at least once every two years to report to the NRC the status of its decommissioning funding for each reactor or part of a reactor that it owns. Once the nuclear power plant is within five years of the projected end of its operation, it will annually submit to the NRC a status of its decommissioning funding. It is important to note that specific decommissioning funding requirements can also be outlined in license conditions or agreements between regulatory authorities and licensees. Licensees typically accumulate funds over time through trust fund investments. The minimum amount of funds considered adequate is established by the NRC’s decommissioning funding formula.

Once the plant is no longer operational, the licensee transitions to decommissioning in accordance with 10 CFR 50.82, *Termination of license* [112]. As one of the first activities, the licensee must submit a post-shutdown decommissioning activities report to the NRC. This report is offered for public comment and provides a description of the planned decommissioning activities, a schedule for accomplishing them, and a site-specific decommissioning cost estimate (DCE). Initially, the owner can use up to 3% of its set-aside funds for decommissioning planning. The remainder becomes available 90 days after submittal of the planning report unless the NRC staff has raised objections.

Two years prior to license termination, the owner is required to submit a license termination plan. The plan addresses many attributes, but for the purpose of this report it provides the owners with updated estimates of the remaining decommissioning costs. The plan must address financial assurance needed to comply with the requirements for license termination. Until the licensee has completed activities that permit termination of its license, the licensee must annually submit to the NRC, by March 31st, a financial assurance status report.

The most important milestone of decommissioning is the removal and disposal of the contaminated systems, structures, and components so that ongoing monitoring can be discontinued. Congress passed the Nuclear Waste Policy Act in 1982, assigning the federal government’s long-standing responsibility for disposal of the spent nuclear fuel created by the commercial nuclear generating plants to the DOE. Since the original legislation, the DOE has announced several delays in the program schedule and has failed to accept any spent fuel or high-level waste, as required by the Nuclear Waste Policy Act. Due to the lack of a DOE spent fuel repository for commercial fuel, spent fuel is stored onsite in an independent spent fuel storage installation (ISFSI) until such time that it can be transferred to a DOE facility to terminate the license.

The NRC requires that licensees establish a program to manage and provide funding for the management of all irradiated fuel at the reactor until title of the fuel is transferred to the DOE. These costs are not included in the NRC's decommissioning funding formula; therefore, additional funding may be required to manage and subsequently decommission these storage facilities. Due to additional funding required to manage spent fuel, the funding reported as total decommissioning costs in the Decommissioning Funding Status Report provided by the licensee may not be a sufficient total if the minimum amount of funds considered was established by the NRC's decommissioning funding formula. In Figure 5 the generic steps for decommissioning a nuclear power plant have been provided.

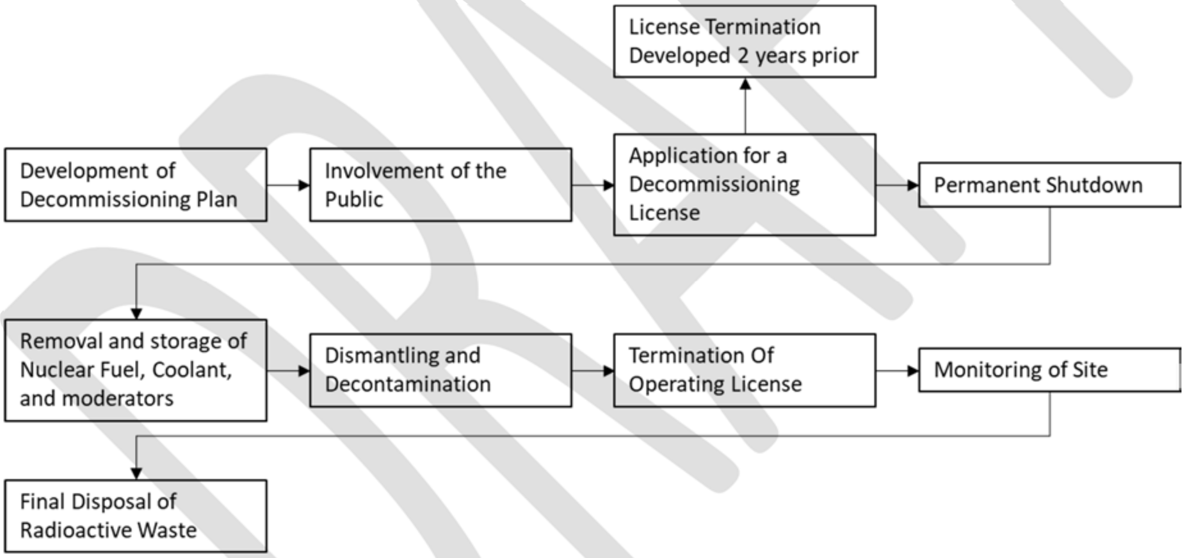

Figure 5 A flow diagram representing the general steps taken for decommissioning a nuclear power plant.

Based on the requirements above, estimated decommissioning costs can be obtained from public sources and are readily available for each nuclear power plant within Michigan, whether operating or decommissioning. It is important to note, however, that decommissioning costs can evolve over time due to various factors such as inflation, regulatory requirements, and site-specific conditions. The following estimated decommissioning costs for nuclear power plants in Michigan, both in operational and decommissioning status, are reported in 2022 dollars:

Table 2 Cost analysis of the decommissioning cost and the respective allocated fund.

Site and [Reference]	Operator	Total Estimated Decommissioning Costs	Decommissioning Fund Balance
Palisades Nuclear Plant- (Non-Operational) [113]	Holtec Palisades, LLC	$644M [114]	$547M
Big Rock Point ISFSI- (Decommissioned) [113]	Holtec Palisades, LLC	$2.4M [115]	$2.8M
Donald C. Cook Nuclear Plant Unit 1- (Operating) [116]	Indiana Michigan Power Company	$575M [117]	$883M
Donald C. Cook Nuclear Plant Unit 2- (Operating) [116]	Indiana Michigan Power Company	$580M [117]	$803M
Enrico Fermi Nuclear Power Plant, Unit 1- (Decommissioned) [118]	DTE Electric Company	$24M [119]	$3M [119]
Enrico Fermi Nuclear Power Plant, Unit 2- (Operating) [120]	DTE Electric Company	$1,349M	$1,692M

3.3 Environmental Review of Existing Nuclear Facilities

The applicable federal regulations for siting a nuclear power plant are described in Regulatory Guide 4.7 (RG 4.7) and are broadly summarized as:

- Title 10, Part 50, of the Code of Federal Regulations (10 CFR Part 50), "Domestic Licensing of Production and Utilization Facilities," requires that structures important to safety be designed to withstand the effects of expected natural phenomena during accident conditions without a loss of capability to perform their safety functions.
- The National Environmental Policy Act of 1969 (NEPA) (42 U.S.C. 4321 et seq) and the Council on Environmental Quality's regulations (40 CFR Parts 1500 – 1508)

require detailed environmental statements on proposed major federal actions that will significantly affect the quality of the human environment.
- 10 CFR Part 51, "Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions," provides the regulations associated with the preparation of EIS pursuant to NEPA as well as the Clean Water Act (CWA).
- 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," provides regulations on the issuance of early site permits and combined licenses for nuclear power facilities.
- 10 CFR Part 100, "Reactor Site Criteria" specifies the attributes required to be considered in determining a site to be acceptable for a nuclear power reactor.

The regulations above provide a framework for the site selection process. When applying for a license to operate a nuclear reactor, an environmental report is required to be submitted as part of the application. Following the site selection process, detailed in RG 4.7, will ensure that the environmental report generated meets the requirements of Regulatory Guide 4.2 "Preparation of Environmental Reports for Nuclear Power Stations," in accordance with the guidance of NUREG-1555 "Standard Review Plans for Environmental Reviews for Nuclear Power It is recognized that during early site selection efforts, limited information is available. During early efforts to define the region of interest, candidate areas, and potential sites with a low level of detail will need to be evaluated. Early siting efforts generate documentation to show the regulator that the applicant considered locations with environmental diversity and viable alternative sites were investigated. Following the identification of potential sites, more detailed analysis is developed to identify the candidate sites and ultimately, the proposed site.

The existing operating nuclear facilities in the State of Michigan are Fermi 2 and DC Cook. The third facility, Palisades was recently shut down. Palisades was included in this evaluation as the owner is seeking to restart power generation operations. In order to characterize the environmental impacts of existing nuclear plants in Michigan, a review of publicly available environmental documents was performed. Such documents included environmental reports, environmental impact statement (EIS), and supplemental EIS (SEIS) which provide detailed assessments of the environment at the plants as well as the plant's potential impacts on the environment.

The NRC considers as part of their licensing approval process 13 environmental topic areas, which are:

1. Land Use
2. Visual Resources
3. Meteorology
4. Air Quality
5. Noise

6. Geologic Environment
7. Water Resources
8. Ecological Resources
9. Historic & Cultural Resources
10. Socioeconomics
11. Human Health
12. Environmental Justice
13. Waste Management

The NRC categorizes environmental issues for nuclear licensing actions as either Category 1 or Category 2. Category 1 impacts are issues that do not require a plant-specific analysis unless there is new and significant information that needs to be considered. Category 2 issues require plant-specific environmental assessments. The NRC's environmental impact standard considers Council on Environmental Quality terminology, including revisions in Part 1501—National Environmental Policy Act (NEPA) and Agency Planning (40 CFR 1501); and for Category 2 or new and significant information an impact finding significance level rating of small, moderate, or large.

To meet the needs of this study under Public Act 166 of 2022 and Public Act 218 of 2022, information was reviewed for Fermi 2, DC Cook, and Palisades and primarily focused on the physical setting including geologic setting, water resources, ecology, air quality, human health, and waste management, followed by an environmental review which considers the NRC's evaluation of Category 1 and Category 2 environmental issues and recent reports on radiological effluent releases. Transmission line impacts to ecology, air quality, and human health are also considered. In addition, climate change and electromagnetic field (EMF) considerations are also addressed in the NRC's process for licensing actions at all plants, as discussed in Section 4.2.d and 4.2.e respectively.

3.3.a Enrico Fermi Nuclear Generating Station Unit 2

The environmental reports reviewed for Fermi 2, upon which the below discussion is based, were:

- Generic Environmental Impact Statement (GEIS) for License Renewal of Nuclear Plants , Supplement 56 Regarding Fermi Nuclear Power Plant, Final Report, Chapters 1-8, NUREG-1437, Volume 1 September 2016 [121].
- Fermi 2 License Renewal Application Appendix D Technical Specification Changes and Appendix E Environmental Report. April 24, 2014. Accession Nos. ML14121A538, ML14121A539, and ML14121A540 [122].

3.3.a.1 Environmental Setting, Location & Features

The Fermi 2 site is located on the western shore of Lake Erie in Monroe County, oriented about 8 miles east-northeast of Monroe, 28 miles south-southwest of Detroit and 26 miles northeast of Toledo, Ohio [121]. Monroe County designated the land as "industrial" and zoned agricultural and "public service" by Frenchtown Township. Land in the vicinity of the site is primarily rural and both agencies project that industrial and utility uses are anticipated to continue [122].

The Fermi site is approximately 1,260 acres: 212 acres account for the developed areas including both Fermi 1 (decommissioned) and 2 and their associated support facilities; 744 acres are vegetated or woody wetlands due to flooding and open water; 168 acres are grassland, mostly shrubland and thicket. Approximately 650 acres is designated Detroit River International Wildlife Refuge Boundary, managed by the operator and the U.S. Fish and Wildlife Service [122]. Some of the wetlands in coastal areas, including those on the Fermi site, are further protected under Act 451, NREPA, Part 323, Shorelands Protection and Management [121].

Quarry lakes are located in the western portion of the site and include two adjacent quarries that were previously used to provide construction materials for Fermi 2 [122].

The site owner controls 99.93% of the mineral rights within the Fermi property, including all mineral rights within the exclusion area boundary. A third party, the Michigan Department of Natural Resources, owns 0.88 acres of mineral rights in the far southeastern portion of the Fermi site. There are no activities at the Fermi site or adjacent areas that involve exploration or otherwise extracting minerals. The geological character of the subsurface and land use in the vicinity indicate that commercial mineral production appears unlikely in the foreseeable future [121].

Lake Erie has a surface area of 9,910 square miles and is the 12th largest freshwater lake on Earth. [121] Lake Erie is the shallowest, warmest, and most productive of the Great Lakes due to three basins that provide a variety of offshore habitats and coastal wetlands that serve as nursery habitat for fish and waterfowl. [123]. Plant cooling water is withdrawn from Lake Erie with a maximum (hypothetical) surface water withdrawal rate of 53,500 gpm and average withdrawal rate of 31,000 gpm [121].

3.3.a.2 Vicinity & Region

The 2014 ER summarized the region within the emergency planning zone 50-mile radius centered on the Fermi 2 site as including portions of the following counties within Michigan, Ohio, and Ontario, Canada:

- Nine Michigan counties: Jackson, Lenawee, Livingston, Macomb, Monroe, Oakland, St. Clair, Washtenaw, and Wayne (Wayne County also falls within the 6-mile radius)
- Eight Ohio counties: Erie, Fulton, Henry, Lucas, Ottawa, Sandusky, Seneca, and Wood
- Ontario, Canada

In 2010, Monroe County had a population of 152,021 people. Neighboring Wayne County, Michigan, which includes a significant portion of metropolitan Detroit, had a population of 1,820,584 in 2010. Lucas County, Ohio, to the south of the plant had a population of 441,815 in 2010. In 2010, Frenchtown Township had a population of 20,428. The nearest residence is approximately 0.72 miles west-northwest [122].

The Canadian province of Ontario falls within the 50-mile radius and had a population of 12,851,821 in 2011 [122].

The region has a highly developed roadway network. Interstate 75 (I-75), which extends through Monroe County and Frenchtown Charter Township, is situated two miles west of the Fermi site and provides access from the Fermi site north to Detroit and south to Toledo. Interstate 275 splits from 1-75 north of the Fermi site and continues in a northwesterly direction, providing a western bypass around the Detroit metropolitan area and access to Detroit Metropolitan Wayne County Airport, western Wayne County, and Oakland County. It connects to Interstate 94 and Interstate 96, which are the primary east-west interstate highways in Michigan [122].

There are three major railway systems that provide service near the site: Canadian National Railway, CSX Transportation, Inc., and Norfolk Southern Corporation. There is a rail spur from the Canadian National Railway main line that extends into the Fermi site parallel to Enrico Fermi Drive. This rail spur allows large and heavy equipment to be transported to the plant [122].

Two natural gas pipelines run roughly southwest to northeast, about ten miles to the west of Fermi. Barges, freighters, and bulk cargo ships use Lake Erie with most of the barge traffic occurring to and from the ports of Toledo, Detroit, and Monroe, which are part of the Great Lakes-St. Lawrence Seaway system that connects shipments from the Atlantic Ocean to the American Midwest [122].

There are two private heliports, three private airfields, and three general aviation airports open to the public within ten miles of Fermi. The Detroit Metropolitan Wayne County Airport, a full-service commercial airport, is approximately 18 miles north-northwest of the plant [122].

Regarding cultural resources, Fermi 2 and the surrounding region show evidence of both prehistoric and historic occupation and/or settlement by Native Americans and Euroamericans that has continued through to the present. Archaeological records suggest that the area has had the potential for occupation from the Paleo-Indian Period, the Archaic Period, and the Woodland Period. Based upon surveys, a total of 17 historic and archaeological sites were identified at the Fermi site. One of these, Fermi 1, is a National Register of Historic Places eligible site[38]. The other archaeological sites have either been determined by the Michigan State Historic Preservation Officer as ineligible or have been recommended not eligible for listing on the National Register of Historic Places. The Monroe County Comprehensive Plan anticipates that the County will experience an 8% increase in population over the next 20 years. The County plans to manage its land resources in a manner that will discourage sprawl and encourage future development to occur in and around existing developed areas so that farmland, open spaces, and natural and

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[38] The National Register of Historic Places is the official list of the Nation's historic places worthy of preservation. Authorized by the National Historic Preservation Act of 1966, the National Park Service's National Register of Historic Places is part of a national program to coordinate and support public and private efforts to identify, evaluate, and protect America's historic and archeological resources. To be considered eligible, a property must meet the **National Register Criteria for Evaluation**. This involves examining the property's age (50 years or older), integrity (look the way it did in the past) and significance (was it associated with events, activities or developments in the past). [384, 385]

cultural resources are preserved. There are stipulations contained in the Memorandum of Agreement between the NRC, Michigan State Historic Preservation Office, and Fermi 2; the Michigan State Historic Preservation Office confirmed that all requirements of the agreement have been met. The NRC concluded that no historic properties would be adversely affected by the license renewal decision [121].

3.3.a.3 Site Geologic Setting

The bedrock strata in the area ranges in age from Silurian to Precambrian. The estimated thicknesses of these deeper units are based on logs of boreholes drilled in the general area and on interpretation of regional structural geologic maps. Unconsolidated material consisting of plant fill, lake, and glacial deposits overlies the Bass Island Group. Dolomite of the Bass Islands Group forms the uppermost bedrock stratum at the site and overlies the Salina Group. The maximum thickness of Salina Group strata penetrated during drilling was 354 feet. None of the borings passed through the Salina Group into lower strata. Some brecciation was noted at the Bass Islands-Salina contact. Soils within the site boundary are loam to silty clay loams, with some beach sands located along the lake shore and stream channels that poorly drain [122].

3.3.a.4 Water Resources

In addition to Lake Erie, there are several other bodies of water, including Swan Creek and the Huron River to the north and Stony Creek to the south. Stony Point is a landform projecting into Lake Erie to the south of the site [122].

The site drains to Lake Erie to the east and Swan Creek to the north through the North Lagoon. The North Lagoon and South Lagoon are connected to Lake Erie through direct contiguous waterways. There are two manmade canals on the western side of the Fermi site. The North Canal receives stormwater, other effluents, and flows to the North Lagoon [121].

The South Canal (also known as the discharge canal) flows to the South Lagoon. Nearby wetlands are hydraulically connected to the canals through culverts, except for a small pond between the lagoons. The wetlands, canals, and lagoons are all hydraulically connected to the western basin of Lake Erie and subject to lake level changes and weather conditions. In addition, there are two quarry lakes and other manmade impoundments. Three impoundments receive various discharges including cooling tower blowdown, wastewater, stormwater, and other effluents before being discharged through the National Pollutant Discharge Elimination System (NPDES) permitted outfalls. Sanitary waste is processed through an off-site, publicly owned treatment facility [121].

Other streams near the Fermi site include Stony Creek, located approximately three miles southwest of the site; the River Raisin, located about six miles southwest of the site; the Huron River, located six miles to the north of the site; and the Detroit River, located approximately 6.5 miles northeast of the site [121].

The NRC staff's review of Discharge Monitoring Reports from 2009 through 2013 found no substantial or recurrent exceedances of NPDES permit requirements or unusual conditions of operations, with reported discharges in compliance with specified effluent limitations. Additionally, the site reported that it has not received any Notices of Violation, nonconformance notifications, or related infractions associated with the site's NPDES permit within the past five years. However, the site identified a number of self-reported permit exceedances, permit non-compliances, and reportable releases (reported to responsible regulatory agencies) that have occurred over the last five years [121].

A shallow water table exists at the site from surface to an approximate depth of 9 feet. Groundwater flow in the unconsolidated sediments is laterally to or away from surface water bodies and vertically downward into the underlying Bass Islands and Salina Groups. Flow in the Bass Islands Group bedrock is influenced by dewatering at a quarry located north and southwest of the site. Groundwater is not used at the site [121].

Tritium has been detected in groundwater at concentrations well below the EPA's drinking water standard of 20,000 pCi/L and increasing trends have not been observed. No other radionuclides have been detected in groundwater samples above their baseline values [121].

3.3.a.5 Ecology

The Michigan Natural Features Inventory natural heritage database indicates that 87 State-listed terrestrial species occur in Monroe County, seven of which occur within 1.5 miles of the site. These are categorized as state: endangered, threatened or species of concern and are the bald eagle, common tern, barn owl, eastern fox snake, and plants (American lotus, giant arrowhead, and trailing wild bean) [121] [124].

In addition, under the US Fish & Wildlife Service there are ten federally listed threatened or endangered species that occur in Monroe County. Of the ten federally listed species, the NRC concluded that five are not likely to reside in the area, indicated with an asterisk (*): birds (red knot, piping plover), mammals (northern long-eared bat, Indiana bat), insects (Karner blue butterfly*), plants (eastern prairie fringe orchid), and mussels (northern rifleshell*, snuffbox mussel*, rayed bean*), along with one proposed threatened reptile (eastern massasauga*). For the remaining five species, the NRC determined that the proposed action "may affect, but is not likely to adversely affect" these species [121].

The National Wetlands Inventory indicated that 31 types of wetlands totaling approximately 1,508 acres lie within a 6-mile radius of the Fermi site. Within Michigan, EGLE administers Section 404 of the Federal Water Pollution Control Act of 1972, as amended. EGLE issues Section 404 permits, which are required for actions that result in the discharge of dredge or fill material into wetlands that are considered waters of the U.S. Within Michigan, some wetlands in coastal areas, including those on the Fermi site, are further protected under Act 451, NREPA, Part 323, "Shorelands Protection and Management [125]"

The NRC documented the impact to terrestrial and aquatic resources would be small, during the license renewal term. For special status species and habitats, the findings ranged from no effect to "may affect, but is not likely to adversely affect" the identified species [121].

3.3.a.6 Air Quality

Under the Clean Air Act of 1970, as amended (CAA) (42 U.S.C. 7410), EPA has set primary and secondary National Ambient Air Quality Standards (NAAQS) (40 CFR Part 50) for six common criteria pollutants to protect sensitive populations and the environment. The NAAQS criteria pollutants include carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO2), ozone (O3), sulfur dioxide (SO2), and particulate matter (PM). Particulate matter is further categorized by size—PM10 (diameter between 2.5 and 10 micrometers (μm) and PM2.5 (diameter of 2.5 μm or less). To comply with these regulations, DTE maintains a Renewable Operating Permit for air emission sources and is required to submit annual reports. Permitted sources include combustion turbines (peakers), auxiliary boilers, diesel driven fire pump, diesel generators, and cold (degreaser) cleaner units. As stated in the 2016 SEIS there have been no reported violations for a five-year period at Fermi 2 [121].

3.3.a.7 Human Health

For nuclear facilities, the NRC evaluated human health relative to five issues: radiological exposure and risk, chemical hazards, microbiological hazards, and other hazards.

The regulations require radiological exposure and risk monitoring as part of the facilities radiation protection program designed to protect onsite personnel, including employees, contractor employees, visitors, and offsite members of the public from radiation and radioactive material generated at Fermi 2. As reported in NUREG–0713, worker exposure was well below the NRC occupational dose limit of 5.0 rem [121].

State and federal environmental agencies regulate the use, storage, and discharge of chemicals, biocides, sanitary wastes, plant discharges and minor chemical spills. Fermi 2 has chemical control procedures, waste management procedures as well as plans to prevent and minimize the potential for a chemical or hazardous waste release that could Impact workers, members of the public, and the environment. Chemical hazards to plant workers resulting from continued operations associated with license renewal are expected to be minimized by the licensee implementing good industrial hygiene practices as required by permits and federal and state regulations [121].

Plant workers are most likely to be exposed to pathogenic microorganisms from power plant operations when cleaning or providing other maintenance services that involve the cooling water system. The NRC recommends that plant operators should continue using proven industrial hygiene principles to minimize workforce exposures to microbiological organisms that may occur in the cooling water system. Thermal effluents produced may enhance the growth of naturally occurring thermophilic microorganisms during nuclear power plant operations which discharge to lakes, ponds, canals, or rivers. The public may come into contact with these water bodies through swimming and boating activities. Although the NPDES permit does not have discharge temperature limits, Fermi 2 discharges into an industrial area along the shoreline that is not used for recreational [121] use.

The NRC found that electric shock resulting from direct access to energized conductors or from induced charges in metallic structures has not been found to be a problem at most operating plants. These transmission lines are entirely within the Fermi 2 owner-controlled area and span industrial areas within the Fermi site. Therefore, the public does not have access and could not come into contact with these energized lines. Therefore, there is no potential shock hazard to members of the public from these transmission lines [121].

The Michigan Occupational Safety and Health Administration governs nonradiological worker safety. Additionally, the site has practices in place to minimize potential hazards and protect workers [121]. The NRC considers other hazards that include physical and electric shock which ensures that he site operates with a job safety and health program to satisfy the requirements under Federal Occupational Safety and Health Administration and Michigan Occupational Safety and Health Administration programs [121].

3.3.a.8 Waste Management

Relative to radioactive waste, the site uses liquid, gaseous, and solid waste processing systems to collect and treat materials produced as a byproduct of operations. Gaseous effluents are reduced so that the resultant dose to members of the public is well within standards. Radionuclides that can be removed from liquid and gaseous wastes are converted to a solid waste for disposal to a licensed facility. The site has not had any planned liquid effluent releases into Lake Erie since 1994 [121]. This effluent release was based on an emergency response plan due to a turbine failure that caused flooding in the basement of the facility. The NRC concluded that the action would not have a significant effect on the quality of the human environment. [126]

There are procedures and plans in place to manage nonradioactive waste as well as a pollution prevention plan. Furthermore, the site has a stormwater pollution prevention plan to manage the quality of stormwater discharges. This is also regulated under the site's National Pollution Discharge Elimination System permit that requires monitoring [121].

3.3.a.9 Environmental Review

In the latest environmental review for Fermi 2 associated with the license renewal of the facility, the NRC evaluated a total of 78 environmental issues contained in the 13 topic areas. Category 2 issues required site-specific analysis for 17 of the 78. The NRC staff's review of site-specific environmental issues in the SEIS leads to the conclusion that issuing a renewed license for Fermi 2 would have small impacts for the Category 2 issues applicable to license renewal at Fermi 2. The NRC staff considered mitigation measures for each Category 2 issue as applicable and concluded that no additional mitigation measure is warranted. Based upon their review, the NRC concluded that the adverse environmental impacts of license renewal for Fermi 2 are not so great that preserving the option of license renewal for energy-planning decisionmakers would be unreasonable [121].

The Annual Radioactive Effluent Release Report is a report that provides the monitoring results for liquid and gaseous effluent monitoring at Fermi 2 and the ISFSI. The years reviewed were 2017-2021. The data presented indicates the offsite radiation exposures are well below the applicable allowable levels set by the NRC and the EPA. There were no releases of liquid radioactive effluents from Fermi 2 [127] [128] [129] [130] [131].

Well sampling for tritium indicated that none of the samples exceeded or approached reporting levels for the years 2017-2021 and there were no detections noted for the period 2019-2021.

Therefore, the reports concluded there is no indication of any leak from plant systems into the groundwater at Fermi 2 [127] [128] [129] [130] [131].

The Annual Radiological Environmental Operating Report (AREOR) is a report that summarizes the sites of the Radiological Environmental Monitoring Program. The program has four major monitoring areas: direct radiation monitoring, atmospheric monitoring, terrestrial monitoring, and aquatic monitoring. The results of 2018-2021 data showed that environmental radioactivity levels have not increased from background radioactivity levels detected prior to the operation of Fermi 2 [127] [128] [129] [130] [131].

3.3.b Donald C. Cook Nuclear Power Plant

Donald C. Cook Nuclear Power Plant (DC Cook) consists of two Westinghouse PWRs, Units 1 and 2 (SEIS 2005). The environmental reports reviewed for DC Cook were:

- NRC NUREG-1437 Supplement 20, GEIS for License Renewal of Nuclear Plants, Donald C. Cook Nuclear Plant, Units 1 and 2, Final Report, May 2005. ADAMS Accession No. ML051150556 [124].
- Appendix E, Applicant's Environmental Report Operating License Renewal Stage. Donald C. Cook Nuclear Plant. October 2003. Accession No. ML033070185 [116].

3.3.b.1 Environmental Setting, Location & Features

The DC Cook site is located in Lake Charter Township, Berrien County, Michigan, on the southeastern shoreline of Lake Michigan. The site is positioned approximately 55 miles east of downtown Chicago, Illinois; 50 miles southwest of Kalamazoo, Michigan; and 11 miles south-southwest of the twin cities of St. Joseph and Benton Harbor, Michigan. The nearest town is Bridgman, Michigan which is approximately two miles to the south.[88] Based on the 2000 US Census Bureau data, approximately 1.4 million people live within 50 miles of the plant and is considered a high population area [124].

The DC Cook property is approximately 650 acres and includes 4,350 feet of lake frontage. The property extends approximately 1-1.25 miles eastward from Lake Michigan. The local terrain consists of a gentle upward sloping beach that rises sharply into sand dunes after about 200 feet. The area surrounding DC Cook property is largely rural, characterized by agriculture and heavily wooded, rugged sand dunes along the lakeshore [88].

3.3.b.2 Vicinity & Region

Berrien County is rural in character, with its land either in agricultural production, forested, or vacant. Approximately 84% of land area is classified as agriculture or unused, about 9% is residential with 3% manufacturing, commercial, or sand and gravel mining activities and about 4% public and semipublic uses, with the Lake Michigan lakefront, parks, and recreational areas being strong attractions for seasonal visitors. [124].

The Berrien County Planning Commission has an overall land use strategy that encourages the implementation of “smart growth” by municipalities. [124] The strategy requires each municipality to create development and planning tools for preservation of open space, farmland, natural beauty, and critical environmental areas and direct development toward strengthening communities and promoting mixed land uses [124].

According to the July 1, 2022, US Census data estimate Berrien County population is approximately 152,900 [132]. The nearest residence is approximately 0.4 miles (659 meters) from the site boundary [133].

Berrien County has 20 sites listed on the National Register of Historic Places with three properties located within a six-mile radius: Avery Road-Galien River Bridge (built in 1922), Sandburg House (built in 1928), and the Snow Flake Motel (built in 1960). The Old Berrien Courthouse (built in 1839) and the Ring Lardner House (built circa 1850) are two additional National Register of Historic Places properties that are located nearby. The NRC documented continued operation of the DC Cook would likely protect any cultural resources present within the DC Cook site boundary by protecting those lands from development and providing secured access. However, there is the potential for significant cultural resources to be present at the site and care should be taken by the applicant during normal operations and maintenance activities that could inadvertently affect cultural resources [124].

3.3.b.3 Geologic Setting

DC Cook is located within a physiographic area known as the Grand Marais Embayment. This area extends 16 miles parallel to the lake with an average width of one mile. On the Lake Michigan side, it is characterized by high sand dunes and shoreline features of several glacial lake stages. The area is bounded on the east by a glacial moraine known as the Covert Ridge, which serves as a drainage divide and groundwater barrier [124].

The geology of the site consists of a surface Pleistocene deposit of dune sand that overlies older beach sand, which in turn is underlain by glacial lake clays, glacial till, and shale bedrock. In the eastern half of the DC Cook property, the beach sands are absent, and the dunes rest directly on glacial lake deposits. The dune sand is generally loose at and near the surface and becomes moderately compact at increasing depth. The underlying beach sands are generally compact and commonly range from about 25 to 35 feet in thickness in the west-central portion of the property. The deeper bedrock formations consist predominantly of interbedded dolomite, limestone, shale, and sandstone [124].

3.3.b.4 Water Resources

DC Cook uses a once-through circulating water system that draws from and discharges to Lake Michigan with more than 98% of the water returned. Lake Charter Township supplies the drinking water (NRC 2005).

Lake Michigan is the third largest lake in the US with a surface area of 22,300 square miles and drains an area of 45,600 square miles. The major tributaries of Lake Michigan include the Fox-

Wolf, Grand, St. Joseph, Menominee, and Kalamazoo rivers and is connected to Lake Huron at the Straits of Mackinac; thus, hydrologically connected [124].

DC Cook is authorized to discharge to groundwater with set daily volumetric maximums at two locations: 2.4 million gallons per day (gpd) of process wastewater using two absorption ponds, and 60,000 gpd of treated sanitary wastewater to two sewage lagoons [124].

The NRC concluded that the cumulative impact to groundwater resources for continued operation during the license term would be small and that additional mitigation would not be warranted. In addition, the NRC concluded that although the impacts to groundwater quality that results from continued disposal of wastewater to onsite absorption ponds and sewage lagoons during the operation period are considered a new issue, they would be small and, therefore, not significant. Further mitigation is not warranted [124].

3.3.b.5 Ecological Resources

Protected species are listed by the state of Michigan that have the potential to occur in the vicinity of DC Cook and its associated transmission lines. At the DC Cook site, 121 State-listed terrestrial species potentially occur within the vicinity of the site, 10 of which are believed to be extirpated within the state of Michigan. No federally listed threatened, endangered, proposed, or candidate aquatic species occur in Lake Michigan in the vicinity of the DC Cook. However, there are state-listed aquatic species that have the potential to occur in the vicinity of DC Cook and its associated transmission lines. These aquatic species include insects, mussels, fish, and plants. There are federal and state listed, proposed, or candidate terrestrial species found in Berrien County and therefore possibly present at the site. However, no designated critical habitat is known on the DC Cook site, within the vicinity, or the associated transmission line Right of Way. Therefore, the NRC concluded that continued operation of the plant and maintenance of associated transmission line ROWs during period of operation is not likely to adversely affect any federally listed aquatic or terrestrial species and the associated impact would be small and additional mitigation is not warranted. In addition, the NRC noted the U.S. Fish and Wildlife Service has indicated that the-project should have no impact on listed species or critical habitats [124].

3.3.b.6 Air Quality

Under the Clean Air Act of 1970, as amended (CAA) (42 U.S.C. 7410), EPA has set primary and secondary National Ambient Air Quality Standards (NAAQS) (40 CFR Part 50) for six common criteria pollutants to protect sensitive populations and the environment. The NAAQS criteria pollutants include carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO2), ozone (O3), sulfur dioxide (SO2), and particulate matter (PM). Particulate matter is further categorized by size—PM10 (diameter between 2.5 and 10 micrometers (μm) and PM2.5 (diameter of 2.5 μm or less).

DC Cook is located in Berrien County, Michigan, which is part of the South Bend-Elkhart (Indiana)–Benton Harbor (Michigan) Interstate Air Quality Control Region (40 CFR 81.73) [88]. Berrien County, Michigan is designated a nonattainment area for the 2015 National Ambient Air Quality Standard, effective August 3, 2018 [134]. The NRC concluded that there are no air quality impacts of transmission lines. Further, the NRC found impacts of continued operation on air quality were small [124].

3.3.b.7 Human Health

Relative to human health the NRC evaluated potential radiation exposures and electric shock.

Based upon the review, the NRC concluded that there are no impacts of radiation exposures to the public or occupational radiation exposures during the period of operation [124].

To comply with 10 CFR 51.53I(3)(ii)(H), the applicant must provide an assessment of the potential shock hazard if the transmission lines that were constructed for the specific purpose of connecting the plant to the transmission system do not meet the recommendations of the National Electrical Safety Code for preventing electric shock from induced currents. All DC Cook transmission lines were constructed to the National Electrical Safety Code and industry guidance in effect at the time the lines were constructed. An evaluation was performed due to the introduction of a new criterion, induced currents due to static effects to 5 mA, for power lines exceeding 98 kV and indicated the lines also met this criterion. The NRC concluded that the impact of the potential for electric shock is small [124].

3.3.b.8 Waste Management

The NRC noted that radioactive wastes resulting from plant operations are classified as liquid, gaseous, and solid wastes and that DC Cook [124].

Regarding offsite radiological impacts for spent fuel and high-level waste, the NRC concluded that there are no offsite radiological impacts related to spent fuel and HLW disposal during the renewal term. In addition, the NRC concluded that there are no impacts of low-level waste storage and disposal, including mixed and non-radiological [124].

3.3.b.10 Environmental Review

The NRC considered a total of 92 environmental issues contained in the 13 environmental topic areas. Of the 92, 69 Category 1 environmental issues were evaluated and there was no new and significant information identified; therefore plant-specific analysis was not necessary and the conclusions of the GEIS remained valid, with these impacts categorized as small. The NRC concluded the impact level significance was small for the remaining 23 Category 2 issues that applied to DC Cook and that additional mitigation measures are not likely to be sufficiently beneficial as to be warranted [124].

The evaluation of liquid and gaseous releases was performed and based on the information presented in the DC Cook Annual Radioactive Effluent Release Report for years 2017 through 2021, concluded that the units performed their intended design function with no demonstrable adverse radiological effect on the health and safety of the public [135] [136] [137] [138] [133].,

Radiological impacts were also evaluated in samples collected from air, fruit, vegetation, water, fish and sediment. As documented in the DC Cook AREOR years 2017 through 2021, none of the samples exceeded or approached reporting levels. Data review determined that non-tritium radioactivity detected by the radiological environmental monitoring program was from outside sources, such as fallout from nuclear weapons tests, external nuclear events and naturally occurring radionuclides. In addition, tritium was not detected in the water samples collected [139] [140] [141] [142] [143].

3.3.c Palisades Nuclear Plant

Palisades shut down in May 2022 with the intent of decommissioning. However, Holtec Palisades Energy, LLC (Holtec) is now seeking to restart commercial power operations at Palisades and announced that a power purchase agreement (PPA) is in place with Wolverine Power in the event regulatory authority for a restart is granted [103].

The plant consists of one pressurized light-water reactor that produced steam that turned turbines to generate electricity. The main environmental documents reviewed included:

- NRC NUREG-1437 Supplement 27, Generic Environmental Impact Statement for License Renewal of Nuclear Plants, Regarding Palisades Nuclear Plant, Final Report, October 2006. ADAMS Accession No. ML062710300 [144].
- HDI (Holtec Decommissioning International, LLC & Comprehensive Decommissioning International, LLC), Post-Shutdown Decommissioning Activities Report December 23, 2020. ADAMS Accession No. ML20358A232 [145].

3.3.c.1 Environmental Setting, Location and Features

Palisades occupies approximately 432 acres located in Covert Township, Van Buren County, Michigan, on the southeastern shoreline of Lake Michigan with approximately one mile of frontage. The developed area is approximately 80 acres, and the remainder of the site is largely wooded with occasional wetlands. The area surrounding the site is primarily rural in character, with agriculture representing the primary land use. In the Palisades 2006 SEIS, the NRC evaluated onsite and offsite land use impacts based on information in the 1996 GEIS [144].

3.3.c.2 Vicinity & Region

Palisades is bordered by Lake Michigan on the west and the Blue Star Memorial Highway and adjacent Interstate-196 (I-196) on the east in Covert Township, Van Buren County, Michigan. The nearest town is South Haven, Michigan, which is approximately 4.5 miles north of the plant, and has a population of about 5000 people. The major towns are Kalamazoo and Portage, Michigan, and Elkhart, Mishawaka, and South Bend, Indiana. Based upon the 2000 U.S. Census Bureau data, approximately 1.3 million people live within a 50-mile radius of the plant [144]. The nearest residence is approximately 0.5 miles south-southwest of the site [146].

The local terrain consists of a gentle upward sloping beach at an elevation of about 580 ft above mean sea level that rises sharply into sand dunes at an elevation of approximately 780 ft mean sea level and then drops off abruptly to about 610 ft mean sea level at the eastern site boundary [144].

There are few urban areas with only one major industrial facility in the immediate vicinity of the site (Covert Generating Station, east side of I-196). This station is not part of Palisades and consists of three natural-gas-fired combined-cycle units that generate up to 1100 MW of electricity. The electricity from the plant is connected to the grid at the Palisades switchyard [144].

Within 50 miles of the site, there are a large number (more than 200) of municipal and privately owned parks and recreational areas and state-owned areas including eight parks, two recreational areas, seven game areas, one fish and wildlife area, and seven wilderness and natural areas. Two of the State Parks in the region are on abandoned railroad paths. The site is bordered by Van Buren State Park on the north and a privately owned residential and lakefront recreational community [144].

Intact archaeological sites could be present within the undeveloped areas as well as in soils below the depth of ground disturbance in most areas of the site. Native American villages are known to have been situated within physiographic settings similar to portions of the Palisades site: on the shorelines of Lake Michigan and on the edge of forested land, adjacent to prairies and convenient to streams and the lakeside. The NRC documented that the operation of Palisades will not have an adverse effect on historic or cultural property in the region and, therefore, a survey of the project area is not necessary, based upon the small extent of potential land-disturbing activities, the absence of known historic properties in the vicinity of Palisades, and the existence of adequate environmental controls to ensure protection of cultural resources. The Michigan State Historic Preservation Office concurred with these conclusions and stated that no historic properties are affected in the project area [144].

3.3.c.3 Geologic Setting

Regional geology in Van Buren County consists of 300 to 400 feet of glacial and post-glacial deposits overlying sedimentary bedrock consisting of shale or limestone of the lower Mississippian Coldwater Formation. A drilling program conducted at Palisades in the 1960s indicated that the uppermost material is dune sand, which ranges in thickness from about 10 ft in the switchyard area to well over 100 ft near the lake. Below the dune sand is dense to very dense gray silty sand or sandy silt, stiff gray clay, and stiff to hard gray glacial till. The bedrock underlies these glacial sediments [144].

3.3.c.4 Water Resources

Early site studies indicated that unconfined groundwater in the vicinity of Palisades has a hydraulic gradient of approximately 13 ft/mile in a westerly direction, flowing to Lake Michigan at an estimated rate of 650 ft/yr and a calculated groundwater flow velocity at this site is westward at approximately 23 ft/yr. Field permeability tests during exploratory drilling in 1965 yielded values ranging from 30 to 1720 ft/yr in the site area. The NRC concluded that these impacts would be small, and additional plant-specific mitigation measures are not likely to be sufficiently beneficial to be warranted [144].

Lake Michigan is the source and receiving body for the plant's cooling system. Municipal water has been available at Palisades since approximately 2002. The only groundwater use at the site is from three small production wells, total capacity of 24 gpm, used for grounds maintenance or other miscellaneous uses. Based upon the NRC's review, they concluded that the impacts would be small, and additional plant-specific mitigation measures are not likely to be sufficiently beneficial to be warranted [144].

3.3.c.5 Ecology

No federally listed threatened or endangered aquatic species occur in Lake Michigan in the vicinity of the Palisades site, and no federally listed threatened or endangered species occur in the streams crossed by the Palisades-Argenta transmission line. Also, no designated critical habitat for aquatic species occurs in the site's vicinity. However, there have been state-listed aquatic species that have the potential to occur in the vicinity of Palisades and its associated transmission lines. These species include plants, insects, mussels and snails, as well as fish. Contamination is emerging as an important concern in fish in Lake Michigan and its tributary streams. Some fish cannot be sold commercially because of high levels of PCBs, mercury, or other substances. The State of Michigan has published advisories governing the consumption of fish from these water bodies. Based upon this, continued operations would have no effect on any federally listed aquatic species [144].

The USFWS identified four federally listed and one candidate terrestrial species that could occur on site or along the associated transmission line rights-of-way. Further, 101 State-listed terrestrial species potentially occur within the vicinity of the site. These threatened or endangered species include plants, insects, amphibians, reptiles, birds, and mammals. No designated critical habitat for terrestrial species occurs on the Palisades site or vicinity, or the associated transmission line rights-of-way [144].

The NRC found that the impact on threatened or endangered species for an additional 20 years of operation and the associated transmission lines would be small, and further mitigation is not warranted [144]. However, this issue will continue to require consultation with appropriate agencies to determine whether threatened or endangered species are present and whether they can be adversely affected by continued operations of Palisades as part of a new license renewal.

3.3.c.6 Air Quality

Under the Clean Air Act of 1970, as amended (CAA) (42 U.S.C. 7410), EPA has set primary and secondary National Ambient Air Quality Standards (NAAQS) (40 CFR Part 50) for six common criteria pollutants to protect sensitive populations and the environment. The NAAQS criteria pollutants include carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO2), ozone (O3), sulfur dioxide (SO2), and particulate matter (PM). Particulate matter is further categorized by size—PM10 (diameter between 2.5 and 10 micrometers (μm) and PM2.5 (diameter of 2.5 μm or less).

The Palisades site is located in the Moist Continental Climate zone, characterized by the dominance of tropical air masses in summer, the polar air masses in winter, and by the presence of deciduous forest that covers the Great Lakes region of the U.S. and Canada. Seasonal changes between summer and winter are very large, with an average seasonal temperature change of 46°F. Cold winters are caused by polar and arctic air masses moving south.

Air quality within a 30-mile radius of Palisades is generally considered good, with the exception of areas within 16 mile of designated ozone nonattainment areas. Localized sources of emissions include man-made sources of commercial, residential, and transportation-related emissions. Natural sources of windblown dust contribute to temporary increases in air pollution [144].

Palisades is located Van Buren County which is within air quality control region 82 along with two other counties to the south, Berrien and Cass. This region, with the exception of the 8-hour ozone standard, is designated as being in attainment or unclassifiable for all criteria pollutants (40 CFR 81.333). The air quality control region 82 is designated as the Kalamazoo-Battle Creek 8-hour nonattainment area for ozone (Clean Air Act Amendments of 1990, Title 1, Part D, Subpart 1). No Prevention of Significant Deterioration Class areas are located within 62 miles of Palisades [144].

Two small generators are used for emergency backup power. These sources are not regulated under Michigan’s Permit Operating Program since their annual emissions are less than the defined significance levels in EGLE, Part 2, R 336.1119 and R 336.1212. Palisades also has three No. 2 diesel oil-fired boilers that are used for evaporator heating, plant space heating, and feedwater purification and are permitted to operate under Michigan’s Air Pollution Control Rule 336.1210(1). There are no mandatory Federal Class 1 areas within 100 miles of the site in which visibility is an important value, as designated in 40 CFR Part 81 [144].

3.3.c.7 Human Health

The NRC staff evaluated the potential impacts for electric shock resulting from operation of Palisades and associated transmission lines. Palisades transmission lines are below and therefore meets the National Electric Safety Code 5 mA criterion (discussed in more detail under DC Cook). The NRC staff concluded the impacts of electric shock during the renewal period would be small, and that no further mitigation measures would be warranted [144].

The NRC reviewed and concluded that there would be no impacts of radiation exposures to the public or occupational exposures during the term beyond those discussed in the GEIS [144].

Regarding microbiological organisms, occupational health impacts are expected to be controlled by continued application of accepted industrial hygiene practices to minimize worker exposures. The NRC concluded that there would be no impacts of microbiological organisms during the renewal term beyond those discussed in the GEIS [144].

3.3.c.8 Waste Management

Palisades used liquid, gaseous, and solid radioactive waste management systems to collect and process these wastes before they are released to the environment or shipped to offsite commercial waste processing or disposal facilities. The waste disposal system meets the design objectives and release limits as set forth in Title 10 of the Code of Federal Regulations, Part 20 (10 CFR Part 20) and Part 50 (10 CFR Part 50), Appendix I (“Numerical Guide for Design Objectives and Limiting Conditions for Operation to Meet the Criterion ‘As Low As is Reasonably Achievable’ for Radiological Material in Light-Water-Cooled Nuclear Power Reactor Effluents”), and controls the processing, disposal, and release of radioactive liquid, gaseous, and solid wastes. The waste disposal system collects and processes all potentially radioactive reactor plant wastes for removal from the plant site within limitations established by applicable governmental regulations. In addition, the system was capable of liquid waste segregation and reuse. All planned releases of liquid and gaseous effluents may be either batch or continuous. Before a batch may be released, a sample was collected and submitted for analysis in a laboratory. A gas release was made only if the release can be made without exceeding federal standards, and lack of reserve holdup capacity requires such a release. Radiation monitors were provided to maintain surveillance over the release operation, and a permanent record of activity released is provided by radiochemical analysis of known quantities of waste [144].

The NRC concluded that there would be no impacts of onsite spent fuel associated with license renewal. The NRC also concluded that there would be no impacts associated with low-level waste storage and disposal. In addition, the NRC concluded that there would be no mixed waste or non-radiological waste impacts from license renewal.

3.3.c.9 Environmental Review

The NRC evaluated a total of 92 environmental issues contained in the 13 environmental topic areas. Of the 92, 69 Category 1 environmental issues were evaluated and there was no new and significant information identified; therefore plant-specific analysis was not necessary and the conclusions of the GEIS remained valid, with these impacts categorized as small. The NRC concluded that impact significance was rated small for the remaining 23 Category 2 issues that applied to Palisades and that additional mitigation measures are not likely to be sufficiently beneficial and warranted. In addition, the NRC determined that the adverse environmental impacts of license renewal for Palisades are not so great that preserving the option of license renewal for energy-planning decision makers would be unreasonable [144].

Over the years, any releases to the groundwater and soil that were subsequently remediated and closed [144]. Palisades continues to monitor onsite to identify and correct leaks from plant systems. Although the 2018-2021 annual radioactive effluent release reports stated all releases for the reporting periods were well below the limits defined in the Offsite Dose Calculation Manual, in 2021, Palisades implemented several plant enhancements to mitigate and correct the potential release of tritium to groundwater, including lining below-grade pipes and sumps that contain secondary plant water and installing a one-way valve on the discharge of below-grade piping going to the mixing basin. All of the monitoring wells and temporary wells which detected tritium in 2021 are located within an area approximately 140 feet wide (north to south) and 90 feet long (east to west) [147] [148] [149] [150] [151].

The sample results documented in the AREOR for years 2017-2021 support the conclusion that the surrounding environment is not or is minimally affected by Palisades' effluents [152] [153] [154] [155] [146].

3.3.d Climate Change

Climate change research indicates that the cause of the Earth’s warming over the last 50 years is due to the buildup of GHGs in the atmosphere resulting from human activities. The EPA has determined that GHGs “may reasonably be anticipated both to endanger public health and to endanger public welfare. [156]” The analysis was based on the U.S. Global Change Research

Program 2009 report and companion studies that predicted greater temperature and associated lake level impacts (i.e., a 1.5-ft decline) under the highest emissions scenario.

Lake Erie is representative of Lake Michigan for climate change projections. Since 1994, the average surface water temperatures in Lake Eerie have slightly increased. Although great uncertainty persists with respect to the precise extent of regional warming, future precipitation patterns, and related factors, the latest projections indicate that Lake Erie surface water temperatures could continue to increase by 2.8 to 5.7 °F under a low-emission-modeled scenario and 2.7 to 7.0 °F under a high-emission-modeled scenario by 2050. Lake Michigan is projected to see similar water temperature increases. In addition to these future projections, the average measured surface water temperatures have increased slightly since 1995 [157]. This projection is driven by increased evaporative losses despite the increases in the frequency and intensity of heavy precipitation across the region. Furthermore, annual mean water levels for Lake Erie, which fluctuate along with Lake Michigan's water levels, are projected to be below historical levels with the potential for average water levels to decrease by 7.8 to 9.8 inches as compared to the current long-term mean by 2050. As a result, the volumetric loss in Lake Erie may be lower than that presented by NUREG–2105 [158]. The National Oceanic and Atmospheric Administration has been monitoring deep water temperatures of Lake Michigan and has found the temperatures to be warming. These deep water temperatures have been monitored in Lake Michigan for 30 years. [159]

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of some species, increases in invasive species and harmful blooms of algae, and declines in beach health. [160] Over the past few years, the water levels have seen notable increases toward the top of the historical range, measured since 1860.

To provide carbon-free electricity many states have considered or implemented measures and standards, they are: zero-emissions credits and nuclear preservation programs; 100% clean energy standards and the Governor's clean energy goals. Another measure supported by the State of Michigan is new nuclear incentives and support [161]. The United Nations International Panel on Climate Change predicted in March 2023severe effects of climate change by 2030 and identified nuclear as one of the technologies necessary to hold warming to 1.5 degrees Celsius [162]. Nuclear energy is low-carbon and can be deployed on a large scale at the timescale required, supplying the world with zero-carbon, reliable, and affordable electricity [163].

The Nuclear Energy Institute (NEI) states that nuclear energy is the largest clean energy source of electricity generation in the U.S., producing more carbon-free electricity than all other sources combined, and 2020 figures show that it generates more than half of America's emission-free electricity [164].

3.3.e EMFs

The chronic effects of 60-Hz EMFs from power lines were not designated as Category 1 or 2 and will not be until a scientific consensus is reached on the health impacts of these fields. Additionally, EMFs are produced from all power sources with voltage drops, and these affects occur with all power producing and transmitting systems. Studies of 60-Hz EMFs have not uncovered consistent evidence linking harmful effects with field exposures. EMFs are unlike other agents that have a toxic effect (e.g., toxic chemicals and ionizing radiation) in that dramatic acute effects cannot be forced and long term effects, if real, are subtle. Because the state of the science is currently inadequate, no generic conclusion on human health impacts is possible [165].

3.3.f Conclusions

The existing nuclear power plants in Michigan have operated for over 50 years with no major safety or environmental incidents [166]. The sustained viability of nuclear power generation in Michigan is evidenced by the existing facilities. Climatic conditions have deemed favorable for existing nuclear power plants in the state in addition to its availability of freshwater resources. For example, Michigan has the longest freshwater coastline in the world, touching four great lakes and over 11,000 small lakes [167]. The presence of these surface waters provides an opportunity to support operations over a large portion of the state. Further, the state’s ecological and environmental regulations ensure continued compliance of nuclear facilities to mitigate and eliminate any impacts to aquatic and terrestrial resources, water resources, air quality, and human health. As evidenced by the continued operation of the existing nuclear facilities, Michigan has the natural resources, trained workforce, environmental regulations, and infrastructure in place that support safe, reliable nuclear operations.

3.4 Extension of Current NRC Licenses

The current fleet of commercial nuclear reactors are moving toward a subsequent license renewal (SLR) to allow for 60 – 80 years of operation. The intent of the SLR is to ensure that a reactor can produce power for its true lifetime and safely bolster the grids power supply with clean energy. Each SLR is specific to a reactor site as systems can vary between various LWR configurations, but each reactor still has the same intention of furthering its lifespan. The SLR has three key features 1) to optimize the current operation, maintenance, and useful life of systems, structures, and components, 2) to maintain an acceptable performance and safety within the plant, and 3) to maximize the return on investment over the useful life of the plant. The utility company responsible for the SLR must consider the application from a cost benefit perspective and how the reactor’s continued operation will affect the cost of electricity.

The equipment contained in reactors that are licensed for a 60 year period are maintained to its utmost capabilities, but some mechanical components may require replacing in beyond the 60 year operating license by the utility owner. The SLR process is composed of scoping and screening information and components which are either safety or non-safety related which must be considered for replacement rather than continued maintenance. Through the operations of the reactors, components and systems are monitored to determine whether they are in proper working order and have been maintained to an acceptable condition. Additionally, as a plant evolves, both mechanical and electrical boundaries change either for ease of use or additional modifications required of the plant itself. An SLR considers all the safety and non-safety related items that can affect operations. Plant boundaries are put into question which allow for plant personal and the NRC to identify necessary work within the reactor to increase the optimization of the system or remove unnecessary components while also maintaining a safe and operable environment.

The generic and nationwide application of managing the operations over time is related to the Aging Management Programs (AMPs) stated in the Generic Aging Lessons Learned report [168]. EPRI and the NRC created documentation for the industry which address multiple aging stressors within reactors through their operating experience based on long term operations. Through this documentation, aging effects requiring management were discovered by identifying the key components that will experience wear through its lifetime both internally and externally. This is mainly attributed to the loss of material due to mechanical corrosion through various means such as internal chemical corrosion, cracking, pitting, and reduction of strength through irradiation. By monitoring the progression of a mechanical component through its normal operation on site, it can be ensured that the operation, maintenance, and useful life is sustained or appropriately replaced. A set of programs were created by the NRC which concern the operation of every component within a reactor and are stated through 53 AMPs which generically cover the operation of all LWRs in the U.S. These AMPs have evolved over the years and are specific to each plant using the license application itself, the specific Safety Evaluation Report, Requests for Additional Information from the NRC, and the generic aging lessons learned [168]. These documents work in tandem to ensure that the required AMPs maintain each system, structure, and component for the site. All AMPs work together to ensure that the reactor also maintains an acceptable performance and safety within the plant.

By maintaining a monitoring system established for the key components in a facility there is a reduction in replacement of major components by identifying component performance issues prior to upstream components being affected. However, over the life of a plant, replacements will be necessary and are most common in AMPs such as XI.M16A PWR Vessel Internals, XI.M41 Buried and Underground Piping and Tanks, and X.E1 Environmental Qualification (EQ) of Electrical Components. These components are under constant use, high radiation conditions, and high thermophysical conditions, so due to their harsh environment some of these components will require replacement.

Time-Limited Aging Analyses are performed for systems, structures, and components that have an estimated life based on analyzed conditions and assumptions used to justify the original 60-year operating term. These components are reevaluated to determine if there is support for an additional 20-years of operation. This considers components affected by neutron embrittlement, pressurized thermal shock, cumulative neutron fluence, metal fatigue, environmental qualifications (components in harsh environments subject to possible LOCA), and penetration degradation. These systems operate within defined margins for the initial 60 years of operation, as calculations used to justify these systems for thermal and radioactive strain are performed for a certain amount of power transience from the reactor. However, for the SLR, the aging conditions must be extended to an 80-year life span to redetermine whether there is sufficient margin ensuring the safe operations of these components.

Tools to manage the aging of components have been developed from the continuous operation of these plants and operating experience behind them. Operating experience is a crucial part in developing these AMPs to ensure the safe operation and maintenance of these systems. By evaluating the operating experience from the industry, each site bolsters their own operations by preparing for potential pitfalls that arise due to age-related degradation. Furthermore, this industry operating experience helps the owners and the NRC keep a close understanding of how LWRs across the U.S. are operating to ensure that each site is working to solve and mitigate aging system failures or performance issues. The implementation of operating experience ensures failures of the same kind do not occur. The successful operation and safety of these plants is the primary responsibility of the owner with oversight of the NRC. Successful and safe operations are also fully dependent on the state of aging components, which as mentioned, require implementation of AMP basis documents, the generation of work orders and new procedures, and finally inspections and replacements from the commitments made by the utility company. Pursuing an SLR provides flexibility in utility generation options while also having a financial baseline from prior license renewal.

Subsequent license renewals are very common within the nuclear industry, and therefore substantial operating experience has followed. Additionally, there is a high probability of approval of an SLR, through working with the NRC, for continued operations of the commercial nuclear reactors in the state of Michigan. Below is a list of plants that have applied for or are currently under review for a SLR or a license renewal application, such as Fermi 2, in the past 13 years [169, 170].

Table 3 SLR and LRA submissions from various utility companies in the U.S. [169, 170].

License Renewal Completed Applications	SLR Completed Applications	SLR Applications Under Review
Sequoyah Nuclear Plant, Units 1 & 2	Turkey Point Nuclear Generating Station, Units 3 & 4	St. Lucie Nuclear Power Plant, Units 1 & 2
Byron Generating Station, Units 1 & 2	Peach Bottom Nuclear Generating Station, Units 2 & 3	Oconee Nuclear Station, Units 1, 2, and 3
Davis-Besse Nuclear Power Station, Unit 1	Surry Units Power Station, Units 1 & 2	Point Beach Nuclear Plant, Units 1 & 2
Braidwood Generating Station, Units 1 & 2		North Anna Power Station, Units 1 & 2

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Enrico Fermi Nuclear Generating Station, Unit 2
South Texas Project Electric Generating Station, Units 1 & 2
River Bend Nuclear Generation Station
Waterford Nuclear Generating Station, Unit 3
Seabrook Station Nuclear Power Plant, Unit 1
Monticello Nuclear Generating Plant, Unit 1
Virgil C. Summer Nuclear Generating Station, Unit 1

Regarding the costs associated with an SLR, the overall costs are based on the holistic needs during the period of extended operations for 20 years and usually a cost estimate is developed using a life cycle management evolution which gives an appropriate starting position for capital expenditures using both references from the NRC and EPRI documents “Nuclear Plant Life Cycle Management Implementation Guide” and “Users Guide for the Development of Life Cycle management plans” [171, 172]. All components are evaluated under a certain level of risk and how they will affect the cost basis of the reactor during its 60 – 80 year operation period. Additionally, components can be forecasted for their expenditures during this period of extended operations. Major components, operations, and maintenance that contribute to this cost are as follows:

- Typical Required Expenditures for Period of Extended Operations:
    - Battery Banks
    - Rewinding Emergency Diesel Generator
    - Rewinding and Replacing Components within the Main Generator
    - Rewinding Main Generator Rotor and Excitor
    - Independent Spent Fuel Storage Installation
    - Security Equipment Replacements and Upgrades
    - Replacement of Transformers
    - Rebuilding Reactor Coolant Pump
    - Vendor Refurbishment of Reactor Coolant Pump
    - Repairing and/or Inspection of Reactor Vessel Internals
    - Replacing Reactor Vessel Level Instrumentation
    - Inspecting Steam Generator Tubing
    - Inspection and Cleaning of Steam generator
    - Performing Dry Cask Storage Loading
    - Radwaste System annual cost for shipping, handling, and disposal
    - Heating Ventilation and Air Replacement

  - IT Upgrades
  - System and Components Functional Failure Contingency
  - Corrective Contingent Maintenance
  - Contingent Operations and Maintenance
  - Development of SLR Application
- Suggested Expenditures for Period of Extended Operations:
  - Heat Exchanger Upgrades for Component Cooling Water
  - Upgrading Fire Detection Systems
  - Overhaul Main Turbine Systems
  - Main Turbine Overhaul
- Optional Expenditures for Period of Extended Operations:
  - Main Condenser Tube Replacement
  - Moisture Separator Reheaters Retubing

The items considered above produce the highest cost basis for all the necessary components, maintenance, and upgrades that may be required for a facility to ensure a safe, reliable, maintained, and optimized operation. Additionally, “suggested” and “optional” items listed above aim to improve the operation and maintenance cycles within the system which have the potential to save capital during the period of extended operations. As an example, turbines require routine maintenance for switching out the blades in the low- and high-pressure stages due to general wear and cavitation, but by replacing the entire turbine stage as well, this will eliminate the need to replace the blades of the turbine. Additionally, by replacing the main turbine an increase of power from 20 - 30 MW_e would occur yielding \$80M - \$120M in revenue over the 20-year period of extended operations (Assuming that power is conservatively produced for 8,000 hours a year and sold at an average price of \$25/MWh).

Lastly, system upgrades are crucial for analog systems that have been operating with 40 to 60-year-old technology which have often reached obsolescence. For instance, IT upgrades that could be justified include modifying formerly analog systems to being digital, which could further improve maintenance cycles and identification of plant issues, optimization of operations within control rod drives, system breaker replacements, and some safety features (such as radiation monitoring in all plant components). Key upgrades, maintenance, and replacements can lead to the successful and streamlined operations of reactors older reactor systems.

4. EVALUATION OF NEW NUCLEAR TECHNOLOGY, DESIGNS, AND SITING

4.1 New Nuclear Plant Designs

The field of new nuclear technology and designs has seen substantial interest over the past 15-20 years, starting roughly with the NRC granting design certification for the Westinghouse AP1000 reactor in 2006 [173]. This interest waned following results of the Great Tohoku Earthquake off the coast of Fukushima Prefecture in Japan, slowly gathering interest again as methods of meeting decarbonization goals have received close study, and greatly accelerated in light of the Russian invasion of Ukraine beginning in February 2022 highlighting energy security issues of the mix of primary energy sources used around the world. The recent interest has sparked the U.S. DOE to publish a report on the Commercial Pathways to Liftoff for Advanced Nuclear [29] and has caused the NEI to publish an advanced nuclear section on their webpage [174] which can provide an industry view of “advanced nuclear.

Interest in the AP1000 design stemmed from claims of a simpler overall plant design, owing primarily to the use of passive rather than active safety features (passive safety systems require no electricity-driven fluid systems or actions from the operators but operate due to forces such as gravity driven flows, such as natural convection flows resulting from fluid density differences). The A and P in the design name stand for “advanced” and “passive,” with the 1000 referring to the plant being capable of producing over 1000 MW_e. This design evolved from the smaller capacity AP600 design, which was an evolution of the System 80+ design, originated by Combustion Engineering. In the U.S., construction was started on 4 different AP1000 Units, with Units 3 and 4 at Vogtle, in Waynesboro, Georgia, and Units 2 and 3 at VC Summer located in Jenkinsville, South Carolina. Following numerous issues, the VC Summer AP1000 projects were halted. Unit 3 at Vogtle has recently entered commercial operation (officially as of July 31, 2023), and in late-July of 2023, Vogtle received the final approvals needed to commence fuel loading for Unit 4 [175].

Several other projects during the early years of the nuclear renaissance (from roughly 2003 to 2011[39]) began licensing efforts for submitting a combined operating license application (COLA) referencing the AP1000 design. These included consideration of 2 AP1000 Units at Bellefonte in northeast Alabama (COLA application deferred in 2010), 2 AP1000 Units at Turkey Point in Homestead, FL just south of Miami (Combined Operating License (COL) issued in 2018), 2 AP1000 Units in Levy County in Florida (COL issued in 2016), 2 AP1000 Units at Shearon Harris in North Carolina (COLA review suspended in 2013), and 2 AP1000 Units at William States Lee in South Carolina (COL issued in 2016). Other projects also progressed into the process of submitting COLAs referencing other reactor designs, such as the Mitsubishi Heavy Industries US-Advanced Pressurized Water Reactor (US-APWR), the Toshiba Advanced Boiling Water Reactor (ABWR), the Areva U.S. Evolutionary Power Reactor, and the GE-Hitachi Nuclear Energy (GE-H) Economically Simplified Boiling Water Reactor (ESBWR) [176]. Notable among these for the state of Michigan is the Fermi 3 application referencing a GE-H ESBWR, which progressed all the way to issuance by the NRC of Final SER [177]. The ESBWR design is the predecessor to the GE-H BWRX-300 design which has gained substantial recent momentum. The X in the name BWRX-300 refers to being a 10th evolution of the BWR design.

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[39] This period included licensing activities for several new reactor designs, including the AP1000 design, the Energy Policy Act of 2005 (including support for nuclear power, such as loan guarantees), the Browns Ferry Unit 1 restart, Watts Bar Unit 2 completion, and initial SMR design efforts, with the end being the result of a combination of sentiment following the Great Tohoku Earthquake in March 2011 and low U.S. natural gas prices resulting from widespread gains from hydraulic fracturing.

4.1.a Generations of Nuclear Plant Designs

Nuclear power plant designs have long been lumped into “Generation” categories, with Gen I including the initial smaller-scale pilot plants built in the 1950s and early-1960s. Gen II plants then included the scaled-up gigawatt-scale plants that have made up the majority of the U.S. nuclear power fleet. Gen III plants are evolutionary improvements upon Gen II designs, incorporating some combination of improved fuel technology, higher thermal efficiency, enhanced passive safety features (in contrast to Gen II plants relying predominantly on active safety systems), and standardized designs with the intent of reducing costs. Gen IV plants are designs with improvements upon Gen III or III+ designs. The term “advanced nuclear” is not rigorously-defined but tends to be used for any “new” nuclear designs and generally includes any Gen III, Gen III+, or Gen IV plant designs. Additionally, there is not necessarily a precise definition for delineating reactor generations, but the Gen IV International Forum (GIF) is an organization formed in 2000 by the DOE’s Office of Nuclear Energy [178]. The GIF’s stated goal is “the development of concepts for one or more Generation IV systems that can be licensed, constructed, and operated in a manner that will provide a competitively priced and reliable supply of energy…while satisfactorily addressing nuclear safety, waste, proliferation, and public perception concerns [178].” Subsequently, the GIF’s goals have been clarified into eight specific technology goals relating to sustainability, economics, safety and reliability, and proliferation resistance and physical protection [179]. The GIF selected six[40] general reactor designs that were under development as of the year 2000 and has coordinated research efforts into these reactor type [180]. Figures 6 through 11 show high-level concept views of the reactor power plant designs for these six reactor concept families, which are found across literature regarding Gen IV nuclear reactors. Many different companies are actively developing their own designs within these Gen IV reactor family types. It should be noted that reactor “Generation” designations are independent of reactor size/output.

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[40] These include the: Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR) and Very High Temperature Reactor (VHTR).

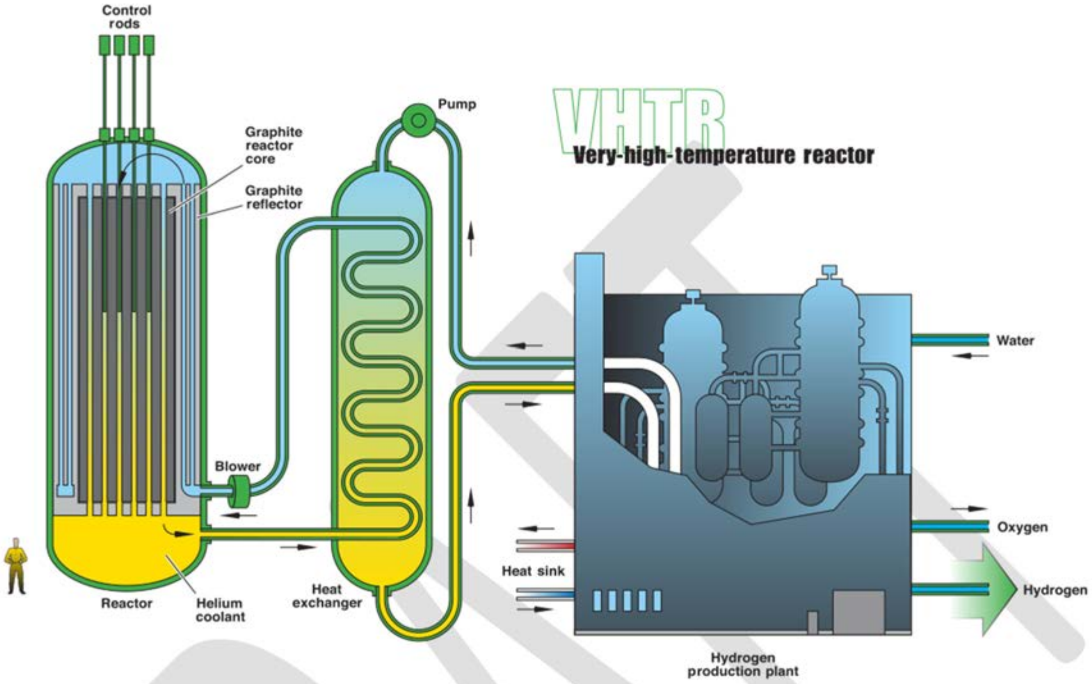

Figure 6 Very High Temperature Reactor.

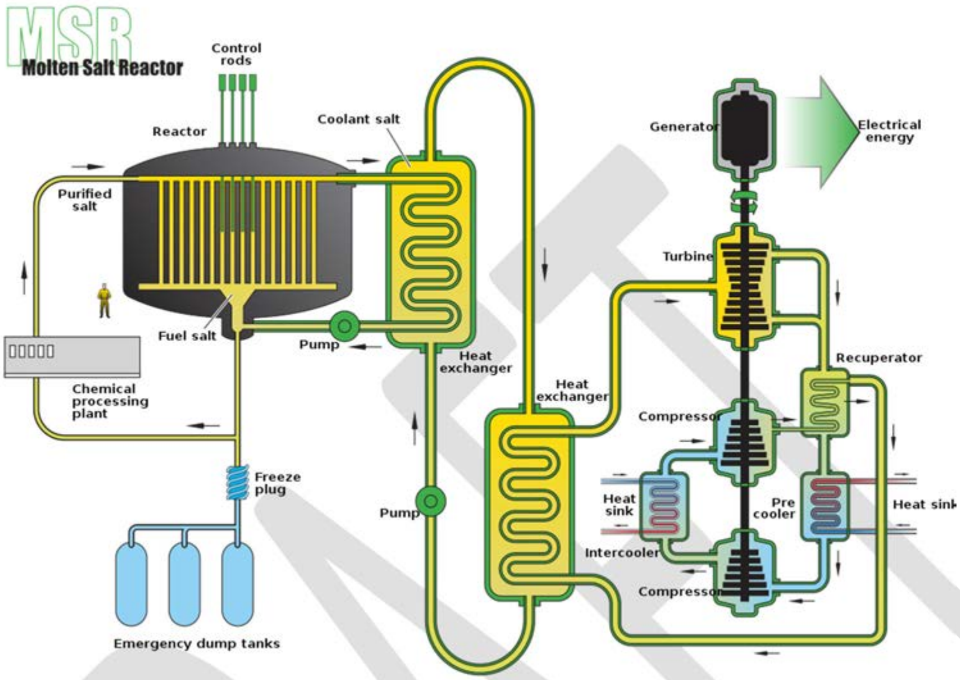

Figure 7 Molten Salt Reactor.

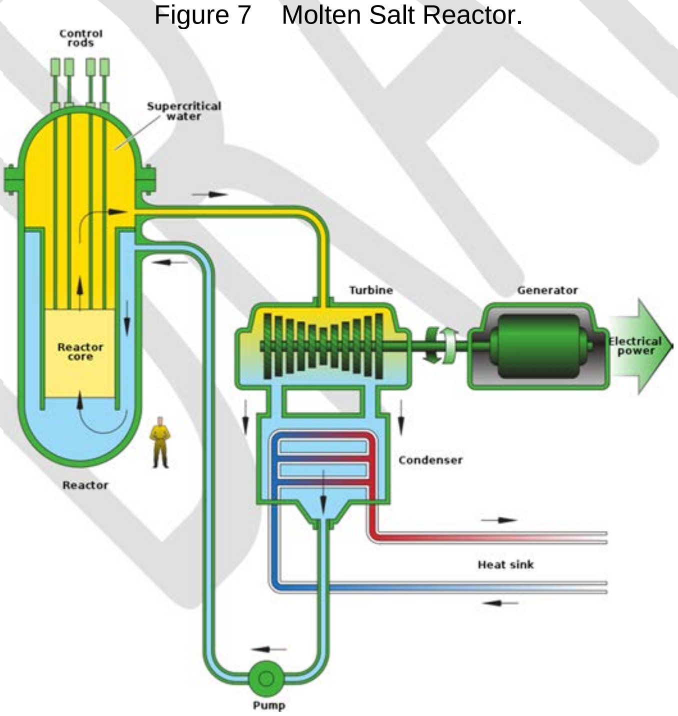

Figure 8 Supercritical-water-cooled reactor (SCWR).

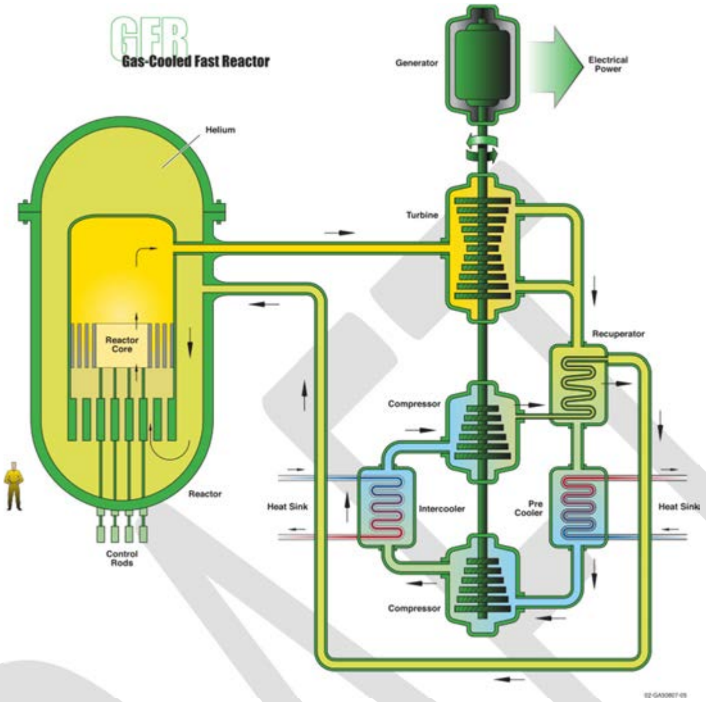

Figure 9 Gas-Cooled Fast Reactor.

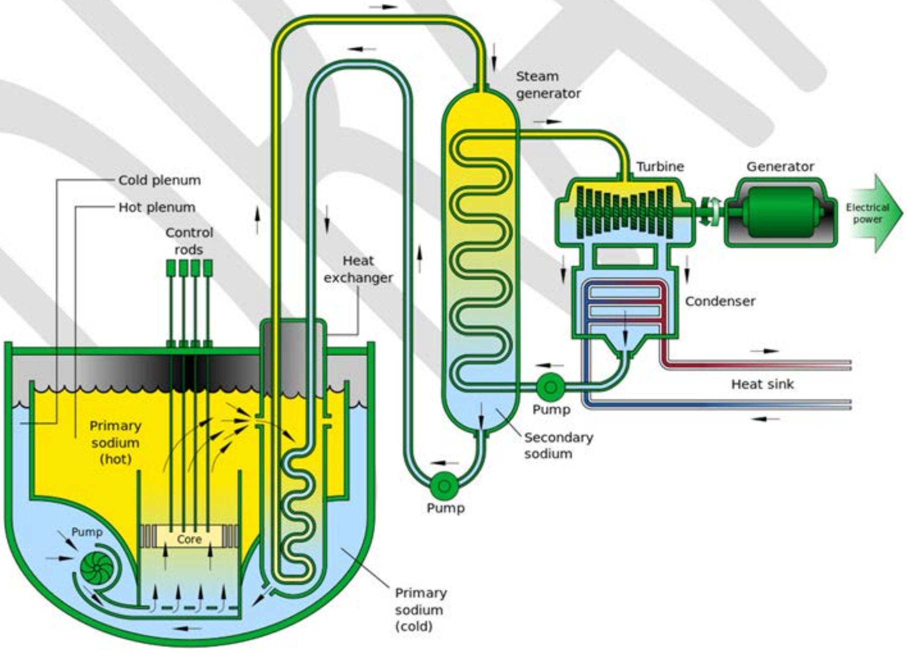

Figure 10 Pool Design Sodium-Cooled Fast Reactor.

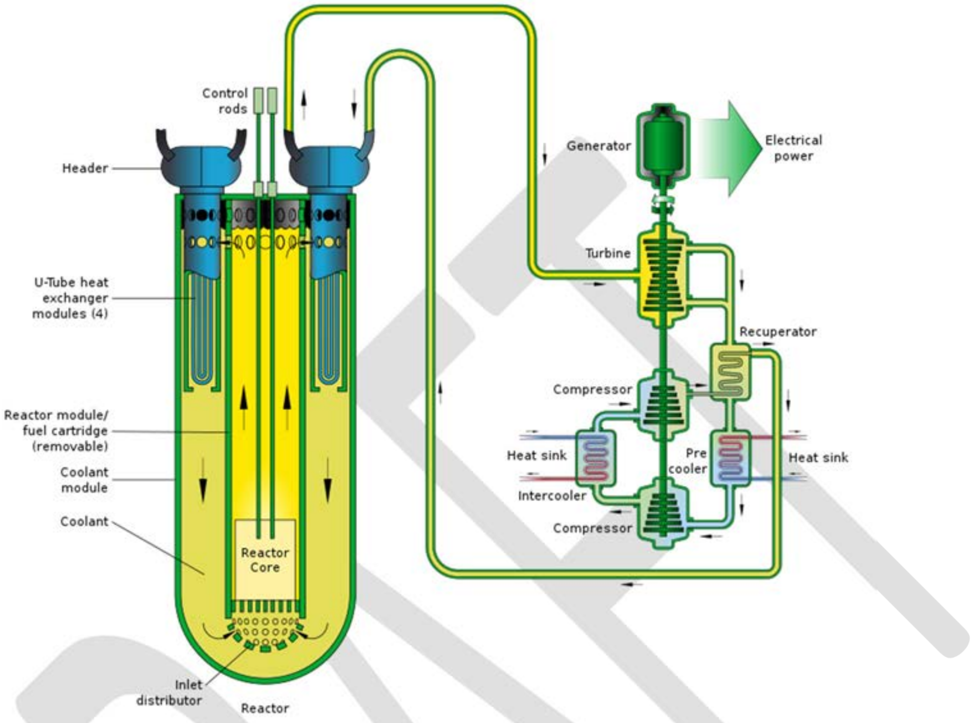

Figure 11 Lead-Cooled Fast Reactor.

4.1.b What are Advanced Reactors?

New nuclear technologies are presently under development at various stages and levels of readiness. Fusion developments are underway in efforts to create efficient ways to confine small nucleus atomic elements under extreme temperature conditions to have them combine into larger nucleus elements and produce energy in contrast to fission being the splitting of large nucleus elements to produce energy and neutrons to cause follow-on fissions; however, fusion technologies are excluded from the scope of this study. The breadth of fission-based new nuclear technologies presents multiple pathways to cleaner energy production, whether that energy is electricity or other potential energy applications. Non-electricity applications could be enabled by reactors operating at higher temperatures to provide process heat as a generalized example. Some new nuclear technologies are evolutionary applications of today's most prominent reactor types, PWRs and BWRs. For simplicity, these two reactor types are frequently collectively referred to as LWRs to differentiate from the heavy water-cooled[41] and moderated CANDU reactors or the various reactor types utilizing non-water coolants.

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[41] "Heavy water" is water made up of hydrogen atoms with both a neutron and proton in the nucleus (known as deuterium), whereas "light water" is made up of hydrogen atoms with no neutrons (hydrogen atoms containing 2 neutrons and 1 proton are known as tritium).

Other new nuclear technologies utilize quite different fuel forms and coolants/moderators than those employed in LWRs. Several prominent types are sodium-cooled fast reactors (SFRs), high temperature gas reactors (HTGRs), and molten salt reactors (MSRs). Different new nuclear technologies are also frequently classified based on the size of each reactor unit. The term small modular reactor (SMR) is used frequently, and SMRs are anticipated to utilize improved construction techniques and reduced financing requirements per unit deployed. As these reactors have yet to be deployed, there is no generally accepted measure of how “modular” these designs must be to qualify for the SMR designation, but a general size limit of 300 MW_e per unit is used as a cap for use of the terminology. New nuclear capabilities with SMRs are developing growing interest due to the anticipated lower costs, land usage, construction times, fuel needs, increases in manufacturability (larger portion of factory manufactured components, at a lower cost), and siting flexibility [181] [182]. The ability to add capacity incrementally rather than only in gigawatt-sized chunks is also a benefit for SMRs as compared to gigawatt-scale reactors, in particular in recent decades where the previous increases in electricity usage have stagnated and even fallen in some instances. Perhaps the most-touted and remaining-to-be-proven benefit of SMR designs is the use of modularity to move many of the assembly/construction activities associated with building a nuclear power plant away from the final installation site by building modules in more easily quality-controlled factory environments. The continuance of work and innovative designs into SMRs has led to passive safety features for shutting down reactors as well as providing the potential for using novel heat sinks beyond simply water.

Additional advanced reactors will be introduced to the commercial market in the coming years as TVA has been issued an early site permit at the Clinch River Nuclear Site for two or more SMRs [183]. Other early site permits for this new generation of reactors have been issued for Exelon, System Energy Resources, Dominion, Southern Nuclear Operating Company, and Public Service Electric and Gas (PSEG) [184]. The DOE’s Advanced Reactor Demonstration Program (ARDP) is also providing cost sharing for deployment of three separate installations of new reactor designs, with the Carbon Free Power Project (CFPP) planning to install 6 of the 77 MW_e NuScale VOYGR reactors[42], TerraPower leading a project to install the Natrium demonstration reactor in Kemmerer, WY to be operated by PacifiCorp [185], and X-Energy partnered with Dow to install 4 Xe-100 reactors to provide electricity and steam for Dow’s facility in Seadrift, TX [186] [29].

4.1.c What are Microreactors?

Microreactors are generally reactor modules sized to be small enough to transport its entire system by land. While there is not a hard cut-off, microreactors usually possess an output capacity of less than 50 MW_e and tend to range from 1-20 MW_e [187]. Several microreactor designs are showing substantial market potential, particularly Oklo’s Aurora reactor, Last Energy’s PWR-20, Ultra Safe Nuclear Corporation’s Micro Modular Reactor, Westinghouse’s eVinci reactor, the

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[42] NOTE: The CFPP was cancelled as of November 8, 2023 during the review process for this report. It is not yet clear whether the ARDP funding that had been planned to be allocated to the CFPP will be re-purposed for a different advanced reactor demonstration project [261].

BWXT-designed U.S. Army-funded Project Pele Reactor, and the Radiant Energy Kaleidos reactor. Notably, it was announced in July 2023 that Oklo will be becoming a publicly traded company via an acquisition by a special purpose acquisition company company (AltC Acquisition Company). Microreactors present substantial potential in their siting versatility, however they are not expected to have lower costs as compared to other reactor technologies on a per MWe basis. Microreactors could be a good fit for remote areas that do not have substantial existing high-voltage transmission grid infrastructure, such as the Upper Peninsula of Michigan. Multiple studies have been issued on the uses of microreactors for "off-grid" and "embedded" applications. These studies consider the possible uses of microreactors alongside other producing sources and their possible roles in production for both thermal and electrical needs [188, 189].

Table 4 List of most relevant reactor technologies in North America.

Reactor Technology	Power Output (MW$_n$)	Company	Type
Aurora	1.5-15 MW$_e$	Oklo	Liquid-Metal Fast Reactor
PWR-20	20 MW$_e$	Last Energy	Pressurized Water Reactor
Micro Modular Reactor	15 MW$_{th}$	USNC	High Temperature Gas Cooled Reactor
eVinci	13 MW$_{th}$	Westinghouse	Sodium Cooled Reactor
Pele	36 MW$_{th}$	BWXT	High Temperature Gas Cooled reactor
Kaleidos	50 MW$_{th}$	Radiant	High Temperature Gas Cooled reactor

Each microreactor technology shows some potential for future use and development of their commercial applications:

- The Oklo Aurora Reactor is a proposed reactor design which uses a fast neutron spectrum and a metallic fuel design allowing for greater efficiencies as compared to LWRs. Following Oklo becoming a public company by merging with AltC Acquisition Corporation, additional funding will be available for further development of their systems for the planned second and third commercial plants at the DOE Piketon Site. The last announced licensing project plan from their company states that they intend to site a commercial-scale fuel recycling plant facility in the U.S. by early 2030s which could revolutionize the nuclear industry's outlook on spent fuel and close the loop for energy production from nuclear sources [190].
- Last Energy's PWR-20 design uses well-known PWR designs and compacts the reactor module into 20 MWe single loop systems. The fuel is a standard 17×17 fuel array commonly used in LWR systems and the facility, with a single unit, only takes up 0.5 acres of land. The subterranean nuclear island is planned to have a fuel cycle of five years with a refueling period of three months giving a predicted capacity factor of nearly 95% [191]. The company most recently secured a PPA for 34 new modules with four industrial

partners in the UK and Poland marking the largest pipeline of new nuclear power plants to be developed as of late [192].

- Ultra Safe Nuclear Corporation has developed the micro modular reactor which ranges from 10-45 MWth producing 3.5-15 MWe and has a lifetime of 20 years without requiring refueling. The company’s focus is on the safety of the reactor core by ensuring the highest surface area to power ratio which allows for the reactor to dissipate/transfer heat faster than any other available Gen III or IV reactor design. The Ultra Safe Nuclear Corporation has five major projects both in the U.S. and overseas to produce test reactors in Illinois, Poland, Finland, and Ontario which will allow for training and additional research to be conducted to determine the proper implementation and economic challenges that the micro modular reactor will have [193]. All installations will apply a ceramic encapsulated fuel which will allow for the permanent shielding for the entire lifetime of spent fuel ensuring the decommissioning of the plant and its fuel remains safe to the operators, environment, and the public. Furthermore, there is minimal chance for contamination due to the primary containment and primary loop existing below grade. Additionally, if the primary coolant loop is breached, the reactor is cooled with helium gas which cannot become activated by neutrons further improving the safety associated with a LOCA [194]. The first demonstration of its operation is scheduled for 2026 [194].
- The eVinci microreactor developed by Westinghouse has an installation plan of 30 days using a solid-state core with minimal moving parts with a range of production of 200 kWe to 5 MWe. The reactor core has an eight year lifespan between refueling and utilizes a cooling system which does not require air [195].In October 2023, Westinghouse announced an eVinci Microreactor Accelerator Hub in Etna, Pennsylvania to streamline the processes and steps for bringing this design to market [196].
- The BWXT Advanced Nuclear Reactor (BANR) could be the first company to produce an advanced microreactor in the U.S. and has plans with Idaho National Laboratory (INL) for initial testing is expected to commence in 2024. The HTGR will operate within the 1 – 5 MWe range and has a transportable configuration. BWXT plans to transport the components of the reactor to the INL construction site where the reactor will be assembled on-site and become operational within 72 hours. This will demonstrate that the reactor can produce consistent and reliable off-grid power while also displaying the ease of installation and disassembly [197]. Additionally, BWXT is working with the Wyoming Energy Authority to develop and further nurture the existing supply chain to support reactor component manufacturing within the state. This comes along with the possible deployment of the BANR reactor to support the growing energy needs of Wyoming [198].
- Radiant Energy is producing Kaleidos, a portable microreactor which has an intended use of replacing diesel generators. Kaleidos similar to the eVinci, BANR, and the micro modular reactor does not require the use of water as a cooling medium as it is an HTGR but takes this a step further by requiring zero on site water. The microreactor is projected to produce 1.2 MWe or 1.9 MWth and has a refueling period of five years and a total lifetime of 20 years. It has plans to perform fueled testing in 2026 [199]. This company was formed by former SpaceX engineers and received funding from multiple investors

initially to kickstart a mobile nuclear power plant with its main application aiming for functionality of remote and isolated energy needs [200].

These microreactors are examples of producing energy in remote, isolated, and sometimes temporary applications that is sustainable for a reasonable fuel cycle. Global microreactor initiatives have also commenced in places such as Sweden, the United Kingdom, Argentina, and South Africa [201]. The following table is a general description of other microreactors technologies not described above that are being developed around the world.

Table 5 The microreactor technologies being developed around the world and their general characteristics.

Reactor Technology	Power Output (MW_e)	Country	Type
SEALER [202]	3	Sweden	Lead-Cooled Fast Reactor
U-Battery [202]	4	United Kingdom	High temperature Gas Cooled Reactor
CAREM [201]	27	Argentina	Integral Pressurized Water Reactor
HTMR -100 [201]	35	South Africa	High temperature Gas Cooled
Leadir-PS100 [201]	36	Canada	Lead Cooled Reactor
RITM – 200M [201]	50	Russia	Integral Pressurized Water Reactor

4.1.d Comparing Advanced Reactors to Other Non-Emitting Sources in Michigan

When considering the power needs of Michigan, a substantial portion of the state is made up of agrarian work which spans up to 9.8 million acres as of 2017 [203]. To preserve the state's natural resources while installing clean energy generation, the land usage of SMRs will be compared to that of selected renewable energy sources. The land usage of other technologies such as solar and wind (under conditions that both wind and solar energy are abundant in the specified area) has been compared side by side with nuclear sources around the world. Nuclear sources have been shown to span, on average, 31 times and 173 times less space than solar farms and wind farms, respectively, over a large average grouping (as compared to the example in Section 1) [204]. Michigan is among the top ten states in both population and total energy usage [205]. To hypothetically convert the remaining fossil fuels using new nuclear systems (69.45 GW_e according to 2020 data [205]) would require 57,783 acres of land usage as compared to 1.79 million acres for solar and nearly 0.5 million acres (considering that 95% of the land around the wind turbines can be farmed) of land for wind [204]. Furthermore, the replacement of older fossil fuel technologies in the electric power industry with a new nuclear fleet (requiring 0.5% of Michigan's available land using nuclear sources) would forgo the emission of 55 MT (1 MT = 1,000,000 Metric Tons) of carbon dioxide, 0.058 MT of sulfur dioxide, and 0.053 MT of nitrogen Oxide [205]. The need for electricity will continue to grow as the world increasingly electrifies. Examples of this include charging stations for EVs and conversion of more home heating fuel sources from natural gas burners to electric heat pumps. As of 2022, only one in ten Michigan households rely on electricity as a primary source for home heating [206]. As this heating source conversion continues and accelerates, new nuclear plants could meet these needs via electric and district heating (steam or hot water produced at nuclear facilities).

4.1.e Small Modular Reactor Deployment

From the wide group of potential SMR candidates, targeting SMRs that have high outlet temperatures and strong progress in licensing their technology will provide opportunities for implementing SMRs sooner and across a wider range of applications. Expanding the uses of the technology will allow for manufacturing and modularity to grow across many fields, allowing the reactor designs to progress along learning curves reaching Nth of a kind (NOAK) efficiencies, and ultimately increasing the demand of such advanced reactors. Three key applications other than electricity generation could be targeted, such as ammonia production, reducing iron, and generating hydrogen. Ammonia production requires at least 450°C using the Haber Process [207], directly reducing iron requires a reducing agent and uses hydrogen gas [208], and varying high temperature hydrogen production methods have process temperatures up to 800°C [209]. Utilizing SMR technology that can be used for more than electricity generation could be beneficial in Michigan's SMR deployment success. Pairing of technologies will allow decarbonization of other sectors and efficient use of a dependable, carbon-free, base load electricity source.

The Organization for Economic Co-Operation and Development's (commonly known as OECD) NEA has reported on a multitude of different SMR technologies across the world currently under development with 21 different reactor designs evaluated in the initial release of their SMR Dashboard in early 2023 and an additional 21 evaluated in the release of Volume II in the summer of 2023. As an example of the interest in SMRs and rapidly changing landscape, a new Westinghouse AP300 was announced in May 2023 which was too recent to be included in the Volume II release of the NEA SMR dashboard. With the rapid pace of announcements relating to new reactor designs, it is almost inevitable that new offerings will be announced shortly after completion of this report, and thus are not mentioned. A summary of some high-level information from the initial two volumes of the NEA SMR Dashboard is included in the following paragraphs.

The Central Argentina de Elementos Modulares (CAREM) prototype SMR was authorized to start construction in 2014 and construction of the reactor has begun and remains in-progress in Argentina. Construction was halted from November of 2019 to April of 2020 where a transition contract was signed to establish a duration of 36 months to complete the reactor [210]. This reactor was projected to be completed in 2023 but no further information could be gathered. The low reactor temperature makes the system limited in capability for wide-scale uses beyond electricity generation, but it will be one of the FOAK SMRs to operate in the commercial market.

Another low outlet temperature reactor that has stoked great interest is the NuScale VOGYR reactor. This design has received substantial engagement among university studies in the U.S.

The initial 50 MW_e version of this reactor design has achieved Standard Design Certification approval by the NRC [211]. An application for Standard Design Approval for an uprated 77 MW_e version has been submitted to the NRC [212], with an anticipated approval in 2025 [213]. Substantial effort has been expended to-date to support design maturation and licensing activities for the NuScale reactor design. NuScale is well-capitalized and became a publicly-traded company in 2022 [214]. Plans are underway for construction of an initial installation of NuScale reactors at Idaho National Lab (INL) as part of the Carbon Free Power Project, to eventually supply power for Utah Associated Municipal Power Systems with operation planned to begin by 2030 [215] [216]. A major benefit of this reactor design is that the fuel used within VOGYR is of the same form as that used in the current fleet of PWR reactor systems and will not require further development within the supply chain.

The KLT-40S has received its commercial license to operate in Russia and has a 10-year operating license. Despite the fact that KLT-40S is a foreign technology, it shows promise for providing lessons learned and improving the development of the Gen IV fleet [181], pending the major caveat of the geopolitical issues surrounding Russia subsequent to the 2022 invasion of Ukraine.

The BWRX-300, by GE Hitachi, has entered the second phase of pre-licensing with the CNSC. This SMR design been selected for various siting opportunities in Canada, for a potential installation in Estonia, and is currently the leading candidate for installation at the Tennessee Valley Authority's Clinch River Nuclear site which has already been granted an early site permit (ESP) by the NRC [217]. The Clinch River ESP was pursued with the intent of retaining flexibility to site differing reactor designs, with the basis of a plant parameter envelope to bound the potential designs for the site. Sites in Michigan could gain an earlier start on the licensing progress for a nuclear site, prior to selecting reactor technology, by utilizing a similar methodology. The BWRX-300 also leverages pre-existing supply chains and commercially proven fuel sources.

The licensing activities for the SMR-160[43], designed by Holtec, have commenced for this reactor design in the U.S., Canada, and the UK. Holtec is a privately-held company, with development of the SMR-160 primarily funded from corporate funds derived from Holtec's historical business lines relating primarily to spent fuel management, both in spent fuel pool racking systems and dry cask storage. Holtec has also received $116M of funding from the U.S. DOE through the ARDP as a risk reduction award. The SMR-160 design is Holtec's first foray into reactor design. Holtec possesses in-house manufacturing capabilities at their Camden, New Jersey facility. The SMR-160 design is not intended to introduce any revolutionary new design attributes, but rather to take advantage of modular, off-site construction techniques paired with well-understood designs and systems. Similar to NuScale's VOYGR and GE-H's BWRX-300 designs, existing fuel supply chains are planned to be used with the Holtec SMR-160 design [182].

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[43] This reactor design is no longer planned to be 160 MWe. The reactor is now known as the Holtec SMR-300, as mentioned in the December 4, 2023 announcement of plans to build the first 2 SMR-300 units at Palisades [396].

For high temperature applications, the HTR-PM, Hermes, and XE-100 reactors are worthy of further investigation. The HTR-PM is an advanced reactor that is fully licensed and connected to the electrical grid in China. The HTR-PM is sited at Shidaowan Nuclear Power Plant in the Shandong province of China. This nuclear facility also has high outlet temperatures which allows for its uses to span across generating electricity, ammonia, and even steel through the directly reduced iron methods. The HTR-PM may be able to demonstrate an advantage for high temperature reactor operations, such as Hermes and the Natrium reactors, as more operating experience will come from its operations further bolstering the technology. Information sharing from China, however, could be a challenge due to geopolitics. The high-quality heat provided by these reactors approaches that of natural gas plants (>700°C). Furthermore, each reactor uses HALEU fuel despite differences in operating neutron spectrums [181].

Other high temperature reactors such as the X-Energy Xe-100 and Kairos KP-FHR reactors, also show promise due to their level of project engagement. Dow Chemical Company has invested in X-Energy and is partnered with them to deploy an initial installation of 4 Xe-100 reactors at their Seadrift, TX facility to provide both electricity and steam. The system benefits from its 750 °C outlet temperature in allowing dual use beyond solely electricity production. The Xe-100 and Hermes reactors are similar to the HTR-PM design in terms of its usage of TRISO[44] fuel pebbles. The Xe-100 is currently in review with the NRC and CNSC for pre-licensing. Kairos is developing the Hermes test reactor in support of the larger KP-FHR technology development. They have submitted a construction permit for the Hermes test reactor and in June 2023 submitted another construction permit for 2 additional reactors adjacent to Hermes, termed Hermes 2 which are planned to generate electricity. The NRC's Advisory Committee on Reactor Safeguards (ACRS) has recommended as of June 2023 that the construction permit for the Hermes test reactor be granted [218]. Additionally, Kairos has partnered with TVA to gain engineering, operations, and licensing support for their reactor design [219] [181].

The Natrium Demonstration Project is receiving the most substantial portion of cost-sharing in conjunction with the ARDP. This project involves partnerships between TerraPower, GE-H, Bechtel Corporation, Pacific Corp, and other groups to build the Natrium Demonstration reactor near the site of the soon-to-retire Naughton coal plant in Kemmerer, WY [185]. This reactor will be a SFR, utilizing molten salt thermal energy storage to allow for dispatchable electricity. Although it will operate at lower temperatures than some other reactors and not be suitable for quite as many industrial use applications, it will operate at higher temperatures than LWRs. This will provide both a relative thermal efficiency benefit for the plant's power conversion cycle, while also allowing for thermal energy storage in molten salt tanks. The pairing of such thermal energy storage with a nuclear power plant has not been previously demonstrated, but it holds promise

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[44] TRISO stands for "tri-structural isotropic" fuel. It is a nuclear fuel form with multiple layers, allowing the fuel to withstand extremely high temperatures without risking release of radioactive fission products [388].

for enhancing the plant's overall economics and is intended to play well on grids with high penetrations of variable renewable generation.

In addition to the NEA SMR Dashboard reports, EPRI has published reports on both siting and technology assessment associated with Gen III and Gen IV (or advanced) reactor technologies [220, 221]. These reports provide in-depth discussion of strategies for using weighting criteria of reactor systems based on basic operation, site selection and characterization, maturity and remaining effort, technology capabilities, and cost/commercial related factors in choosing between reactor designs or different potential sites. Similar to the NEA report, EPRI worked to define the constraints under which reactors and power systems should be analyzed across common metrics. Tables 6 and 7 weigh the discussed nuclear technologies in terms of their progress to deployment according to the NEA's research as well as the technologies long-term applicability for various applications using constraints that can be found in the EPRI reports Table 2-3 [220].

Table 6 Weighting of various LWR reactor technologies based largely on analysis performed by the NEA [181] [182].

Reactor	Licensing	Siting	Financing	Supply Chain	Engagement	Fuel	Versatility[45]	Total
CAREM	5	6	5	5	2	4	3	30
BWRX-300	4[46]	4	5	4	5	4	2[47]	28
VOYGR	4	4	4	4	6	4	3	29[48]
KLT-40S	6	6	5	5	2	6	3	33[49]
AP300[50]	4	2	4	5	3	4	3	25
SMART	4	2	4	4	2	4	3	23
SMR-160	2	2	3	4	2	4	3	20

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[45] The versatility was assessed based on the outlet temperature and applicability for applications beyond electricity production.

[46] Licensing score of the BWRX-300 has been adjusted upward from the Dashboard due to its apparent customer base, noting the agreement between the TVA, Ontario Power Generation, and Synthos Green Energy [387].

[47] Boiling of the reactor coolant within the reactor core limits the uses of reactor heat without adding additional equipment beyond the basic components inherent to a BWR plant, as compared to a PWR.

[48] The recent (early-October 2023) announcement from Standard Power regarding collaboration with NuScale likely boosts the financing and siting scores for VOYGR. Fuel is also likely closer to a 5 than a 4, being essentially the same fuel form as existing PWR fuel, and licensing is closer to a 5 than 4, as the 50 MWe variant has already received certification from the NRC. Total score for the VOYGR is closer to 32-33, rather than 29.

[49] As a Russian design, the KLT-40S design has limited prospects in the western world, at present.

[50] As this reactor design was only announced on May 4, 2023, these values do not include input from the NEA's SMR Dashboard Volumes I or II. The AP300 siting and engagement values remain low as a result of how recently the design was announced.

Reactor	Licensing	Siting	Financing	Supply Chain	Engagement	Fuel	Versatility [45]	Total
PWR-20	1	2	3	3	3	4	4[51]	20

Notes for preceding Table: The licensing, siting, financing, supply chain, engagement, and fuel scores come directly from this analysis which scale from 1-6 (1 = no information, 6 = major progress) [181]. The versatility rating has been added with this report and is based on the fuel type and outlet temperature (1 = low versatility & reproduction, 6 = high versatility & reproduction).

Table 7 Weighting of various non- LWR reactor technologies based largely on analysis performed by the NEA.

Reactor	Licensing	Siting	Financing	Supply Chain	Engagement	Fuel	Versatility [52]	Total
Hermes	3	4	5	4	3	3	4	26
Natrium	2	4	4	4	3	3	4	24
HTR-PM	6	6	5	5	2	6	6	36[53]
XE-100	2	4[54]	4	4	6	3	5	28
IMSR	2	2	3	3	6	2	5	23

Notes for preceding Table: The licensing, siting, financing, supply chain, engagement, and fuel scores come directly from this analysis which scale from 1-6 (1 = no information, 6 = major progress) [181]. The versatility rating has been added with this report and is based on the fuel type and outlet temperature (1 = low versatility & reproduction, 6 = high versatility & reproduction).

Further siting considerations from the EPRI document include recommendations to account for specific conditions which can be captured by a plant parameter envelope [221]. A plant parameter envelope is a set of bounding values for a required site when a technology has not yet been selected. As mentioned previously, this is the methodology utilized by TVA in obtaining the ESP for their Clinch River site. Utilizing a plant parameter envelope allows a site to account for necessary location-based conditions to analyze multiple potential technologies for the same geographic location. These bounding attributes can range from land requirements, cooling water needs, population, seismic conditions, and other weather attributes (which was initially described in NEI 10-01 [222]). The necessary siting procedure contains 5 key elements 1) Identify the Region of Interest, 2) Screen to Candidate Areas, 3) Identify Potential Sites, 4) Screen to

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[51] The Last Energy PWR-20 has been granted a higher versatility score than the other listed PWR technologies due to its smaller size and thus being able to server smaller loads and being more easily transportable.

[52] The versatility was assessed by normalizing the outlet temperature between the minimum and maximum temperatures found in the paper, and type of fuel used (the outlet temperature scaled between 1 for uncommon fuel types, and 2 for common types, where as the temperature scaled from 1-5)

[53] While the highest score shown, being a Chinese-designed reactor, export to the U.S. is not feasible with current geopolitics.

[54] The Xe-100 siting score has been elevated to a 4 now that the Seadrift site in Texas has been selected for an initial installation.

Candidate Sites, and 5) Identify Proposed and Alternative Sites [221]. To properly weigh the merit of any technology within Michigan, it is recommended that regions of interest be developed along with a plant parameter envelope using the regions of interest and plant specific information to narrow down the needs and intended uses from advanced reactor technologies.

Important geographic and weather conditions of Michigan can be used as a basis for siting, such as its location between four out of five Great Lakes giving the state some of the largest seasonal changes as compared to other states in the same region. This requires siting considerations to take into account both hot and humid summers along with cold winters. Additionally, the frequency of “extreme precipitation events” has increased and the events are at their highest in recorded history within the past decade (as discussed in Section 4.2.a – 4.2.e) [223]. The two major siting items to be considered are greenfield vs. brownfield candidate sites. Greenfield sites are undeveloped lands that contain little to no infrastructure or hazards that could stifle new development on the land. Brownfield sites have various categories which describe the types of development that property has undergone from non-nuclear systems to existing and operating nuclear systems [221]. Brownfield sites have many potential benefits from being able to reuse water sources, level graded land, and other additional infrastructure components, along with foregoing the disturbance of the land at a greenfield site. For some further alternative siting considerations such as converting a coal power plant to a nuclear power plant, see Section 6 of this report.

4.1.f Safety and Security Aspects of SMRs

Safety and on-site security are a priority of the existing nuclear fleet and the next generation of reactors have taken a similar approach. NEI created a white paper to illustrate safety as a prominent design feature in SMRs [224]. The SMR engineering designs not only advance reactor technology, but in doing so, also reduce their vulnerability to physical threats. A common feature across many SMRs is a compact reactor coolant pressure boundary, which can be contained mostly within the single reactor pressure vessel. This feature enhances the safety of SMRs such that a Large Break Loss of Coolant Accident (LOCA) may not have to be postulated. This is notable, as postulated LOCAs contributed to the addition of significant active safety systems for many Gen II reactors. Having no need for entire safety systems can present substantial capital cost savings. Additionally, a large portion of the SMR designs have an increase in passive physical barriers and greater simplicity in operation of the systems required for safe shutdown of the reactor. This can differ across SMR designs, but another key feature for many designs is the reactor pressure vessel being completely submerged underwater and/or below grade. The below grade design feature aids in the effectiveness of physical safety of the plant from potential radiological sabotage and minimizes aircraft impact. A reactor pressure vessel being submerged under water provides for a substantial passive heat sink in the event of an accident.

There is effort underway to draft a preliminary new licensing rule/pathway in lieu of 10 CFR Parts 50 and 52, 10 CFR part 53. This effort proposes two frameworks. Technology inclusion for physical protection using a probabilistic risk assessment that is aligned with the Licensing

Modernization Project methodology is included under Framework A, while Framework B is the traditional route that uses a deterministic approach for determining necessary physical protections and is aligned with international guidance [225]. This effort to develop a new licensing pathway has been further pushed as SECY-23-0021 was sent as a request to obtain approval from the Nuclear Regulatory Commission to amend Title 10 of the Code of Federal Regulations which would allow for future commercial nuclear plants to operate under Framework A [226]. Probabilistic risk assessment is a safety analysis technique using a probabilistic framework which considers an initiating event that leads to various outcomes dependent on the physical state of the plant's equipment and human responses within the plant using a set of event and fault trees. The three levels described by probabilistic risk assessment describe the frequency of occurrence that cause damage to the reactor core, estimating the frequency of released radioactivity, and consequences from the release events to the public and the environment.

From a physical security perspective, SMRs can be designed to adhere to the current applicable regulatory framework. Letter SECY-11-0184, suggests the current security regulatory framework is adequate to address SMRs and their deployment [227]. This is directed at 10 CFR 73, which is comprehensive and applicable to all nuclear reactors regardless of size. Changes to 10 CFR Part 73 are proposed within SECY-23-0021. The proposed changes establish a new voluntary consequence-based approach for a range of security issues such as physical security, cyber security, and access authorization to future licensed commercial nuclear power plants under Framework A or B [226]. These new proposed rule changes would still provide the necessary protections to the public's health and safety in consideration of the changes to security that affect the licensees, information, and materials that are currently not covered by existing regulations. This would allow for new information and materials that are proposed to be included in future commercial reactors to be properly regulated for security under Frameworks A or B.

4.2 Siting Considerations for Potential New Nuclear

4.2.a Process Overview Land & Siting Criteria

The general process for deploying a new commercial nuclear energy generation facility includes obtaining approval for siting, construction, and operation from the NRC. The evaluation below was based upon the process requirements provided in the following documents:

- NRC Regulatory Guide 4.7. General Site Suitability Criteria for Nuclear Power Stations. Rev 3. March 2014. (NRC 2014) (Regulatory Guide 4.7) [228]
- Electric Power Research Institute (EPRI) Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities Revision 2022 (EPRI Guide) [229]

Before preparing an application for a new nuclear facility, a suitable site must be selected. The site that is selected must satisfy business objectives for the project, meet regulatory requirements for safe construction and operation of a nuclear plant, and comply with requirements for the consideration of alternative sites. In the U.S., deployment of a nuclear facility is a major federal action, and site selection is subject to NEPA, requiring the development of an EIS [229].

The nuclear siting process begins with defining a region of interest. For this study the region of interest is the geographic area bounded by the Michigan state border lines. This discussion of siting is independent of the hypothetical nuclear locations modeled within Appendix 1, as those modeling efforts were focused on presenting illustrative economic impacts and power system impacts expected to result from a new nuclear plant build. The selection process within the region of interest includes siting constraints such as population density, proximity to load centers, or transmission lines. The selection process will be described in the environmental report that is submitted with the license application. Locations where a facility cannot be sited due to regulatory, environmental, or business constraints (e.g., locations within national parks, upon tribal land, or with no access to transportation networks, as well as unfavorable areas containing wetlands, critical habitat for endangered species, or with no immediately available source of cooling water) are then identified. Eventually, candidate areas are defined, and a number of discrete potential sites may be selected for more detailed evaluation [229].

4.2.b Environmental Considerations

Many factors are considered when siting a new nuclear power facility, such as key siting criteria for land, natural resources, health impacts, as well as environmental impacts including ecological and climate considerations. As discussed in the EPRI Guide, it is sometimes necessary to conduct site-specific studies to support identification of a proposed site from a small list of candidate sites and may include the following:

- Geotechnical borings and analysis
- Seismic boring, trenching, and/or field reconnaissance
- Preliminary water supply planning (including water rights availability) and consultation with water regulators on the viability of water supply plans
- Meteorological monitoring
- Ecological walkdowns and characterization
- Archeological walkdowns and characterization

A plant parameter envelope allows for the identification of potential sites when a specific plant design or technology has not yet been selected. The plant parameter envelope reflects bounding values across all designs being considered for each plant parameter and combines them into a single set of bounding conditions (as discussed in Section 4.4.f). Thus, sites meeting the bounding values would be considered suitable for any of the designs reflected in the plant parameter envelope. The plant parameter envelope then defines the envelope of the facility/site interface as well as conditions that if not satisfied by the site, may prevent locating a nuclear facility in that area [229]

There are several parameters that are evaluated for site suitability with respect to conditions that could lead to an accident at a nuclear facility site. Those conditions that are less likely to produce plant accidents are preferred.

4.2.b.1 Geology/Seismology

Current NRC regulations identify three geologic, seismologic, and soil parameters that must be evaluated to determine if a proposed site is suitable for nuclear development.

The safe shutdown earthquake must be determined to establish a vibratory ground motion design basis which includes detailed information about capable tectonic structures and sources. The occurrence of, or potential for, surface faulting or deformation must be identified to allow evaluation of site conditions with respect to standard facility designs. Finally, other geologic conditions (such as geologic hazards and soil characteristics) that could affect the safety of a facility must be evaluated. A common exclusionary factor are those areas where regional hazard mapping shows that Peak Ground Acceleration exceeds 0.3 g during a design basis earthquake. The presence of capable tectonic structures within the investigative area (within 200 miles of the proposed site), should be avoided to reduce the need for additional detailed geological investigation. Suitability measures have been established to evaluate surface faulting within a 25-mi and 5-mi radius of the proposed site. Geologic hazard areas such as those with active (and dormant) volcanic activity, subsidence, potential unstable slope, potential collapse, mining, etc. should be avoided in site selection. Areas with soils that might be unstable because of their mineralogy, lack of consolidation, water content, or potentially undesirable response to seismic or other events should also be avoided [229].

A seismic design category (SDC) reflects the likelihood of experiencing earthquake shaking of various intensities and is used by building design and construction professionals in building codes to determine the level of seismic resistance required for new buildings. SDCs consider the type of soil at the site, as poor soils can significantly increase earthquake shaking. The SDC ranks from A (low probability) to E (high probability) and are described by FEMA as follows [230]:

- SDC A: Very small probability of experiencing damaging earthquake effects. No potential effects of shaking.
- SCD B: Could experience shaking of moderate intensity. Moderate shaking can cause slight damage.
- SDC C: Could experience strong shaking. Strong shaking can lead to negligible damage in buildings of good design and construction; slight to moderate damage in well-built ordinary structures; considerable damage in poorly built structures.
- SDC D: Could experience very strong shaking. Very strong shaking can cause slight damage in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse; and great damage in poorly build structures. SDC D ranks from D to D3.

- SDC E: Near major active faults capable of producing the most intense shaking. Strongest shaking can cause considerable damage in specially designed structures, with frame structures thrown out of plumb; great damage in substantial buildings, with partial collapse and buildings shifted off foundations. Shaking is strong enough to completely destroy buildings.

According to FEMA, the entire state of Michigan lies within SDC A, meaning that there is a very small probability of experiencing damaging earthquake effects and no potential effects of shaking. The closest hazard zone to Michigan is approximately 350 to 600 miles from Michigan in the Lower Wabash Valley in Terre Haute, Indiana, and the New Madrid Seismic Zone [230].

According to NUREG-1437, Supplement 56, the Fermi site is in one of the most seismically stable regions in the U.S.. Since the beginning of the 19th century, no recorded earthquake epicenter has been located closer than 25 miles and only seven earthquakes have been reported within 50 miles of the site [125].

4.2.b.2 Cooling System Requirements

A cooling source is a requirement for nuclear reactors to remove waste heat. Once a reactor design has been specified, the quantity of available cooling water and ambient air characteristics are taken into consideration as a component of the cooling system requirements. NRC Regulatory Guide 1.27 provides guidance on water supply for nuclear power plants [229].

4.2.b.2.1 Cooling Water Supply

The cooling water supply criteria evaluate the quantity and quality of cooling water and the effects of withdrawal on the source water. In Michigan, the use and consumption of cooling water is governed by the Michigan Department of Environment, Great Lakes, and Energy (EGLE). Once the type of nuclear facility is identified, the cooling demand level for all cooling options and their supply requirements need to be considered. The cooling demand level used in the evaluation should allow for source fluctuation and regulatory policies while not being overly conservative and restrictive of potentially viable sources. The evaluation of water supply capability should include both the effects on water consumption from the source and the effects on water quality [229].

Cooling water sources within Michigan that can supply the cooling water demand (either singly or in combination) should be identified. These sources may include surface water (lakes), groundwater, and reclaimed water supplies (for example, water treatment plant effluent). Water supply plans should be developed to evaluate low-flow conditions based on historical seven-day and ten-year low flows. Cooling water sources not meeting the plant cooling water demand should be excluded from further consideration [229].

The potential effects of cooling water withdrawals on water quality should also be evaluated based on the likelihood of conflicts, based on minimum flow availability, in areas with existing or expected wastewater discharges or other potentially significant water quality constraint [229].

Groundwater is not used at the Fermi site and is not planned for use in the future. The primary cooling-water source is Lake Erie [125]. Groundwater is also not used at the DC Cook and Palisades sites as there is adequate surface water available from Lake Michigan [124] [144].

Michigan has ample lakes, rivers, and streams accounting for 40,175 square miles of surface water compared to 56,539 square miles of land (USGS 2018). The state is bounded by the great lakes to the north, east and west, offering significant surface water resources to support the cooling needs of new nuclear development in the state.

4.2.b.2.2 Ambient Air Requirements

Ambient air characteristics of a potential site affect the design of heat removal systems. Areas within Michigan with the lowest dry bulb temperatures, or ambient air temperatures, not affected by moisture of the air, should be considered the most suitable. Evaluations are based primarily on data obtained from the closest weather station with a reasonable period of record (more than 20 years) [229].

Dry bulb temperatures in Michigan are moderate with the lowest occurring in areas to the north. Ambient air conditions across the state meet suitability requirements for new nuclear plant siting. According to the National Centers for Environmental Information, the average air temperature in Michigan, based on records ranging from 1895 to 2023, is 43.6 °F. The monthly mean for each month for the same period of record are as follows [231]:

- January – 18.1 °F
- February – 19.1 °F
- March – 29.0 °F
- April – 41.9 °F
- May – 53.6 °F
- June – 63.3 °F
- July – 68.1 °F
- August – 65.9 °F
- September – 58.5 °F
- October – 47.5 °F
- November – 34.6 °F
- December – 23.3 °F

4.2.b.3 Flooding

Areas in Michigan that are less prone to flooding are more suitable for a new nuclear plant site. 10 CFR 100 and RG 4.7 provide requirements and guidance regarding the physical characteristics of potential nuclear sites. Major flood-prone areas should be avoided, such as low-lying areas near rivers and streams, marshy areas, and/or elevations at or only slightly above the typical water level. As part of the screening criteria evaluation siting process, the proximity of each potential site with respect to the 100-year and 500-year flood zones should be determined. Consideration of the difference in elevation between potential sites and the nearest major body of water should be evaluated. Additionally, if available, the flood zone designation of potential sites with respect to the 100-year and 500-year flood zones should also be evaluated [229].

Some of the land within the site boundary at Fermi is considered poorly drained. Most undisturbed areas are either covered with water or subject to frequent flooding. In general, the potential for flooding at Fermi exists from storms and winds on Lake Erie that can cause a surge in lake levels and subsequent “seiches” [125]. At the Palisades site, developed or maintained areas occupy about 80 acres of the total 432 acres. Most (68%) of the undeveloped portions of the Palisades site are dominated by forest. The remaining areas include early successional plant communities, steep dunes and flats, and small scattered wetland communities. The region in which Palisades resides is devoted to agriculture, including blueberry farming on poorly drained sites and orchards and vineyards on better drained soils [144]. For the DC Cook site, the majority of the land area is covered by heavily wooded, rugged sand dunes with occasional wetlands [124].

Many low-lying areas of the Great Lakes have been repeatedly damaged by coastal flooding. In Michigan, coastal floods periodically result in property loss to homes and businesses. State and local government facilities and operations are also severely affected by flooding. Approximately 300 miles of Michigan's Great Lakes mainland is subject to coastal flooding [232].

In Michigan, and nationally, the term floodplain describes the land area that will be inundated by the overflow of water resulting from a 100-year flood (a flood which has a 1% chance of occurring any given year). An estimated 6% of Michigan's land is within the 100-year flood-prone areas including about 200,000 buildings [233].

4.2.b.4 Nearby Hazardous Land Uses

The purpose of this criteria is to incorporate NRC guidance on site suitability based on the proximity of airports, dams, transportation routes, and military and chemical facilities. 10 CFR 100.21(e) provides additional requirements for the evaluation of nearby hazardous land uses. RG 4.7 specifies that potential sites located within 10 miles of major airports and within 5 miles of hazardous facilities and activities should be avoided to the extent possible. Siting consideration of potentially hazardous sites needs to be evaluated. This includes both the number, distance, and types of existing land uses. According to RG 4.7, the acceptability of a site depends on establishing that (1) an accident at a nearby industrial, military, or transportation facility would not result in radiological consequences that exceed the dose specified in 10 CFR 50.34, or (2) the accident poses no undue risk because it is sufficiently unlikely to occur (less than about 10^{-7} per year). Sites that do not meet one of these acceptability standards may be constituted as a hazardous site. Consideration for potential hazardous sites includes: major airports, military bases, oil or gas wells and pipelines or storage, manufacturing facilities, chemical facilities, refineries, mining and quarrying operations (involving blasting), smaller airports, dams, freight rail lines, major ports/docks and anchorages for hazardous materials, and nearby power plants [229].

Areas sufficiently remote from such hazardous land uses in the state of Michigan include undeveloped areas like farmland and forests. According to the 2017 Census of Agriculture, Michigan has a total of 9,764,090 acres of farmland including 7,924,480 acres of cropland, 341,391 acres of permanent pasture and rangeland, 975,652 acres of woodland, and 522,567 acres of land in buildings. Thus, a total of 9,241,523 acres of farmland in Michigan is undeveloped [234]. Forests account for approximately 20 million acres of Michigan's geography, or 53% of the total land use [235]. However, brownfield sites or co-located facilities can be a consideration provided that the other siting criteria are advantageous.

4.2.b.5 Extreme Weather Conditions

The purpose of this criteria is to address site suitability with respect to extreme weather conditions. Extreme weather is a concern for nuclear power plants which must be designed to withstand conditions such as tornadoes, wind, and precipitation. It is not necessary to exclude or avoid potential sites based on extreme weather conditions [229]. The data for extreme weather that is readily available for Michigan include fastest mile speed (recorded as peak gusts), number of tornadoes per 10,000 square miles, number of hurricanes (making landfall), and maximum 24-hour precipitation values (rain or snow).

Monroe, Van Buren, and Berrien counties, where Fermi, Palisades, and DC Cook are located respectively, experience severe weather events, such as hail, tornadoes, floods, and heavy snow [125] [124] [144].

Since 1950, 331 tornadoes have struck Southeast Lower Michigan. Tornado intensity is determined by the F-scale, 1-5 with 5 being the most violent. Of the 331, only one tornado reached an F5. Regarding hurricanes, no actual hurricane has ever been observed in Michigan. However, remnants of tropical storms have affected the Great Lakes and Southeast Lower Michigan [236].

4.2.b.6 Radionuclide Pathways

Nuclear power reactors are generally designed to allow for routine liquid and gaseous radioactive discharges from blowdown and cleaning of various systems such as demineralizers, polishers, and HEPA filters. Before any liquid or gaseous waste is released into the environment it is heavily filtered, monitored, and contained to ensure that the effluent release is within the bounds described by Regulatory Guide 1.112. These effluents are discharged at low concentrations and low flow rates in order to limit the consequence of the release to people and the environment. Radioactive liquid releases to surface water such as streams, rivers, or lakes, may be limited based on the potential dilution flowrate, the proximity of the discharge to consumptive users, and the baseline radioactivity of the surface water. Potential sites should be screened at the county level for nearby agricultural sites for food ingestion pathways. Public exposure to radiation through airborne and surface water radionuclide emissions from the power station through the food chain for adjacent crops and pasture operations must be considered. Agricultural uses of land which could be affected by airborne releases include farming and grazing. Agricultural uses of water which could be affected by liquid releases include irrigation. Food and irrigation exposure pathways are generally minimal, but site locations with lower irrigated or non-irrigated crop and pasturelands are preferred [229].

According to the latest water use data provided by EGLE, agriculture had the highest consumptive water use in 2021 at 38% . Following agriculture is electric power generation (29%), public supply (18%), industrial (10%), non-agricultural irrigation (4%), livestock (1%), bottled water (0.2%), and commercial (0.1%) categories followed [237]. Approximately 56% of Michigan residents get their drinking water from surface water and 44% get their drinking water from groundwater [238].

4.2.c Ecological Criteria

Evaluation of ecological criteria for potential effects from both construction and operations needs to be considered.

4.2.c.1 Construction-Related Effects on Aquatic Ecology

The following sections cover the construction-related effects on aquatic ecology under the ecological siting criteria.

4.2.c.1.1 Disruption of Important Species/Habitats

The purpose of this criteria is to address potential construction-related impacts on aquatic or marine ecology. RG 4.7 states that new nuclear facilities should consider the effects on populations of important species or ecological systems. In accordance with the Endangered Species Act, the proposed site should not jeopardize the continued existence of designated critical habitat of threatened or endangered species. The habitat areas (including seasonal use) of particular concern include breeding and nursing, nesting and spawning, wintering, and feeding. Those areas designated critical or protected should be excluded.

Consideration of aquatic species and habitats focuses primarily on potential cooling water sources and their location in relation to potential sites. When possible, cooling waters should not be sourced from critical habitats. If a large portion of available cooling water sources include a critical habitat, it may be considered with significant environmental review. The proposed site is evaluated for effects on important species using the total number of rare, threatened, and endangered species that occur in the county where the site is located [229].

To avoid and minimize impacts to protected species, facility developers use a number of mitigation measures. For example, established facilities such as DC Cook, Palisades, and Fermi closely monitor the cooling water intake and discharge according to their respective NPDES permits. Permit limits are reviewed on a regular basis by State regulatory agencies to ensure the protection of aquatic biota. Further, vegetation management guidelines are followed to avoid potential damage to terrestrial species habitats. Commitments to other protective measures that facilities follow include avian protection plans, wildlife management plans, specialized permits (e.g., Special Purpose Utility Permit) and communications with State agencies [125] [124] [144].

4.2.c.1.2 Bottom Sediment Disruption Effects

The purpose of this criteria is to address potential short-term effects to aquatic/marine resources during construction-related activities (such as from dredging for the intake or for barge access where applicable) that disturb bottom sediments. Sediments in all types of water bodies across the country can have contamination at levels that harm benthic and aquatic communities and potentially threaten human health and wildlife. Consideration should be given to the extent of contamination and grain size. Generally, fine-grained sediments have higher concentrations of contaminants than coarser sediments. Contaminants of greatest concern typically are heavy metals, persistent, toxic, bioaccumulative organic compounds. A report prepared by the EPA addresses general trends in contaminated sediment for major water bodies and can be used to assess sediment quality. In addition, each state compiles information on general water quality for water bodies and submits to the EPA to identify contaminated areas. Brownfield sites can also be considered depending on contamination history [229].

The range of sediment grain size for a potential site would need to be identified. A site with a high percentage of clay and silt would be the least suitable. Coastal sites, such as the Great Lakes, are assumed to have more suitable sedimentation rates. However, the grain size component may be excluded entirely from the site evaluation [229].

There are a number of measures nuclear power facilities can use to mitigate adverse effects on benthic and aquatic communities during construction and operation. For example, water quality monitoring is conducted at various points following a plant's NPDES permit. Storm Water Pollution Prevention Plans are also developed to preserve and improve water quality by identifying potential point sources of stormwater pollution at a specific site. The storm water pollution prevention plan outlines best management practices to reduce pollutants, including those associated with high sedimentation rates. Pre-construction activities including habitat surveys and team trainings can also be utilized to mitigate impacts to aquatic communities.

4.2.c.2 Operations-Related Effects on Aquatic Ecology

The following sections cover the operations-related effects on aquatic ecology under the ecological siting criteria.

4.2.c.2.1 Thermal Discharge Effects

The objective of this criteria is to determine the suitability of the proposed site based on the potential for thermal discharge effects. The two issues that are generally considered are the disruption of important species/habitats and the potential effect on water quality of the receiving water. The ability for a site to obtain thermal discharge permits would depend on the applicable Michigan and federal CWA regulations. For Michigan, this would require a State-issued NPDES permit. NPDES permits are required under Section 402 of the Federal Water Pollution Control Act (the “Federal Act,” 33 U.S.C. 1251 et seq., as amended, P.L. 92-500, 95-217); and Part 31, Water Resources Protection, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended (the NREPA). Part 31 of the NREPA also provides authority for the State to issue NPDES permits. The Michigan Department of Environmental Quality (DEQ) administers the NPDES permit program for the State of Michigan. [239] CWA section 316(a) and its implementing regulations provide for variances from thermal effluent limitations in NPDES permits. Most thermal limitations in NPDES permits are driven by water quality standards (WQS). If a discharger is unable to comply with water quality-based effluent limitations at the point of discharge, applicable WQS may provide specifications for granting thermal mixing zones which allow portions of the waterbody to exceed the temperature criteria if the mixing zone provisions are met. If the permittee is unable to comply with the applicable thermal discharge limits at the edge of the regulatory mixing zone or at the point of discharge if a regulatory mixing zone is not appropriate, a permittee may seek relief from these standards by applying for a variance in accordance with CWA Section 316(a) and its implementing regulations. [240] Once-through cooling systems have more difficulty meeting relevant thermal discharge limits than evaporative (cooling tower) systems. Sites that would need to discharge into sensitive or protected waters and/or with existing thermal pollution concerns would be less favorable [229].

Nuclear power plants can, and are required to, use mitigation measures to minimize thermal discharge effects on aquatic ecology. For example, water temperature is monitored at different point locations following the NPDES permit. Aquatic surveys are also taken periodically to monitor aquatic species within the vicinity of the intake and discharge structures. Reports, such as Receiving Water Monitoring Reports, may also be submitted on an annual basis as part of the NPDES permit regulations.

4.2.c.2.2 Entrainment/Impingement Effects

The objective of this criteria is to evaluate prospective sites for potential entrainment and impingement of aquatic species at water intakes. Potential effects are identified in RG 4.7, which indicates that important aquatic habitats should be avoided as locations for intake structures. The EPA has issued rules encouraging the use of closed-cycle systems and best technology regarding entrainments for new units. In NUREG-1437, the NRC concluded that plants with cooling towers and appropriate intake design would have a minor impact on entrainment and impingement of aquatic organisms [229].

4.2.c.2.3 Dredging/Disposal Effects

The purpose of this criteria is to evaluate sites for potential environmental effects related to maintenance dredging. The two considerations that should be used to predict consequences are the extent of contamination from upstream sources and the grain size of sediments in the area. Sites with coarser-grained sediments and a low concentration of heavy metals/toxic organic compounds would be the most suitable [229].

4.2.c.3 Construction-Related Effects on Terrestrial Ecology

The following sections cover the construction-related effects on terrestrial ecology under the ecological siting criteria.

4.2.c.3.1 Disruption of Important Species/Habitats: Plant Site

The objective of this criteria is to evaluate the sites for the potential of construction-related effects on important species and terrestrial ecology. Thus, the effects on the population of important species or ecological systems should be considered when selecting a potential site. In accordance with the Endangered Species Act, the proposed site should not jeopardize the continued existence of designated critical habitat of threatened or endangered species. The habitat areas (including seasonal use) of particular concern include breeding and nursing, nesting and spawning, wintering, and feeding. Those areas designated critical or protected should be excluded. If possible, the proposed site should avoid ecologically sensitive and special designation areas such as wildlife management areas/national preserves and biological stations. When possible, effort should be made to avoid areas with threatened and endangered species (flora and fauna) are known to be present. The proposed sites may be assessed with and without critical habitat restrictions to determine the overall impact of critical habitats. The proposed site should be evaluated based on the impact to important species using the total number of rare, threatened, and endangered species that occur in the selected county. The proposed site would be rated based on the total number of federally protected species within the selected county [229].

Michigan's NREPA, Part 365, "Endangered Species Protection," contains provisions for the protection of species deemed to be endangered or threatened at the State level. The NREPA designates the Michigan Department of Natural Resources as the agency responsible for determining which species should be listed as State-endangered or State-threatened and for managing protection and recovery programs. Within Monroe County, the site of Fermi, 87 State-listed terrestrial species occur. Of the 87 State-listed terrestrial species, there were 7 with known occurrences within 1.5 miles of the site [125]. At the Palisades site, 101 State-listed terrestrial species potentially occur within the vicinity of the site [144]. At the DC Cook site, 121 State-listed terrestrial species potentially occur within the vicinity of the site, 10 of which are believed to be extirpated within the state of Michigan [124].

4.2.c.3.2 Disruption of Important Species/Habitats – Transmission Corridor

The objective of this criteria is to evaluate potential sites based on environmental impacts of construction of the transmission corridors. Each potential site should be evaluated based on the environmental sensitivity of the area between the site and the nearest transmission interconnection. The potential site should be evaluated based on the proximity/distance to the nearest existing electrical power corridors (345-kV or higher transmission line). The most suitable site locations in Michigan would be those with access to an existing right-of-way to avoid expanded land clearing. For potential sites that would require extensive land clearing for a new right-of-way; land use, land status, and other ecological factors should be considered [229].

4.2.c.3.3 Disruption of Wetlands

The objective of this criteria is to evaluate possible sites based on the potential to disrupt wetlands during constructed-related activities. In accordance with Executive Order E.O. 11990, Protection of Wetlands, adverse impacts to wetlands should be avoided to the extent possible and where there is a practicable alternative. Areas in Michigan with known, large and important higher-quality wetland areas should be excluded from consideration. Factors relating to wetlands disruption would include the total wetlands (acreage) within a proposed site, total acreage of high-quality wetlands within the proposed site, and siting flexibility. When wetlands are present near the proposed site, an evaluation must be performed to determine what affect, if any, will occur due to construction-related dewatering [229].

Coastal emergent wetland is the most prevalent terrestrial habitat on the Fermi site and accounts for approximately 32.8% of the sites undeveloped terrestrial land cover. The Detroit River International Wildlife Refuge consists of nearly 6,000 acres of coastal wetlands, marshes, shoals, waterfront lands, and islands along 48 miles of shoreline on the lower Detroit River and western shore of Lake Erie. Congress established the Detroit River International Wildlife Refuge in 2001, and it is the only International Wildlife Refuge in North America.

The majority of the land area of Palisades is heavily wooded, with occasional wetlands. The majority of the land area of DC Cook is covered by heavily wooded, rugged sand dunes with occasional wetlands [124] [144].

4.2.c.4 Drift Effects on Surrounding Areas

The objective of this criteria is to evaluate the suitability of sites in Michigan with respect to the potential effects of cooling tower drift. The evaluation considers the effects to the surrounding areas and the cooling water source. According to RG 4.7, cooling tower drift may contain trace amounts of water treatment chemicals, dissolved solids, and suspended solids that could affect terrestrial biota and damage other resources. The source water with the highest dissolved solid/salt content would have the greatest negative impacts. Areas with the most important/highest quality habitat and wetlands would be least suitable for a potential site [229].

4.2.d Socioeconomic Criteria

The siting, construction, and operation of a nuclear facility can impact local labor, transportation facilities, and community services. When determining a location within Michigan for a site, the following factors should be evaluated; local labor supply, importing labor, local infrastructure and community services, local taxes and community expenditures, community culture and character, and minority and low-income populations (environmental justice) [229].

4.2.d.1 Socioeconomics: Construction-Related Effects

The objective of this criteria is to evaluate site suitability based on the number of construction workers that will move to the vicinity of the plant site and the capacity of the community to accommodate an increase in population. When evaluating areas in Michigan for potential sites the following areas should be considered; labor requirements, location of the labor pool, and number of in-migrants (direct and indirect). Areas with an adequate labor force or with a reasonable commuting distance from a major metropolitan area would be the most suitable [229].

4.2.d.2 Socioeconomics: Operations-Related Effects

The greatest socioeconomic impacts typically occur during the construction stage. The impacts of an increased number of workers to operate a nuclear facility tends to benefit that the community. Such benefits include special tax plans, support to local emergency planning efforts, and educational programs [229].

Current Michigan nuclear power plants and the communities that support them can be described as a dynamic socioeconomic system. The communities supply the people, goods, and services required to operate the nuclear power plant. Power plant operations, in turn, supply wages and benefits for people and dollar expenditures for goods and services [125].

4.2.d.3 Environmental Justice

The purpose of this criterion is to compare areas in Michigan to determine if there would be potentially disproportionate effects to minority and low-income communities. According to NRC RG 4.7, areas that, if developed, could result in a disproportionate (adverse) effect on minority or low-income populations should be avoided as sites for nuclear facilities. Population data for minorities and low-income populations across Michigan should be collected and compared which can be directly taken from the Michigan Environmental Justice Screening tool (MiEJScreen) [241]. This tool takes into account environmental exposures, environmental affects, the corresponding sensitive populations, and other additional socioeconomic factors. The cumulative score between the environmental conditions and population characteristics provide a composite score which helps asses the level at which the population group would experience adverse human and environmental impacts. Areas with a low population of minorities and low-income populations are the most suitable for various land work and installation of nuclear systems [229].

4.2.d.4 Land Use

The objective of this criteria is to evaluate the suitability of areas in Michigan with respect to potential conflicts with existing land uses. RG 4.7 identifies three general land uses that should be considered when siting a nuclear facility: consistency with land use plans adopted by federal, state, regional, or local agencies; specialty crop production; and aesthetic effects. To acquire a construction permit or operating license, RG 4.2 also requires that water rights, land use restrictions, and cultural/historic impacts be considered as well as state or local zoning and other permitting restrictions that the NRC evaluates if acquisition of permits is feasible. The purpose of the land use evaluations is to avoid sensitive land uses, such as amenity areas, early in the site selection process. Lands that are established public amenity areas- those dedicated by federal, state, or local governments to scenic, recreational, or cultural purposes are generally excluded from consideration. Other types of dedicated land use that may be excluded include Department of Defense military installations and protected habitats for aquatic and terrestrial species. Sensitive protected land areas within Michigan should be identified and avoided during the site selection process. To the extent possible, proposed public amenity areas, ecological preserves, sensitive areas, as well as known large historic places on the National Register of Historic Places should also be identified and avoided [220].

4.3 Advanced Nuclear Recent Announcements

Information regarding the developments of advanced nuclear technologies is constantly evolving on a week-by-week basis. While not discussed in detail due to the timing of development of this report, a brief listing of some late-breaking information with some of the newest nuclear news developed from August – early December 2023 has been provided below.

- Standard Power is a provider of infrastructure to advanced data processing companies and announced in early October 2023 to use NuScale’s technology to develop two SMR-powered facilities [242].
- TerraPower has officially acquired the plot of land that is to be used to construct the Natrium Nuclear Power Plant in Kemmerer Wyoming, as announced in mid-August 2023 [243]..
- The NRC in August 2023 has finished the preparation to issue a final rule for emergency preparedness for SMRs and other new technologies [244]. This will have implications for regulatory guides used within these systems that apply risk-informed, performance-based emergency preparedness requirements to SMRs and other new technologies.
- TVA has officially signed a “two-party agreement with GE-Hitachi” that will support the planning and preliminary licensing for a potential deployment of an SMR which could be completed as early as 2030 [245].
- Microsoft has soft plans to use advanced reactors to power its data centers and AI servers due to the massive energy requirements, as indicated by a September 2023 job posting [246].
- The DOE has completed final testing loops to safely assess and experiment with varying LOCAs within reactor cores at INL and plans to further the testing by applying it to varying coolant mediums such as the sodium used within the Natrium reactor [247].
- Centrus produced and shipped the US’s first 20 kg of HALEU fuel. This project was completed two months ahead of schedule. With this demonstration complete, Centrus

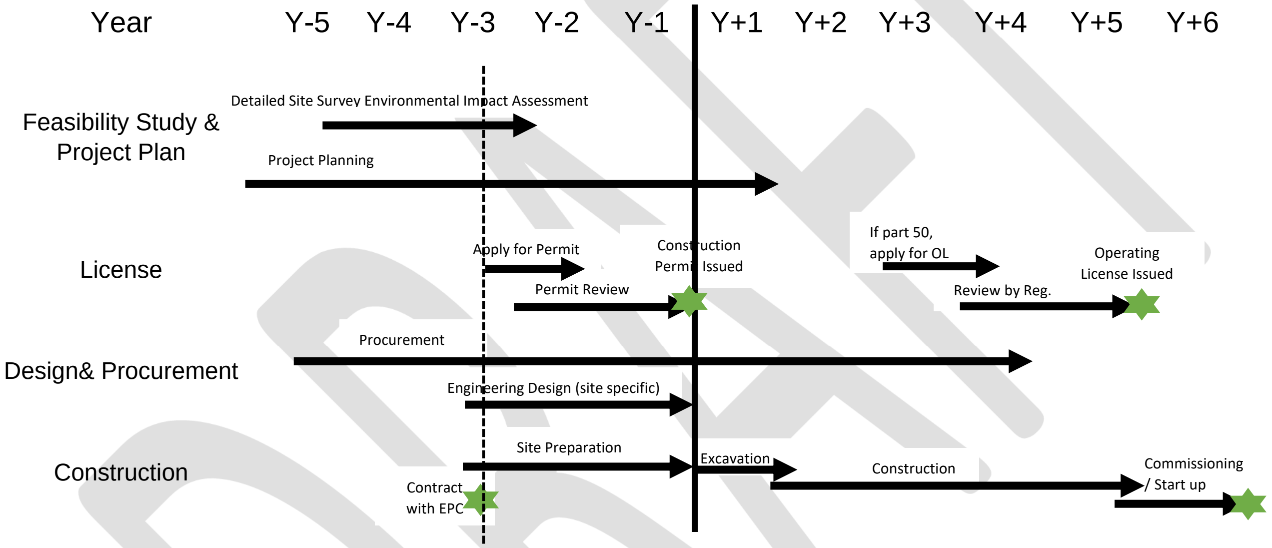
plans to produce 900 kg of HALEU in 2024 which will be used towards fueling the initial cores of two demonstration reactors rewarded under the DOEs ARDP as well as support the fueling and testing of many other reactors [248].

- Oklahoma Senate held a meeting with NEI in October of 2023 about the benefits of reactors within the vast space of Oklahoma including SMR and microreactor technologies. Additionally, it was shown that within the US overall vested public had 61% of people in support of new nuclear systems [249].
- Holtec International announced in early-December 2023 that it would start a program to build two SMR-300 reactor units at Palisades [250].
- Emirates Nuclear Energy Corporation (ENEC), during the hosting of COP28, has announced new memorandums of understanding (MOU) with three different companies which have intentions to deploy nuclear reactor technologies worldwide. The MOUs are used to expedite and centralize the UAE’s approach to developing nuclear technologies and were put in place with the following companies:
    - GE-H has worked with ENEC to identify opportunities for future investments in SMR technology. Additionally plans to lead broader development in regional deployment of the BWRX-300 SMRs in the Middle East and Africa. The partnership also includes the potential applications of the BWRX-300 in non-traditional applications such as hydrogen production [251].
    - Westinghouse has signed an MOU regarding the eVinci microreactor as a solution to energy security and climate change. Under the new MOU ENEC and Westinghouse will scope the future opportunities for the eVinci microreactor implementation in the UAE as well as overseas [252].
    - TerraPower has signed an MOU during the COP28 conference and covers collaboration between ENEC and TerraPower across a range of activities, including technical design and the commercial viability of the Natrium technology in the UAE and US. Further work will include assessing the optimal deployment strategy to support grid stability through various energy storage avenues [253].

5. NUCLEAR PROJECT SCHEDULE ASSESSMENT

Construction timelines for nuclear reactors have been notoriously difficult to nail down. Project schedules have been considered a substantial negative attribute for nuclear power technology within the U.S. since around the mid-1970s. Timelines for completing construction of nuclear power projects increased between the mid-60s and mid-70s. This was attributed to the improper estimation of time required for constructing the large facilities, incomplete designs at the time of construction start, over-extension of reactor vendor companies across too many different projects, changing regulations (particularly following the meltdown at TMI-2), as well as failure to plan sufficient contingencies to account for minor and major setbacks during this period. In the recently-published Advanced Nuclear Liftoff report, the DOE has outlined a general overall project timeline for new nuclear construction. This timeline considers the steps taken before construction can begin, along with the timeline after the construction permit has been issued all the way through testing/commissioning and entry into commercial operation [29]. Some discussion of project timelines is also included within Section 2 of Appendix 1. The timeline utilitzed in Appendix 1 was for the purpose of modeling the economic impacts for the construction phase of a project.

Table 8 Illustrative major steps for building a nuclear power plant adapted from DOE [29].



This timeline suggested by the DOE is representative of a general case for a nuclear power plant and shows a total duration from site selection to startup date taking approximately 11 years. Worse case scenarios than this timeline have been demonstrated in the real-world, such as the most recent new nuclear construction project at Vogtle Units 3 and 4, which has taken over 13 years to-date with Vogtle Unit 3 having just entered commercial operation as of July 31, 2023 and Unit 4 having just begun its initial fuel loading within the same month. Unit 4 is still in the process of startup testing and commissioning, which is expected to be completed in 2024. The long duration of the Vogtle Units 3 and 4 construction project has been due to a multitude of issues that were based on reworking original designs, supply chain delays, and low worker productivity. These issues largely resulted from factors associated with this project having been the first newly-started reactor construction project to have started construction after the 1980s and actually been completed[55] within the U.S. The two prior nuclear power reactors to finish construction and enter

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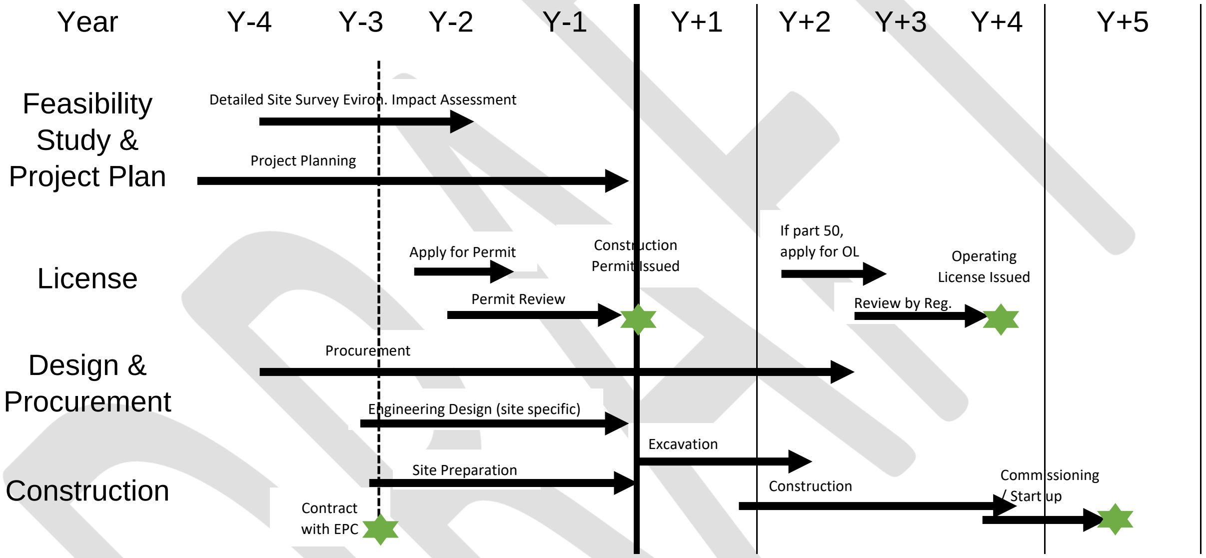
[55] Construction for V.C. Summer Units 2 and 3 began at roughly the same time as Vogtle Units 3 and 4, but construction was halted after substantial work was completed, with the Combined Licenses from the NRC subsequently terminated in March 2019 [393].

commercial operation are Watts Bar Unit 1 which began operation in 1996 and Watts Bar Unit 2 which began operation in 2016 in East Tennessee. Initial construction of the Watts Bar Units began in 1973 [254]. . In consideration of the median and worst-case scenarios, a realistic best-case scenario can be developed by limiting design changes following construction start, ensuring a strong supply chain, and pushing for higher productivity using a skilled workforce and project planning incorporating prior lessons learned. In consideration of the median construction time for reactors globally between 2000 – 2015, a reasonable achievement of a nine year project period, approximately 114 months, from project planning to commissioning is shown below.

Table 9 Best case scenario for completion of a nuclear power plant in the U.S. [29, 255].



This reduction in time would require strong coordination between the project team, reactor licensee, and the NRC due to the regulatory guidelines that must be followed to ensure the proper construction and safe operation of all the components within the commercial plant. The timeline within Table 8 is an example of a new LWR being constructed at a greenfield site (further explained within section 6). Reactor sites that would be using brownfield sites that have undergone prior nuclear licensing evaluations should be able to take advantage of portions of the prior licensing work, reducing the duration of some licensing activities. Of particular interest within the state of Michigan, the possible restart of Palisades would not be subject to the full timeline shown in Table 8, as the structures, systems, and components at Palisades are already in place and have previously been approved for operation, rather than needing to be designed, procured, and constructed. An NRC public meeting was held on August 29, 2023 related to the possibility of a Palisades restart [256]. It should be noted that there is no prior precedent for a nuclear plant to restart in the U.S. after having entered the decommissioning phase. . Holtec will need to work with the NRC to reinstate the previous operating license to operate the plant through 2031, the expiration date for the operating license licensing prior to the prior shutdown. The existing NRC subsequent license renewal process could be pursued by Holtec to extend the operating license an additional 20 years. This push to restart Palisades has great momentum as the state of Michigan has provided support to Holtec which is further discussed in Section 7.5.a.

For another unique siting opportunity within Michigan, work has been previously completed to support potential additional nuclear generation at the Fermi site, as GE-Hitachi in tandem with DTE Electric have previously supported licensing efforts related to future construction and operation of what would be Fermi Unit 3 as a GE-H approximately 1530 MW$_e$ ESBWR [257]. DTE Electric has been granted a COL for Fermi Unit 3 [258], but has not committed to building this reactor technology. By already having the license from the NRC to construct and operate this plant, the amount of time it would take for the reactor to become operational at the Fermi Power Station could likely be shortened from the 11 years outlined since the design of the reactor has been completed substantially enough and site studies have been substantially completed for the NRC to have granted a COL. With the approved COL, the licensing process would not be expected to drive the project schedule. Instead, the project schedule would be expected to be driven by the procurement process. A more detailed deep dive into the procurement process would be necessary to determine the schedule for deploying the ESBWR at the Fermi Power Station. Alternately, if a different reactor design technology were planned to be built at the Fermi site, some of the prior work relating to the Fermi 3 COL application could likely be repurposed to shorten the timeline for a new nuclear project at Fermi. While this might shorten the timeframe from the roughly 11 years outlined above, it would not be expected to have the same shortening potential as completion of the already-licensed Fermi 3 using the ESBWR reference design. Other projects involving SMRs have involved substantial engagement with the NRC and public in multiple states, with hopes for more rapid deployment timelines than those experienced for large scale reactors.

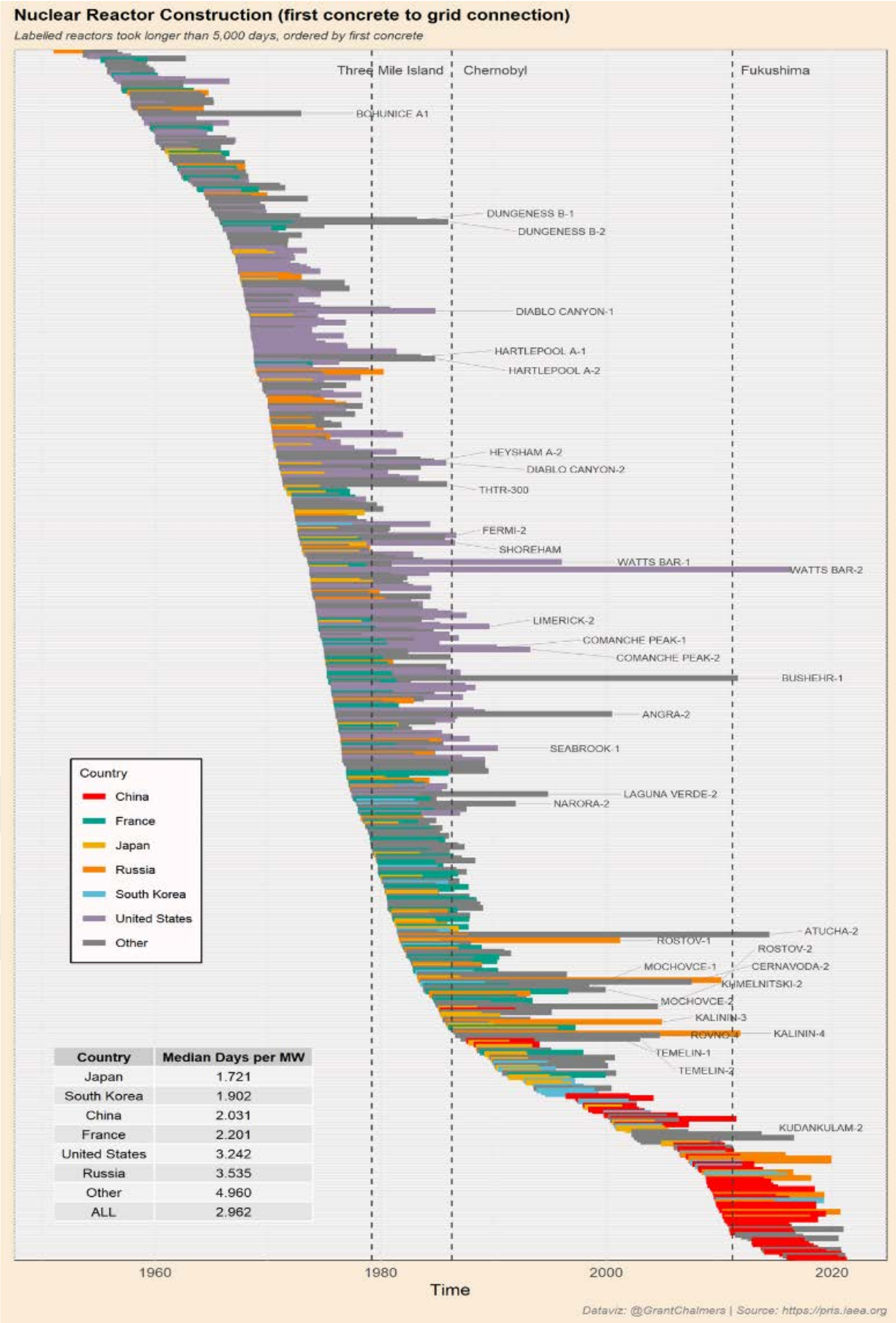
Utah Associated Municipal Power Systems had partnered with NuScale to build the Carbon Free Power Project as a six unit VOGYR-6 on a site at INL. Investigations into siting started in 2021 and the plant had been projected to start operations in 2029 [259]. As of 2023, the projected timeline for starting operations had not changed, giving an eight year timeline from the start of physical site characterization work [260]. In November of 2023, however, this project was cancelled due to insufficient subscriptions for the power the project was planned to generate, following cost escalations driven primarily by raw material cost inflation [261].

X-energy has selected Dow's Seadrift operations manufacturing site in Texas for an installation of Xe-100 reactors. The construction application submittal is currently being prepared for the NRC [262]. This project is projected to have its pre-construction phase completed within the next three years, and to complete the construction and installation of the SMRs by 2030. This project completion will be a substantial milestone for SMR technologies as it will provide both process steam and electricity for a manufacturing site within Texas that covers over 4,700 acres. The Xe-100 reactors will supplant a substantial amount of site emissions (440 MT of $CO2_e$/yr) [262].

TerraPower's Natrium project in Wyoming has been underway in earnest since 2021 with a construction permit application currently being prepared which had initially been planned to be submitted in 2023 [263], with plans to subsequently submit an operating license application (as the project is utilizing the 2-step 10CFR50 Part 50 licensing pathway [264]). The Natrium project has similar timeline goals to the Seadrift site with plans to have a fully constructed and operational nuclear power plant by 2030 [265].

These three new reactor projects across the country are all receiving substantial support from the DOE's ARDP in hopes of showing that smaller commercial reactor technologies can be constructed and become operational within less than a decade. Information gathered from the construction of these plants will further the operating experience for constructing these types of plants, allowing for increased efficiency in future plant construction projects. Success with these projects has the potential to start a boom in the nuclear energy industry, as demonstration of faster licensing and construction times would increase the value proposition for potential energy customers, along with encouraging potential customers that might have not previously considered nuclear power as a feasible option due to the lengthy historical development timelines within the U.S.

When considering the full construction of a reactor, the full global experience must be considered to understand what is technically feasible and achievable and how the U.S. can improve timelines for licensing and construction of commercial reactors. Information has been gathered by Voix du Nucleaire on this subject, including reactor construction timelines since the inception of the commercial nuclear power industry. A highly-illustrative graphic of these construction timeframes was created and can be seen in Figure 12 [266].



Country	Median Days per MW
Japan	1.721
South Korea	1.902
China	2.031
France	2.201
United States	3.242
Russia	3.535
Other	4.960
ALL	2.962

Dataviz: @GrantChalmers | Source: https://pris.iaea.org

Figure 12 Construction times for nuclear reactors around the world (Information taken directly from Voix Du Nucleaire) [266].

The top five producers of nuclear power around the globe have been Japan, South Korea, China, France, and the U.S. The construction experience in each of these countries has been 1.721 D/MW_e[56], 1.902 D/MW_e, 2.031 D/MW_e, 2.201 D/MW_e, and 3.242 D/MW_e respectively, showing nearly a 2-to-1 difference between the quickest and slowest median[57] construction timeline countries [266]. According to statistics from the IAEA, China and Russia are the current leaders in global production of nuclear reactors, and east Asia has a total of 28 reactors currently under construction while the U.S. has only 1 reactor currently under construction as of 2023 [267]. The recent history of long nuclear construction times and high costs have steered utility companies in the US away from building nuclear power as a whole. If construction times, licensing processes, and efficient production of these systems can be be improved, the perception of constructing a reactor will become a more realizable goal and present an increasingly desirable emissions free power generation option.

Michigan has potential to help demonstrate timeline improvements for nuclear projects from several different angles. The restarting of Palisades can demonstrate the potential timeline efficiency for nuclear projects. The Holtec plan to build their initial SMR plants at Palisades presents an opportunity to demonstrate efficiency gains associated with use of a well-characterized existing nuclear site for a new-build nuclear project. The same is possible for the addition of nuclear capacity at Fermi either with construction of an ESBWR or potentially other new reactor designs. The potential to repower retiring coal sites with SMR technologies as Coal to Nuclear (C2N) plants could also present opportunities for Michigan to lead the way in demonstrating operating experience for non-nuclear brownfield construction sites (brownfield construction sites are described in Section 4.1.e and subsequently in Section 6.1).

6. COORDINATION WITH OTHER TECHNOLOGIES

6.1 Re-Purposing Power Plant Sites

Re-using coal-fired power plant sites as nuclear generating sites has been an area of substantial interest in light of an impending wave of coal plant retirements. Loss of jobs for workers from those sites, along with loss of tax revenues, would be detrimental to the economic health of the surrounding communities. Thus, C2N plants, as described by Hansen et. al. in “Investigating the Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants” [268], have been evaluated within the DOE for determining ideal locations for siting new nuclear plants both to replace the energy supplied by the retiring plants and to ease the burden of lost jobs and tax bases within the communities surrounding those plants. From this DOE study, 80% of retiring coal plants have been shown to have amenable conditions for hosting advanced nuclear facilities such as SMRs. According to the referenced study, this presents an opportunity to site over 64 GW_e of

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[56] D/MWe = Days required for construction per MWe

[57] Use of the median construction timelines for this metric smooths out potentially overly skewing the values if an average were used.

new nuclear generation at 125 sites across the U.S., including areas in Michigan. The conversion of C2N is already underway within the U.S. and internationally. A total of 13 coal power plants have been under analysis for retrofitting an SMR by the TVA [268]. TerraPower is working to build their Natrium demonstration plant near a coal plant site in Wyoming, as part of the DOE's ARDP. EPRI is developing reports for using advanced reactors in C2N transitions. TerraPraxis is also working to develop modular strategies for repowering coal power plants with SMRs, with a partnership in place with Canadian-based reactor developer Terrestrial Energy specifically for this purpose. Additionally, NuScale is currently working with Romania's Nuclearelectrica to install an SMR at a decommissioned coal power plants to name a few examples. The DOE has identified the most reasonable locations out of the vetted sites in the U.S. and found the Midwest to have the largest population of retired coal power plants. In fact, Michigan is 2nd among all states for most available retired coal power plants [268]. Further siting studies, within Table 3-7 and Table 3-9 [268], have shown 13 Midwest sites amenable to advanced reactors and 7 Midwest sites amenable to a large LWR within a half mile of a recently-retired coal power plant site that include an available dedicated cooling source, showing that these sites could be used for retrofitting SMR technologies to original coal power plants. This indicates the wide availability of retrofitting pre-existing sites with both advanced and standard LWR reactor designs exists as of today.

A few primary items needed for reusing coal power plant sites relate to the available electrical, heat sink, and steam cycle components on these decommissioned sites. The sizing of electrical systems of the coal power plants may limit the capacity of the nuclear installation unless transmission infrastructure is upgraded. Such transmission upgrades can cost up to $3M/mile, depending on the difference in the maximum capacity of the pre-existing coal power plant and newly installed reactor(s). The needed heat sink for a reactor installation also may not match the cooling water available from the pre-existing coal power plants, which would require component upgrades and potentially further permitting if additional quantities of cooling water are needed. The steam cycle components in place for coal power plants are generally designed for operating at much higher steam temperatures and pressures as compared to existing LWR systems. To directly repurpose the steam cycle components would require matching of relevant steam characteristics to reach the optimized efficiencies for the thermodynamic power generation cycle. However, the temperature and pressure ranges typical of retiring coal power plants show great promise for matching with some non-LWR advanced reactor technologies, as these advanced reactors could better match the typical > 16 MPa and > 600°C conditions of the steam cycles for retiring coal power plants [268].

Hansen et. al. considered the reuse of described components under four simulations described as "C2N#0-C2N#3" to provide cost estimations related to re-use of varying amounts of existing infrastructure at or near retiring coal power plants. The baseline simulation, C2N#0, represented a nuclear power plant replacing a coal power plant with no reused components and does not consider any savings from use of pre-existing water rights or nearby transmission lines. C2N#1 considered the reuse of site, electrical components, and heat sink; C2N#2 considered additional direct reuse of steam-cycle components, while C2N#3 considered indirect (through coupling with a thermal energy storage device) reuse of steam-cycle components. For example, it was found that when compared, up to 19% savings conservatively, in total cost, occur when comparing C2N#2 to C2N#0. This further increases to 22% savings when comparing C2N#2 to constructing a completely new greenfield site nuclear power plant, based on conservative estimations (and up to 35% for baseline assumptions used) [268]. The table of potential cost savings is shared here for clarity to illustrate the range of estimated savings. Substantial additional information can be found within the report.

Table 10 Estimated project cost savings for different C2N projects when compared to greenfield or C2N#0 (information used directly from researchers at INL [268]).

Case	Method	C2N#0	Greenfield
C2N#1	Baseline	-21%	-25%
C2N#1	Conservative	-11%	-15%
C2N#2	Baseline	-33%	-35%
C2N#2	Conservative	-19%	-22%
C2N#3	Baseline	-31%	-34%
C2N#3	Conservative	-14%	-17%

In a separate INL study ("Transitioning Coal Power Plants to Nuclear Power") the basic operating parameters of the most available and in-progress reactor types were compiled to compare the parametric needs of both nuclear and coal power plants. This study further analyzed the differences in needs in their steam cycles and waste production cycles. The key considerations for the transition are based on 1) quality and value of the current grid connection, 2) inherent value of land, 3) retire-ability of coal power plants, 4) condition of the site, 5) suitability to host a nuclear power plant, 6) shared engineering experience between coal power plants and nuclear plants, 7) community support of transition, and 8) transport infrastructure [269].

In this INL study, similar results were found as in the DOE-wide study [268] when it came to reusing pre-existing components, but the INL study expanded on the applicability of specific components and their uses. This study found that HTGRs have the most similar design to coal power plants even though significant differences in key components such as boilers do exist. In the best-case scenarios, a robust reactor design with great thermal margins for transitioning thermal systems from the original coal power plants would require thorough decommissioning due to the demolition, salvage, asbestos abatement, and removal of coal ash. Furthermore, the retention of boilers and primary heat source equipment is highly unlikely. However, by carrying out the transition, job creation would occur at nearly every stage from decommissioning to construction and operation. The construction of 12 reactors was estimated to create 2,000 direct jobs and would result in nearly 13,400 jobs/year both directly and indirectly [269].

Within the INL report, a case study was performed for Colstrip coal power plant to determine the exact requirements of decommissioning and retrofitting a nuclear power plant into the existing plant infrastructure. Decommissioning was estimated to cost $143M based on 358 MW_e coal plants (whereas completely clearing the site could cost up to $900M for the 2,272 MW_e capacity). Retention of the turbine was estimated to save approximately 5.5% of the original plant cost while re-using the electrical switchyard was estimated to save $225M. The report concluded that the decommissioning cost and difficulties included in transitioning results in advanced reactors being more amenable for integrating into modern coal power plant steam systems as compared to older LWR systems. Additionally, the coal power plant's coal and ash handling, desulfurization systems and other coal specific components would not serve a purpose for a new nuclear installation and would have large decommissioning costs. Further systems kept for re-use would require maintenance, analysis, and licensing work to ensure that the reused equipment is suitable for operation. Lastly, one of the major benefits of repowering coal power plants with nuclear systems would be directly supporting the local community by bolstering the job availability and tax base [269].

Coal power plants across the state of Michigan have been slowly decommissioning over time. DTE Electric has plans to retire coal usage at the Belle River Power Plant in 2026 and to repurpose the site into a natural gas peaker plant [270]. Furthermore, DTE Electric has also stated that it would retire its coal facilities at Monroe by 2028 and augment the plant such that it becomes a combined cycle natural gas plant, with carbon capture, or to implement SMRs on site [270]. The Campbell Generating Plant, owned by Consumers Energy Company, has plans to close in 2025 and was officially approved to do so by the MPSC in June of 2022 [271]. In June of 2023, the Karn Generating Plant (544 MW_e) officially decommissioned its coal fired units 1 & 2 [272]. These plants decommissioning removes large amounts of coal power, which will leave a gap in the energy production sector to be fulfilled by some combination of renewable sources such as wind and solar, along with energy storage and/or firm generation. This gap also presents an opportunity for advanced nuclear technologies to fulfill the electricity needs within the state.

For illustrative purposes and quick reference, satellite images of the aforementioned power plant sites in Michigan are included as Figures 13 through 16.

Figure 13 The satellite view picture of Belle River Power Plant (left) and a view of its surroundings (right) [273].

Figure 14 The satellite view picture of Monroe Power Plant (left) and a view of its surroundings (right) (note that the orientation is slightly different between these 2 views) [274].

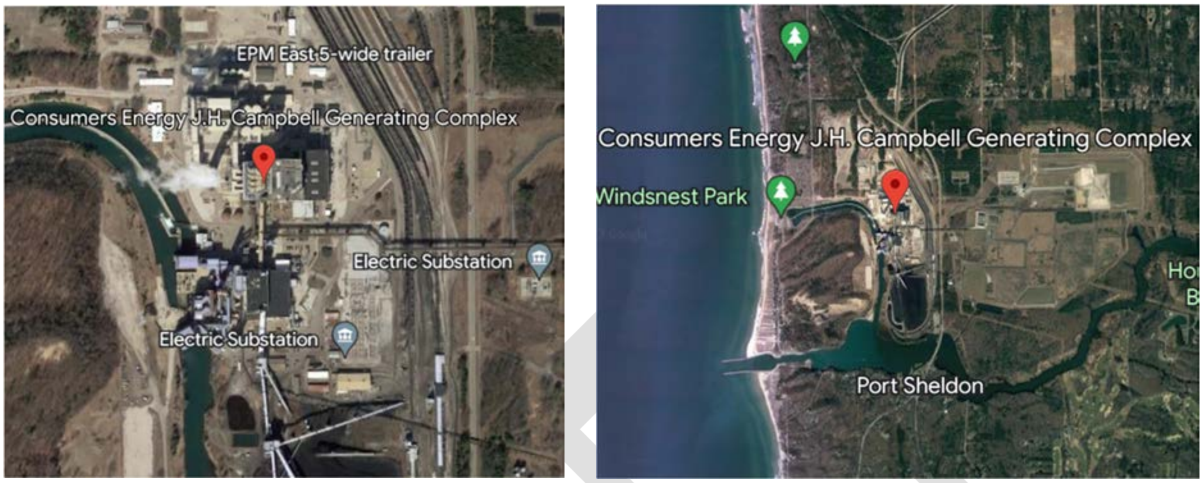

Figure 15 The satellite view picture of Campbell Generating Complex (left) and a view of its surroundings at 7,000 m (right) [275].

Figure 16 The satellite view picture of Karn Power Plant (left) and a view of its surrounding (right) [276].

TerraPraxis, a 501(c)3 nonprofit organization, has completed considerable analysis relating to repowering coal power plants using nuclear energy. Repurposing a large portion of the pre-existing infrastructure could be key to decreasing the risk associated with a large energy transition within the U.S. [277]. The goal of the REPOWER program, a program created and led by TerraPraxis with Microsoft as a partner, targets a cost estimate of $\$2,000/\text{kW}_e$ which could benefit the state of Michigan's, aforementioned, retired or soon to be retired coal power plants. The targeted goal is a 5-year program which starts with a completed and licensed standardized design. This program directly applies the methods discussed by the DOE for a brownfield site [268]. This work is held up by the Global REPOWER Consortium to design a fast, low-cost, and repeatable project model for repowering 2,400 coal plants worldwide by 2050 [278] using partnerships with Microsoft, Schneider Electric, and many others. Michigan happens to host at least four coal power plants that could take advantage of a partnership with TerraPraxis in being the leader of clean energy and set the basis for this developmental model. By doing so they could heavily contribute to the backfitting goal of 198.5 GW_e that is applicable at over 195 sites in the U.S. [277]. This would approach the goals of the DOE which aims to generate 200 GW_e by 2050 and put Michigan at the forefront of clean energy [29]. Michigan, as compared to other states, has an identified 6 GW_e according to TerraPraxis which could be backfit with advanced nuclear systems leading to a potential contribution of 3% to the total C2N backfitting in the U.S. [279].

6.2 Energy Potential Beyond Electricity

Advanced reactors offer many potential applications beyond electricity generation. Such alternative applications often involve the use of nuclear heat as an energy source for other technologies that would otherwise rely on fossil fuel intensive processes. Such applications can range from more exotic aspirational concepts from the early nuclear age like aircraft or rocket propulsion to more practical uses remaining relevant to the modern era, including:

- Hydrogen Production
- District Heating
- Desalination
- Direct Air Capture
- Chemical / Petroleum Applications

The various potential uses are dependent on the available temperatures from a given reactor type, as some processes (steelmaking, for one) require temperatures considerably higher than those available from conventional LWRs. Some processes can, however, utilize the temperatures available with conventional LWRs for purposes other than electrical production.

6.2.a Hydrogen Production

Hydrogen has been of particular interest, as its use results in no carbon dioxide emissions, whether combined with oxygen in fuel cells to generate electricity, combusted for various uses, or used for the direct reduction of iron. Interest in hydrogen has also been fueled by its potential versatility, having often been referred to as “the Swiss Army Knife” of clean energy. Use of hydrogen generated via nuclear power could play a role in achieving decarbonization goals by being utilized as a substitute for some of the higher temperature industrial processes, such as direct reduction of iron for steel-making. As perhaps the most substantial example of interest in hydrogen, the DOE announced the “Hydrogen Earth Shot” in 2021, with a goal of producing clean hydrogen for $1/kg within 1 decade [280] which would be a reduction of 80% according to the current cost of hydrogen generated from renewable energy. Funding has been set aside as part of the Bipartisan Infrastructure Law of up to $7 billion to support 6 to 10 different regional “Hydrogen Hubs” to support the Earth Shot goals through the Office of Energy Efficiency and

Renewable Energy [281]. Of the hydrogen hubs selected, the Michigan-backed Midwest Hydrogen Hub was awarded up to $1 billion in funding. Part of the plan for this hub is to produce hydrogen using nuclear energy [282].

There is an on-going uncertainty regarding hydrogen production from electrolysis using electricity from nuclear power plants (also known as pink hydrogen, occasionally as red). Constellation has paused a $1 billion project to produce “pink hydrogen” as the tax credit situation related to hydrogen production as instituted with the IRA is in question [283]. Describing the full “hydrogen color wheel” other than hydrogen produced from nuclear energy is beyond the scope of this present report. Some constituencies oppose allowing nuclear generated hydrogen from qualifying for the full amount of the tax credit, which is supposed to be based on the emissions profile of the hydrogen production. Constellation’s project(s) are paused pending further clarification for this tax credit (which can reach a maximum value of $3/kg H_2 produced).

Hydrogen has many existing applications from fuel usage to ammonia production, processing of fossil fuels, metallurgic processes, and the generation of various pharmaceuticals. There are several processes by which nuclear energy can be used for hydrogen production including electrolysis, steam reforming, natural gas reforming, and various thermochemical cycles, though many of these processes require steam temperatures beyond the range of many available reactor technologies. Hydrogen production paired with nuclear power has long been contemplated as a key component to a future decarbonized economy. The IAEA published a comprehensive report titled “Hydrogen Production Using Nuclear Energy” in 2013 [284].

A potential solution for transporting hydrogen is converting it to ammonia. Hydrogen is 17.65% of the mass of ammonia which can be liquified under mild conditions as compared to the -253°C temperature required to maintain pure H_2 as a liquid [285]. Companies like AmmPower and Nutrien have already expanded into Michigan and are pursuing green ammonia. Ammonia can be created using the Haber process which combines nitrogen and hydrogen. The Haber process is currently a carbon intensive process and can utilize by-products of the nuclear process such as steam for steam conditioning and high temperature electrolysis to produce hydrogen. Hydrogen in the form of ammonia can then be easier to transport. In this form, ammonia has multiple potential uses such as ‘cracking’ (decomposition back into nitrogen and hydrogen), for fertilizer production, or to be used in a Fischer-Tropsch process to produce synthetic diesel fuel[58]. The Fischer-Tropsch process has a by-product of water/steam that could be fed back to the nuclear plant for use in auxiliary systems to start the cycle over. Additionally, initiatives for ammonia-powered shipping vessels are underway, so hydrogen in all forms of this cycle have the potential to contribute to decarbonizing multiple sectors. These initiatives for other uses of ammonia allow potential growth of demand for ammonia to be year-round rather than merely seasonal for use in fertilizer. Michigan is well positioned to capture this growth in demand, from

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[58] For beneficial life-cycle CO2 emissions from such a process, biomass having removed CO2 from the atmosphere during growth would be necessary as an input material to the process. Such a system is described in a paper from Charles Forsberg and B.E. Dale [394].

the existing fertilizer industry, or potentially within the maritime transportation industry with Michigan's advantageous positioning on the Great Lakes.

Michigan has expansive agrarian land usage making the production of hydrogen applicable due to its uses in producing ammonia for fertilizer. The company Nel and General Motors have already made a commitment to producing clean hydrogen using electrolysis in the state of Michigan. This plan includes a plant capable of the production of electrolyzer equipment that can generate 4 GW_e of hydrogen per year, making it one of the largest such facilities in the world [286] [287]. The production of hydrogen through electrolysis requires substantial amounts of electricity, which could be provided by nuclear sources such as SMRs or existing operational nuclear power plants within Michigan. The cost of storage and transportation of hydrogen can be extremely high, so by using the hydrogen within the state to constrain those costs could have substantial benefit to normalizing hydrogen implementation within the region for various realizable applications.

Michigan consists of approximately 9.8 million acres of farmland, and on average each acre of farmland requires approximately 171 lbs (1lb =0.00045359 Metric Tons) of ammonia for the planting season [288]. This would total 0.76 MT of ammonia per year, assuming there is a single planting season and that every acre used ammonia for its fertilizer. Producing hydrogen from low-temperature electrolysis generates 1 kg of hydrogen per 39 kW-hr of electricity. For hypothetical illustrative purposes, if the full production from 1 year of electrolyzer production from the Nel and General Motors 4 GW_e factory were able to operate 24/7 with a capacity factor of 90% and be dedicated entirely to ammonia production (4 GW x 8760 hrs x 0.9 = 31,536 GW-hr x 1 kg/39kW-hr $\approx$ 0.809 MT of hydrogen per year), this could support producing nearly 4.56 MT of ammonia per year, more than quintuple the amount needed for Michigan's own agriculture [289]. Using further chemical processing would require high temperatures to process nitrogen and hydrogen to generate the ammonia (temperatures > 450°C), which could be provided by advanced reactors with high outlet temperatures. Even though electrolysis is not as efficient as other processes such as natural gas reforming (NGR), it does have the benefit of being a clean source of hydrogen. With increased generation capacity, Michigan could become a significant supplier of hydrogen or ammonia to other agrarian based states.

Other processes of using reactors for hydrogen production have been explored by other researchers such as INL which have combined the high outlet temperatures of a reactor with the NGR process to show an increased efficiency of generating hydrogen [290]. Through a simulation of a reactor with an operating power of 600 MW_{th} and an outlet temperature of 700°C using the NGR process, the plant was able to produce 0.113 MT of hydrogen per year (which could support generating $\approx$ 0.628 MT of ammonia as a final product). With the production of 2 such high temperature reactors, the entire state of Michigan could generate all of its needed ammonia for agrarian uses. As a comparison to the hypothetical capability of one year's electrolyzer output from the GM/Nel plant, where 4 GW_e generates approximately 4.56 MT of ammonia, if we considered a thermal to electric efficiency of 40%, the high temperature reactor could produce 4.56 MT of ammonia at an equivalent capacity of 1.74 GW_e. This shows that the efficiency of the

NGR process is over double that of the electrolysis process but has the downside of producing 0.312 MT of carbon dioxide per year (with carbon capture) [290].

Hydrogen has also been identified for potential use as a fuel for transportation. This has shown promise both in reducing the amount of emissions and cost incurred by each driver for fuel. To show this, an example can be drawn between standard gasoline and hydrogen vehicles. In automobiles proposed by Hyundai, Toyota, and Honda the worst-case vehicle requires 5.64 kg of hydrogen to drive 265 miles [291] resulting in an efficiency of 47 miles/kg. For a future, hypothesized price of hydrogen of approximately $3.5/kg [292], this results in a cost of $0.074/mile. While a fueling station retail H_2 price at this level is not realistic today and will require substantial future developments to achieve, the DOE Hydrogen Earth Shot goal of production of clean hydrogen for $1/kg would be expected to support a retail H_2 fueling station price in this vicinity. Presuming a conventional gasoline car with an average fuel economy of 25.4 mpg [293] and a recent average cost of gas in the state of Michigan of $3.35/gallon [294], results in a cost of $0.131/mile. This is nearly double that of the hypothetical future cost of using hydrogen within vehicles. Considering an average car driving about 14,000 miles/yr [295] would save an individual $792/yr in the worst-case comparison for hydrogen fueled cars. Advanced SMR developers coordinating efforts with automotive retailers to produce hydrogen at $3.5/kg could save the driving population of Michigan $2.3B/yr if all the registered cars in Michigan were converted to hydrogen, based on the assumptions outlined above [296]. This would require a substantial overhaul in infrastructure to distribute and store the hydrogen which is not analyzed in this example but could be further investigated. If hydrogen produced from SMRs using less efficient but cleaner technologies, such as electrolysis, generated the hydrogen for every registered automobile, considering the average car generates 400 grams of CO_2/mile [297], this would reduce CO_2 emissions from driving by 16.211 MT/yr. This represents nearly 11% of Michigan's total emissions, in 2021, according to the U.S. Energy Information Administration [298].

An advanced nuclear application using process heat from a HTGR to produce hydrogen with an iodine-sulfur solution has been used to produce a small constant stream of hydrogen. This technology is in the earlier stages of development, but studies have been conducted to verify the feasibility of the process [299].

6.2.b District Heating

In cold-weather climates, district heating is an efficient method to provide heat from a common source to meet the needs of larger centralized municipalities. District heating is prevalent in northern and eastern Europe but is used throughout the world and has over 660 applications in the U.S. According to information maintained by the International District Energy Association [300], the state of Michigan employs district heating through Detroit Thermal, Lansing Board of Water, Vicinity Energy Grand Rapids for approximately a dozen applications including universities, hospitals, and airports [301].

Adoption of district heating offers many advantages in the form of higher energy efficiency, reduced building construction and operation costs, high reliability, and reduced peak energy demand. Because of higher energy efficiencies, there are benefits to the environment in the form of reduced greenhouse gas emissions. The application of nuclear technology as a heat source for district heating could serve to further curb the emission of greenhouse gases, beyond the gains solely from increased efficiency.

District heating is a more accessible alternative than other applications of nuclear energy in terms of temperature and pressure restrictions. Essentially all potential power reactor technologies operate within the temperatures that would be viable for such an application, and many reactor vendors are incorporating optional design features to support district heating with this purpose in mind. Regardless of the land and spacing required between a reactor site and a city, by using well-insulated systems and various heat storage mediums, it is possible to transport heated fluids at useful temperatures substantial distances to provide district heating.

6.2.c Desalination

Desalination has been proposed as a potential technology to pair with nuclear power plants. Access to freshwater sources is a major concern for a large portion of the world. However, Michigan's advantageous Great Lakes location makes such a technological pairing unnecessary for the state. This potential use could be highly advantageous for areas without ready access to freshwater, but considering the state of Michigan's access to freshwater, the potential for pairing desalination with nuclear power plants is limited only to this brief mention within the present report.

6.2.d Direct Air Capture

Direct Air Capture has been proposed to be integrated with power plant cooling towers to utilize the substantial volumes of air already moving within the cooling towers at a centralized location. The general concept involves taking advantage of air flow paths associated with the cooling tower operation to allow ambient air to travel over a medium which would selectively absorb carbon dioxide from the atmosphere. There is no direct production of CO_2 from a nuclear reactor, but the motion of the air through a cooling tower presents an opportunity to pull carbon dioxide out of the ambient air at any cooling tower for a reactor found the in US. Furthermore, direct air capture systems utilizing stand-alone fans have limited economic potential due to the relatively low concentration of CO_2 in the atmosphere (ranging at approximately 420 ppm in 2023, up from approximately 370 ppm in 2000) and so, utilizing a fast-moving air source through the nuclear reactor cooling towers provides an efficiency advantage to these systems [302] [303]. Direct air capture technologies have yet to be commercially deployed, but $3.5 billion in federal funding has been set aside for regional Direct Air Capture Hubs through the DOE Office of Clean Energy Demonstrations [304].

6.2.e Chemical / Petroleum[59] Applications

Many proposed advanced reactors systems have a high quality of heat which make them viable for other chemical processes as well such as methanol production, heavy oil desulfurization, and petroleum refining.

Inorganic Membrane Reactors can be used to generate methanol, which presents strong potential as a nearly drop-in ready substitute liquid fuel source and could be integrated into existing infrastructures with minimal necessary changes. Methanol production takes advantage of using CO_2 as a predominate feed constituent in a varying three-part reaction [305]. The temperature range for many of these membranes to operate efficiently are between 250°C - 374°C for system operations or constituent feeds into the chemical reaction, making it an ideal candidate for lower temperature reactors [305].

Heavy oil desulfurization is a crucial step in using high sulfur crude oil resources due to the reduction of sulfur dioxide that is generated when burning the oil itself. High contents of sulfur within heavy oil that is burned can lead to acid rain, which is why scrubbers are used in most oil plants to further reduce the trace amounts of sulfur dioxide injected into the atmosphere. A literature review, by Javadli & Klerk [306] into various desulfurization methods shows a method suitable for operational temperatures in the 350°C – 450°C range, oxidative desulfurization. This method starts with heavy oils, then uses a thermal after treatment to minimize thermal degradation of hydrocarbons when held between 350°C – 450°C.

Petroleum refining is another crucial method for generating various fossil fuel based sources of energy, which includes many process such as vacuum distillation (370°C – 425°C), fluidized-bed catalytic cracking (470°C – 525°C), and coking (480°C – 590°C) that require high quality heat sources [307].

All three methods mentioned above are possible applications of SMR integration that require high quality heat and have potential for future integration with advanced reactor technologies, which could hold promise in integrating into operations of the 140,000 barrel per day Marathon Detroit Refinery [308].

7. POLICY ASSESSMENT

7.1 Historical National Nuclear Policies

Nuclear policy in the U.S. began with the Atomic Energy Act in 1946, followed by its 1954 amendment in conjunction with the Atoms for Peace program. The original Act established the AEC to promote the "utilization of atomic energy for peaceful purposes to the maximum extent

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[59] It is noted that these applications would not present emissions benefits, but are included to present potential economic uses of nuclear energy.

consistent with the common defense and security and with the health and safety of the public" [309]. The 1954 amendment declared that the policy of the U.S. is that

> "(a) the development, use, and control of atomic energy shall be directed so as to make the maximum contribution to the general welfare, subject at all times to the paramount objective of making the maximum contribution to the common defense and security; and (b) the development, use, and control of atomic energy shall be directed so as to promote world peace, improve the general welfare, increase the standard of living, and strengthen free competition in private enterprise" [310].

This amendment allowed private companies to begin to gain information and expertise relating to nuclear energy production, which allowed the initial development of nuclear power plants, beginning with Shippingport. Subsequent policy included the separation of the regulatory and promotional roles of the AEC by the Energy Reorganization Act of 1974, with the formation of the NRC and DOE [311]. The NRC is the organization responsible for granting licenses to construct or operate nuclear power generating facilities within the U.S.

7.2 Summary of Recent Nuclear-Related Policy Actions

There have been significant recent changes in policies or policies in development that provide financial support, strengthen the nuclear supply chain or reduce the regulatory burden for the current nuclear fleet as well as advanced nuclear reactors and SMRs. Instances occurred in 2021 with the bipartisan Infrastructure Investment and Jobs Act which created a relief fund $6 billion that was intended "preserve the existing nuclear fleet and its jobs through 2021" [312]. Historical laws related to the prohibition of nuclear power plants were repealed in states such as West Virginia (passed bill S.B.4 [313]), Montanna (passed bill H.B. 273 [313]), Kentucky (passed bill S.B. 11 [313]), and Illinois (passed S.B. 76, but was later vetoed by [60]Governor J.B. Pritzker [313]) showing a clear intention from multiple states that the acceptance and want for nuclear technologies is here. These policy changes are not only driven by lawmakers' desire to reduce carbon dioxide emissions, but to also strengthen the U.S. nuclear industry due to Russia's war in Ukraine and China's expansion of their nuclear technology at home and abroad [314].

7.3 Federal Incentives

7.3.a Infrastructure Investment and Jobs Act

The Infrastructure Investment and Jobs Act, passed in 2021, included a Civil Nuclear Credit Program that provides up to a $6 billion strategic investment to preserve the existing U.S. nuclear fleet. To qualify, the owners/operator must demonstrate that a nuclear reactor is projected to close for economic reasons. Also, the closure of the plant would need to lead to the rise in air pollutants.

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[60] HB2473 passed the Illinois Senate on November 8, 2023 and Illinois House on November 9, 2023, which Governor Prizker has stated he will sign. This bill intends to lift the construction moratorium in Illinois as of 2026 for Small Modular Reactors of 300 MW_e or less [392].

Selected reactors can receive the credit for up to four years with the credits being awarded through September 30, 2031, or until the available funds are exhausted. In 2022, Pacific Gas & Electric received a conditional award of $1.1 billion from the Civil Nuclear Credit Program to allow Diablo Canyon Nuclear Plant to remain open [315, 316]. Additionally, $2.5 billion in funding was included in this act for the ARDP. As mentioned in earlier sections of this report, X-Energy and TerraPower have projects underway with cost-sharing from these ARDP funds for the construction of four Xe-100 plants in Seadrift, Texas and for the Natrium Demonstration Plant in Kemmerer, Wyoming, respectively [29]. These will be the first installations of each of these respective reactor designs.

In 2022, Holtec International applied to the Civil Nuclear Credit Program to re-start Palisades. Holtec International took over the plant in 2022, planning to decommission the plant. If approved by the NRC, Palisades would be the first U.S. nuclear plant to resume operations after being shut down for decommissioning. Holtec's application for the DOE Civil Nuclear Credit program was denied. However, Holtec recently applied to the DOE's Loan Office for a loan of approximately $1 billion to support restarting Palisades. Holtec's loan application is currently under review [317, 318, 319].

7.3.b Inflation Reduction Act

In the summer of 2022, the IRA was passed that included up to $369 billion in climate change provisions. The IRA contains a number of incentives to support the commercial nuclear power industry:

- Production Tax Credits for Existing Reactors

  This production tax credit provides up to $15/MW-hr for the existing fleet of nuclear reactors. There are certain labor and wage requirements that must be met for nuclear plant operators to receive this credit. The credit is available for nuclear reactor facilities in service from 2024 through 2032.

- Advanced Nuclear Deployment

  To incentivize the deployment of new nuclear facilities, owners of zero carbon power plants can choose either a production tax of $25 per megawatt-hour for the first ten years of plant operation or a 30% investment tax credit for power plants placed in operations in 2025 or after. A 10% bonus is available if the new nuclear facility is sited at a brown field site or in a fossil energy community.

- Hydrogen Production

  Production tax credits are also included to incentivize the production of clean hydrogen from new or existing nuclear reactors. These credits could ultimately be as high as $3/kg of clean hydrogen produced.

- High-Assay Low-Enriched Uranium (HALEU)

  The IRA also invests $700 million to support a domestic supply chain for HALEU.

Finally, the IRA provided further investment tax credits for disadvantaged communities with environmental justice concerns [320, 321].The total funding targeting disadvantaged communities is $60 billion overall with nearly $25 billion directly targeting affordable housing while the remaining amount can be used for reducing carbon emissions [322]. These financial incentives are intended to improve the air quality in these disadvantaged communities where fossil plants are frequently sited.

7.3.c ADVANCE Act – Proposed Legislation

In July 2023, the U.S. Senate passed the National Defense Authorization Act (NDAA) in a bipartisan manner, which incorporates the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) *Act* that was passed by the Environmental and Public Works Committee in early in 2023. This Act contains a provision that extends the authorization of the PAA to indemnify licensees and contractors in the event of nuclear accidents beyond the current 2025 expiration date. U.S. nuclear utilities, including the owners of the current Michigan nuclear plants rely on the PAA to provide financial coverage in the event the public would incur damages due to a nuclear or radiological incident. In addition to the extension of the PAA, the ADVANCE Act also includes a number of provisions that would support the potential deployment of additional nuclear facilities [314, 323, 324]:

- Develop and Deploy New Nuclear Technologies
    - Reduces the regulatory costs for companies seeking to license advanced nuclear technologies.
    - Creates incentives to deploy the next generation of nuclear reactor technologies.
    - Requires the NRC to develop a pathway to enable the timely licensing of nuclear facilities at brownfield sites.
- Strengthen America's Nuclear Fuel Cycle and Supply Chain Infrastructure
    - Directs the NRC to establish an initiative to enhance the preparedness to qualify and license advanced nuclear fuels.
    - Identifies modern manufacturing techniques to build nuclear reactors more efficiently.
- Improve NRC Efficiency
    - Provides the tools to hire and retain the specialized staff to review the ANR licenses.
    - Requires the NRC to periodically review and access the performance metrics and milestone schedules to ensure licensing can be completed on an efficient schedule.

This bill needs to be voted on by the U.S. House of Representatives and then approved by the president prior to becoming law. Additional in-process legislation was discussed in late-October 2023 by the U.S. House Energy, Climate, and Grid Security Subcommittee. Twelve separate items relating to nuclear energy were discussed, with the overall theme being to support enabling the deployment of nuclear energy [325] [326]. The Advance Act was originally included in the National Defense Authorization Act that was being negotiated in Congress, but it was excluded from the final approved bill. Based on statements from representative Shelly Moore Capito, who is leading the bill, there is continued support for the bill and additional avenues will be pursued to pass the legislation [327]

7.4 Nuclear Regulation (NRC)

7.4.a Nuclear Energy Innovation and Modernization Act - Licensing Modernization Program

In early 2019, the Nuclear Energy Innovation and Modernization Act passed that requires the NRC to develop new processes for licensing nuclear reactors. This Act requires the NRC to implement the use of risk-informed, performance-based licensing evaluation techniques and guidance and establish by the end of 2027 a technology-inclusive regulatory framework that encourages greater technological innovation [328].

The Licensing Modernization Project led by Southern Company, coordinated by the NEI and cost-shared with the U.S. DOE, issued NEI 18-04, Revision 1. The guidance from NEI 18-04 is intended to reduce the regulatory uncertainty challenging the nuclear industry and streamline the advanced reactor design and licensing policies. In 2020, the NRC Commissioners issued a Staff Requirements Memorandum that concluded that the methodology provided in NEI 18-04 is a reasonable approach for the licensing of non-light water reactors. Six of the reactor vendor developers participated in the development of the methodology provided in NEI 18-04 [329, 330].

In support of the Nuclear Energy Innovation and Modernization Act, in March 2023 the NRC issued a new draft regulatory framework within the Code of Federal Regulations (10 CFR Part 53) for the licensing of advanced reactor technologies. A bipartisan group of lawmakers issued a letter to the NRC in July 2023 urging the NRC Commissioners to review and modify the draft of 10 CFR 53, as necessary, to resolve the remaining stakeholder comments to meet the congressional intent of using 10 CFR 53 for the next generation of nuclear reactors. The NRC had plans to issue the final 10 CFR Part 53 rules by December 2024. Many of the reactor vendors that are pursuing the licensing of advanced reactor designs are using the current licensing framework contained in NEI 18-04 Revision 1. Therefore, a potential delay in the final issuance of 10 CFR 53 will not likely impact the reactor vendor designs utilizing the current licensing framework [329, 331].

7.4.b Emergency Planning Zones

To reduce the cost and impact associated with the siting of advanced reactor designs, the industry has pursued initiatives to reduce the size of the EPZs for the advanced reactor designs. The EPZ for the current operating nuclear plants is a 10-mile radius around the plant. Within the EPZ, protective actions areas are designed to avoid or reduce dose from potential exposures such as inhaling radioactive particles. Some of these actions include sheltering, evacuation, and the use of potassium iodide pills [332].

In the Clinch River ESP Application, the Tennessee Valley Authority demonstrated that the EPZs can be scaled down due to the safety and performance attributes of SMRs, smaller amount of fuel in the reactor core and the passive safety features eliminating several potential emergency scenarios. The NRC found that TVA's dose-based, consequence-oriented methodology provided a "reasonable technical basis" for determining the size of the EPZ for Clinch River. With an approval from the NRC, a granted exemption for the 10-mile EPZ for future construction and operating license applications was submitted for the site [333] and was further discussed in the prior section 1.6.g.

In 2022, the advanced reactor vendor NuScale Power Company received NRC approval for their methodology to limit the EPZ to the site boundary for their VOYGR SMR design for their first reactor deployment at INL [30].

Many of the other advanced reactor vendors are expected to submit similar applications that reduce the size of the EPZ from the 10-mile EPZ for conventional nuclear reactors. Reducing the EPZ will minimize the impact on the public, reduce the EP costs, and minimize the impact to off-takers that may be sited next to advance reactor facilities.

7.4.c Other NRC Regulations

The issuance of an NRC license to construct and operate a new nuclear facility is a major federal action, and therefore is subject to NEPA. To support new reactor licensing and meet NEPA requirements, the NRC is developing new and updating existing regulations and guidance for new reactor licensing. Many of the new NRC regulations are being pursued with the expectation of reducing the effort needed to site and license an advanced nuclear reactor design. A summary of some key NRC regulatory and guidance documents supporting new reactor licensing is provided below [334]:

- NUREG-2249 (Draft Generic Environmental Impact Statement for Advanced Nuclear Reactors) – Published in 2021, the NRC developed the advanced nuclear reactor Generic Environmental Impact Statement. The advanced nuclear reactorgeneric environmental impact statement evaluates the potential environmental impacts of licensing the construction, operation, and decommissioning of advanced nuclear reactors in the . The advanced nuclear reactor generic environmental impact statement is based on a technology-neutral plant parameter envelope and presents analyses of the potential environmental impacts that are common to many advanced nuclear reactors that can be addressed generically. The current published NRC schedule indicates that the final advanced nuclear reactorgeneric environmental impact statement will be published in early 2025.

- COL/ESP-ISG-026 (Environmental Issues Associated with New Reactors) – The NRC's environmental standard review plan for new reactor license applications is NUREG-1555, which was initially published in 1999. In 2007, the NRC published draft revisions of key selected sections; however, they were never finalized. While reviewing the environmental reports for numerous COLA, the NRC identified additional necessary changes for the standard review plan. This interim staff guidance (ISG), published in 2014, captures this information until NUREG-1555 is updated. During the 2023 Regulatory Information Conference, the NRC announced that it had plans to begin review of potential standard review plan revisions.
- COL/ESP-ISG-027 (Specific Environmental Guidance for Light Water Small Modular Reactor Reviews) – Similar to COL/ESP-ISG-026, this ISG was published in 2014 to clarify the NRC's application of NUREG-1555 to licensing application environmental reports for construction and operation of light water SMRs.
- Regulatory Guide 4.24 (Aquatic Studies for Nuclear Power Stations) – This regulatory guide, published in January 2017, provides technical guidance for aquatic environmental studies for licensing application environmental reports subject to meeting the requirements of 10 CFR Part 51, Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions.
- Regulatory Guide 4.11 (Terrestrial Environmental Studies for Nuclear Power Stations, Revision 2) – Published in 2012, this guidance document provides updated technical guidance for terrestrial environmental studies in support of new nuclear licensing from the earlier revision (1977).
- COL-ISG-029 (Environmental Considerations Associated with Micro Reactors) – In October 2020, the NRC published this ISG to assist the NRC staff in determining the appropriate scope for their environmental reviews of licensing applications for micro-reactors. The ISG discusses unique considerations for micro-reactors and recognizes that streamlined documentation and reduced review times should be possible due to the potential limited impacts associated with the plant's construction and operation. (O'Neill 2021)
- DG-4032 (Preliminary Draft Revision 4 to Regulatory Guide 4.1, Preparation of Environmental Reports for Nuclear Power Stations) – Published in May 2022, this preliminary draft provides updated guidance to applicants specific to format and content requirements for new reactor license application environmental reports.

7.5 State Policies

7.5.a Michigan – Palisades Nuclear Restart

In 2023, Holtec requested $300 million from the state of Michigan to restart Palisades. The State of Michigan included $150 million in the most recent state budget to support the restart of Palisades. This state funding was approved to restore to commercial operation the 800 MW_e of carbon-free power to the state's electric generation supply and address the negative economic impact of its shutdown. There are reports that Holtec may receive the additional $150 million in funding that they requested from the state when Holtec receives the requested DOE funding [335, 334].

7.5.b Michigan Clean Energy Future Bill

In November 2023, the Michigan Governor signed the Clean Energy Future Bill into law. This bill requires 80 percent electric generation in the state of Michigan to be from carbon free sources by 2035 and 100 percent of the electrical generation from carbon-free electricity sources by 2040. The bill requires 50 percent of utility electric generation from wind, solar and other renewable sources by 2030 and 60 percent of electric generation from renewal sources by 2035 [336]. The remaining portion of the 100 percent carbon free generation can be generated from nuclear power or fossil generation that captures 90 percent of the carbon emissions. The bill doesn't include specific incentives to spur the expansion of nuclear in the state of Michigan, but the bill does require the MPSC to include climate impacts in the utility integrated resource plans that are reviewed by the MPSC, which will include the carbon free benefit from nuclear power [337].

7.5.c Recent Legislation in Other States

Many states have passed laws to lift the previous bans on siting new nuclear plants or to encourage the development of the nuclear supply chain and/or the nuclear workforce. The state of Michigan does not have a law banning the siting of new nuclear plants. Below is a selection of this recent legislation in these other states [313, 338, 339, 340]:

- California – In 2022, the Governor and Legislature reversed course and decided to support the extension of the operational life of Diablo Canyon, which had been planned to shut down in 2025, with a $1.4 billion state loan [341]. Subsequently in November 2022, a $1.1 billion federal civilian nuclear credit from the DOE was awarded in support of the extension of Diablo Canyon's operational life [342].

- Indiana – In 2022, the state of Indiana passed a law that provides guidelines for state regulators to evaluate the siting of a new nuclear plant if one of the utilities in the state considers building a new nuclear plant to meet their power generation resource mix.

- Tennessee – In 2023, an executive order was signed to support the growth of Tennessee's nuclear industry related businesses with the establishment of a state Nuclear Energy Advisory Council. In addition to this executive order, Governor Lee, working with the Tennessee General Assembly, created a $50 million nuclear fund in the state's 2023-24 budget. This nuclear fund provides grants and other assistance to support nuclear power related businesses that choose to relocate or grow their business in the state of Tennessee [343].

- Virginia – In 2023, legislation was issued to create the Virginia Power Innovation Fund for the research and development of innovative energy technologies, including nuclear, hydrogen, carbon capture and utilization and energy storage. The program also creates a nuclear innovation hub and support grants to support energy innovation.

Additional legislation in Virginia creates a Nuclear Education Grant Fund to award grants to higher education providers to establish or expand nuclear education programs as well as to create employment and training pathways for nuclear engineering and nuclear welding.

7.6 Declaration to Triple Nuclear Energy (COP28)

The World Climate Action Summit held its 28th Conference of Partners with the main objective to discuss the key role of nuclear energy limiting global temperature increase. Within this conference a “Declaration to Triple Nuclear Energy [344]” globally by 2050 was made from the countries which endorsed this action such as the “United States, Bulgaria, Canada, Czech Republic, Finland, France, Ghana, Hungary, Japan, Republic of Korea, Moldova, Mongolia, Morocco, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden, Ukraine, United Arab Emirates, and United Kingdom [344].” The countries committed to not only tripling nuclear generation but also ensuring high safety standards and non-proliferation of nuclear systems, mobilizing investments on nuclear power, and supporting the newest wave of small modular reactors and microreactors. The conglomerate of nations will also welcome and encourage complementary commitment from the private sector to further push the progress of nuclear systems within each partnered nation [344].The additional work that the US committed to at and after COP28 span a range of topics to ensure food security, better weather forecasting, increases in green energy production, and further cooperation with international partners to reduce the long-term impacts of climate change. This included the $3 billion pledge to the Green Climate Fund, launching the Clean Energy Supply Chain Collaborative with $568 million backing the group, providing $6 million for the Weather - Ready Pacific Program, an additional $50 million has been provided for the Vision for adapted Crops and Soils Multi Donor Fund, and many more projects which promote increasing the climate stability of the planet [345]. With many additional avenues of funding available it seems that any state which is motivated and well supported by its public base could access funds for constructing new nuclear technologies as the global momentum continues to increase for nuclear generation.

7.7 Policy Summary & Recommended Policy Actions for Michigan

Many recent or proposed federal and state policy changes can provide financial support for maintaining the economic viability of the current nuclear fleet in the state of Michigan as well as supporting the potential deployment of advanced nuclear reactor designs. The policies also support the nuclear supply chain and the development of the nuclear workforce. Additionally, there are on-going initiatives to modernize nuclear regulations which are expected to reduce the regulatory burden for siting advanced reactor designs.

With the growing list of new federal and state nuclear policies that have been enacted or are currently proposed, there is growing evidence that the nuclear industry is receiving bipartisan support which is a sign that there will likely be future policy changes that support the nuclear industry. According to Senator Shelley Capito, one of the co-authors of the ADVANCE Act,

> “America can and should be a leader when it comes to deploying nuclear energy technologies, and this bipartisan legislation puts us on a path to achieve that goal. This bill prioritizes the future of American energy security by establishing commonsense policies to help deploy nuclear energy, which is a clean and reliable generation source for our nation’s electric grid. It also directs the Nuclear Regulatory Commission to create a pathway for conventional energy source sites to be repurposed and used in the future.”

Nuclear generation has not always been credited in some states as an option to decarbonize the electric generation industry. The passage of the Michigan Clean Energy Future Bill, crediting the use of nuclear as a potential source for reaching 100% carbon-free electric generation, allows nuclear generation to be properly considered along with renewable and fossil generation with carbon capture technology. Additionally, the requirement to include climate impacts in utility integrated resource plans will allow nuclear to be credited with its carbon free benefit.

One specific policy action that Michigan could consider is to provide a state tax credit program to encourage new nuclear development within the state. This could include options for either an investment tax credit or production tax credit. These credits could be scaled based on the level of Michigan labor utilized in the development or based on the amount of local economic benefits to be accrued for a given project. As stated in Section 1.6.a, the initial cost of FOAK nuclear deployments is expected to be substantial for the first movers, with followers positioned to reap the benefits from lessons learned and increased supply chain efficiencies leading to lower costs for follow-on deployments. To remove this roadblock prohibiting first movers from getting started, Michigan could also consider collaborating with the other states interested in adding nuclear power to provide pooled financial support for these first movers. Such interstate collaboration would allow Michigan and the other states absorbing the higher costs for FOAK nuclear deployments to then be positioned to benefit from the reduced costs associated with the subsequent NOAK nuclear deployments.

Other state-driven activities that may be considered include development of information and awareness materials that may be distributed to state, county or local agencies and stakeholders (e.g., State Historic Preservation Office, Department of Health, Department of Environment, Great Lakes and Energy, etc.) that may contribute to new reactor licensing activities. The materials could provide a discussion of the licensing and permitting process associated with new reactor and existing reactor license renewal applications and highlight the potential information and consultation requests that their agency may be asked to support.

A consolidated process for obtaining necessary state, county, and local permits may also be considered. A state-led initiative to consolidate the permitting process could increase efficiency, transparency, and consultation for new reactor projects in Michigan. As a collaborative process, agencies that issue necessary permits for new reactors would have the opportunity to jointly review and discuss permit applications and information submitted for the proposed project. This synergy in process would help to identify and overcome potential conflicts and gain regulatory consistency across potential projects being considered within the state.

8. SUPPORTING STUDIES SUMMARY

“Advanced” Isn’t Always Better (Union of Concerned Scientists)

The Union of Concerned Scientists in 2021 published a report summarizing advanced (non-light water reactor) nuclear power technologies, with comparisons to LWRs [346]. This report explored some of the history of nuclear power developments, assessed the sustainability of nuclear power, evaluated proliferation and terrorism risks for nuclear power, and then evaluated three specific advanced reactor technologies. The report also included a chapter on “breed-and-burn reactors,” provided conclusions and recommendations, and included an appendix outlining models of burner/breeder cycles. Conclusions from the report include that there is limited support to claims that non-light water reactors will exhibit enhanced safety as compared to LWRs, that claims that a reactor system can “burn” or “consume” nuclear waste is an oversimplification, and that potential improvements to sustainability and resource utilization may be too small to justify proliferation or safety risks associated with non-light water reactors as compared to LWRs. This report recommended that the DOE suspend the ARDP and consider focusing nuclear energy research and development on improving LWRs rather than commercializing non-light water reactors.

Study of Seabrook’s Economic Benefits to Massachusetts

Seabrook is a nuclear power plant located in New Hampshire, just across the border between New Hampshire and Massachusetts. Producing just under 1250 MW_e, it generates 8% of New England’s power supply. A 2023 study was conducted to review Seabrook’s economic and environmental contributions within Massachusetts. As part of the study, the generation of the reactor was simulated with the goal of estimating future electricity bills and determining the environmental impact over the period from 2023-2032. Furthermore, a PPA was modeled to determine the effects of Seabrook on the power market at 1000 MW_e of production. The first scenario simulated the use of natural gas for power and the resulting market is based on the forward cost of the resource and a lowering of the fuel cost to historically predicted values. The second scenario modeled a PPA set up with Seabrook. The results showed continued operation of Seabrook produces a savings of $880M - $2,610M for Massachusetts power consumers. Additionally, the amount of CO_2 production is reduced by 12% – 21% (5 million short tons of CO_2/year) with continued operation of Seabrook. Both scenarios were run with projected growth and production from solar, wind, and battery storage in the state. In both cases, a noticeable cost reduction in $/MWh was shown over the modeled ten year period and the annual energy cost for both New England and Massachusetts was reduced by setting up a PPA with Seabrook [347]. This study shows that PPAs can be a powerful tool for commercial nuclear reactors to use to allow reliable cost estimates for electricity. Lessons such as this can be applied to the state of Michigan, as evidenced by the recent announcement of the Wolverine Power Cooperative PPA for the power from Palisades following a restart [103]. Furthermore, this study indicates that with more time of operation the cost of electricity will slowly decrease, positively affecting the electricity consumers in the state of Michigan under a PPA similar to the study shown for Seabrook.

DOE’s Pathways to Commercial Liftoff: Advanced Nuclear Study

Research by the DOE, published in 2023, has indicated goals of reducing the carbon footprint of the U.S. by creating 200 GW$_e$ of Nuclear power within the U.S. by 2050. This would expand the needed workforce (375,00 workers), fuel supply chain needs (additional 5,000 MT/yr of fuel fabrication which need 50,000 MT/yr of U_3O_8), component supply chain (large forges), licensing rate (application capacity from 0.5 GW$_e$/yr – 13 GW$_e$/yr), and spent nuclear fuel sites will be needed to support this increase. Various scenarios were populated within a model to determine the role of nuclear to have an energy market with net-zero carbon by 2050 (needing 550 GW$_e$ – 770 GW$_e$ of which nuclear comprises 200 GW$_e$). The LCOE was used to compare renewables with storage, natural gas with carbon capture, and advanced nuclear to show the competitiveness between each generation method. It was found that due to the high-capacity factor (93%) and low land usage (57,000 MWh/yr per acre), nuclear is much more efficient than other renewable systems by comparison. Cavicchi and Franklin also noted that job creation with higher pay in the nuclear field benefits the local economy more than other renewable jobs. Estimated costs of Gen. III and Gen. IV reactors FOAK and NOAK systems were analyzed to project the LCOE for NOAK to be $66/MWh (by taking overnight costs from $10,000/kW$_e$ to $3,600/kW$_e$ with no additives or IRA deductions). Construction of these new Gen. 4 reactors, including project planning of new nuclear sites, required a minimum of 11 years from start to finish (citing Vogtle Units 3 and 4 which took 13 years). Fuel supply chain mining would have to increase by 22 times to make it by 2050 (200 GW$_e$ implementation). Further a 10 GW$_e$ gap of large forging capacity also exists for generating components. Deployment would require $700B in capital by 2050 for 200 GW$_e$ deployment (that is predominantly overnight cost). Lastly, the most prevalent issues at this point are manufacturing, constructing, and funding the first 5-10 reactors. Solutions to the cost of advanced reactors are provided as follows 1) a group of companies share the cost of the reactor, 2) a developer sites several U.S. based reactors to reach a critical cost efficiency of production while setting up a PPA to the end users 3) a developer sites reactors internationally increasing the number of reactors built (combined with domestic reactors sited) to reach critical cost efficiency of production and speed up the learn curve and reduce manufacturing times of the reactors. This paper provides a great description of the possibility of bringing online new reactors even if the goal of being carbon neutral by 2050 is not achievable [29].

MIT Future of Nuclear Study from 2018

A study from MIT showed that nuclear energy supplies about 11% of the world’s electricity and goals from these advanced systems should aim for a reduction in carbon emissions of 100 gCO_2/kWh (cutting the current production of CO_2/kWh by 80%). The capital investment in the west for nuclear reactors is still too high to be profitable but shows that an improvement in modularity and manufacturing approaches can increase the probability of success. This message is echoed for advanced reactor technologies and focus should be put into lowering the capital costs. Aligning licensing internationally would also reduce the issues of modular design across many countries, but the differences in regulation between countries does not allow for a universal law to be generated around the technology. Most of the world's energy is fed by petroleum, coal, and natural gas as of 2018. The transportation sector has the lowest efficiency in electricity use in the U.S. by sector. A simulation was performed without reactors, and then with reactors under three conditions of a nominal cost, low cost, high-cost (25% higher than predicted 2050 FOAK), and an extreme low cost using a 2050 projection for nuclear installation along with varying renewable systems. The study concluded that natural gas is a necessary component in energy generation and efficient for optimal capacity mixes in all the cases studied for varying areas. The benefits of nuclear at lower implemented CO_2/kWh were negatively affected by using storage for other renewables which is the cause of the extreme cost of those systems [348]. This study shows the usefulness of transitioning to nuclear energy sources over time, as the use of natural gas can allow for the flexible deployment of reactors while enabling energy needs to be met during the transition period. This could positively benefit Michigan due to the large number of natural gas plants within the state, and further provides insights for reducing storage needs (such as batteries) as these technologies do not economically benefit the production of hybrid renewable energy production.

DOE's Pathways to Commercial Liftoff: Clean Hydrogen Study

The DOE also investigated scaling electrolyzers to an industrial level due to a projected decrease in CAPEX from \$760-1000/kW$_e$ to \$230-400/kW$_e$ by 2030 (similar changes can also be seen in other electrolysis methods). Electrolysis technologies must deploy at larger scale using the IRA clean credits per kg of hydrogen to improve costs to be competitive with natural gas reformation in future markets. Near term utilization relies on ammonia generation and oil refining which can transition into fuel-based commodities to balance the new supply with another form of demand. That would enable end use costs of hydrogen within reasonable ranges of current generation, \$2/kg$_{H2}$ - \$4/kg$_{H2}$. The main steps proposed include investing in hydrogen distribution and storage infrastructure (\$45-\$130B), catalyzing supply chain investments by increasing the electrolysis from less than 1 GW to 25 GW$_e$/year, developing new regulations, standardizing processes, performing new R&D, and expanding the work force. It was found that the production of hydrogen relates to 10% of the world's emissions of CO_2, and by generating clean hydrogen, a large portion of those emissions can be removed from the yearly production of greenhouse gases. If the larger issues of transportation and storage can be remedied, the benefits of clean hydrogen can affect multiple industries such as the chemical, industrial, and transportation sectors. Using the cost of varying hydrogen production manufacturing methods, a levelized cost of hydrogen for electrolysis was determined. 2050 is projected to have a domestic hydrogen demand of 27-80 MMTpa (MMTpa = 1,000,000 Metric Tons per annum) of which will be dominated by transportation and industrial uses (The US predicted model is much lower than the high value from the McKinsey Power Model). To meet the demands of hydrogen, it is projected that the steam methane reformation process will be necessary. As this process still produces emissions, the CO2 must be captured for such hydrogen to be considered “blue hydrogen” rather than “gray hydrogen.” Capital requirements according to the projected growth require $85-$215B of cumulative investment into hydrogen by 2030. A massive increase in materials required for proton electron membrane (PEM) electrolyzers will be required for this implementation (needing lanthanum, yttrium, and iridium, which would become 30% of the worlds iridium production). The projected demand for hydrogen by 2035 cannot be met by the current workforce. A predicted 100k jobs must be created to serve the hydrogen workforce indirectly by 2030. The risk for completely neutralizing carbon production, with respect to H2, is dependent on the required specialized workforce needed of 200,000 direct and indirect workers to fill these fields (pg.56 for all challenges). A few major takeaways are the massive strain put on the production of workers, resources, and infrastructure for full carbon neutralization. Using hydrogen for industrial heat, natural gas blending, and power from combustion is shown to be inefficient [349].

Public Opinion Study Relating to New Nuclear

The various applications of advanced nuclear systems make it a widely sought after and applicable piece of technology in the energy infrastructure landscape. Determining the level of social support from the public for various technology choices is important for the electricity grid’s mix for energy production. Surveys have been conducted to determine the public’s support around nuclear applications and it has been found that over 3 continents and more than 13,000 total respondents, that on average a ratio of 5:1 individuals (note an equal share of both male and female respondents) were in strong support of the statement “I support the use of the latest nuclear energy technologies to generate electricity, alongside other energy sources [350]” as compared to a contrary statement opposing nuclear energy. The support around advanced nuclear stems from key groups such as the younger generation and environmentalist groups. The results of this survey have also shown that nuclear implementation plans are bipartisan issues. Furthermore, the survey showed support of more than 50% across nearly all recognized political parties from eight countries, ranging from Sweden to Japan, including the U.S. The surveys also revealed that most of the discontent and skepticism about advanced nuclear systems came from older generations. When breaking down the support between four separate groups of 1) Pro-Established Growth (28% of survey group), 2) Concerned Professionals (27%), 3) Hard Working Pragmatists (30%), and 4) Determined Skeptics (15%) showed a support of 90%, 70%, 45%, and 15% respectively between each group [350].

Report/Study Relating to AP1000 Capital Costs

Surveying has shown the interest of the public and the new fleet of reactors, however, this interest does not address the economic issues the nuclear industry faces. MIT has been a part of leading the charge for estimating the overnight capital costs of the AP1000 reactor design developed by Westinghouse. Efforts have been made to predict the realistic outcome with respect to the previously constructed Vogtle 3 & 4 plants by introducing initial estimates of a FOAK construction time and cost estimate of 100 months and $6,800/kW$_e$, respectively. These conservative estimates were made in consideration of regulation and communication issues that can occur when constructing a plant over a long period of time [351].

Construction of Gen III+ reactors have been shown to be feasible as four operating AP1000 plants within China were completed to power the Shandong Province within nine to ten years' time [352]. Further examples such as the ABWR within Japan was completed in less than 50 months due to the experienced EPC contractor and modular construction approaches [351].

The largest issue for these larger Generation III+ reactors has been shown to be the indirect cost due to engineering and home office services, construction services, field supervision and field office service, and payroll insurance and taxes. These indirect costs have been realized as 72%-77% conservatively of the total project costs. The NCET Tool used by MIT further estimates the levelized cost of reactors with respect to construction labor productivity according to Vogtle 3&4, the increased inflation, world economy, and increase material supply index. The FOAK cost ranges from \$5,100/kW$_e$ to \$6,800/kW$_e$. Despite the cost for a large-scale reactor system, when comparing the levelized overnight capital and O&M cost with that of other advanced SMR designs, it was found that it is less per \$/kW$_e$ for a large scale reactor as compared to SMR as long as SMR construction takes longer than 36-months. The goal of this simulation was to use impacts of the real world on the cost of newer large-scale reactors and compare that to the other projected plans of advanced reactors. Through this report, it was shown that SMRs have a higher predicted total levelized cost and that the Gen III+ reactors would be the most economic and impactful option. The SMR (such as the NuScale plant) reduces the risks associated with construction, and therefore indirect costs, and contains a similar power density to large reactor counterparts [351]. The predicted costs within this study are similar to those predicted within Section 1 of this report.

Nuclear Innovation Alliance Report on Advanced Nuclear Reactors

The Nuclear Innovation Alliance has provided numerous recommendations domestically to gain support of the new generation of reactors and give appropriate direction within the DOE and Congress. There is a clear basis of support for advanced nuclear, but this interest could be undermined by economic issues. Legislation and implementation of new federal programs show a strong support for nuclear systems in the U.S. such as the \$700M included in the IRA for the DOE's Advanced Nuclear Fuel Availability Program. This program's resources will be allocated to generating High-Assay Low-Enriched Uranium fuel, the needed transportation systems for HALEU fuels, and the full development and testing of the fuel. On top of the domestic progress, Team USA (the nuclear export technology group), seeks to offer enveloping nuclear package to countries for their hardware, fuel, financing, regulatory support, and technical support (however, this team has been underutilized since its inception whether it is due to the costs or regulations). To produce increased interest, the report concludes that early design, research and proof of concept ideas need to be worked through in the U.S. through the DOE to find out critical issues that arise in nuclear technologies. Furthermore, early design can be further fleshed out by setting milestone-based funding for demonstration of the new energy technologies. This will allow for funding to be based on specific hardware and technology milestones that improve the efficacy of these technologies. Key recommendations of the report include the following [353]:

1. The DOE needs to integrate their Advanced Nuclear Energy work with other sectors of the DOE to integrate the fuel cycle and supply chain innovation.
2. The DOE needs to assess the carbon energy landscape to identify the scale and range of advanced reactor technologies for the economy, security, and climate goals.
3. The DOE must align its operations with entrepreneurial businesses to streamline, standardize, and optimize contracting, communicating, and staffing to deploy viable and needed products.
4. The DOE should fund projects contingent on their progress, by setting payments based on achievement of technical and economic milestones to further push progress and the lessons learned for these newer systems.
5. Congress should support DOE efforts to implement the HALEU fuel availability program, develop fast neutron testing capability, and hire more staff through targeted additional funding and flexibility.

DOE (INL) Report on Microreactor Applications in the U.S.

The goal of this report was to evaluate state-level legal, regulatory, economic, and technology implications for microreactor applications. Alaska and Wyoming were the primary focus of this report, as both are relatively remote while also presenting energy needs to support energy production activities within these states. With the remote locations within Alaska, many energy needs have historically been met with diesel generators, including associated transportation costs to get the fuel to the remote locations. As such, microreactor technology could present cost improvements. Rural communities in Wyoming and Alaska export a large portion of their produced fuel and energy to outside states, as the needs within these states are relatively small. As such, microreactors not being oversized for the needs of these smaller communities could be a particularly good fit, as compared even to SMRs in the range of roughly 50 to 300 MW_e. Wyoming is a major coal producer, but due to this being a major commodity export, it is subject to the booming and busting of the energy market. Alaska's economy relies heavily on natural gas and crude oil production. Microreactor interest in Alaska rose in 2022 as Eielson Air force base announced a site for a microreactor project for producing power and Copper Valley Electric partnered with Ultra Safe Nuclear Corporation to assess to the technical feasibility of a 10 MW_e microreactor [354]. This report also includes a table summarizing state level work toward developing policies within nearly every state in the US to either adopt a clean energy standard, support nuclear adoption, expand the definitions of nuclear being constituted as a clean energy source, repealing prohibitions on nuclear development, and proposing studies aimed at potential sites for permitting advanced reactors such as the states mentioned above have done. To further the push toward microreactor implementation, this report has proposed deeper analysis toward public acceptance and resistance toward microreactor technology, evaluating various microreactor markets (also discussed in Section 4 of this report), researching regulatory issues with the application of microreactors within the industry, and even evaluating taxing on the supply chain and potential incentive packages for manufacturers and workforce training. The result of this paper was to further recognize and adapt the current movement of nuclear technology from Alaska and Wyoming to other states to further the benefits provided by microreactor technology which can uphold isolated communities.

9. CONCLUSIONS

Many considerations come into play in determining the feasibility of new nuclear power for the state of Michigan. Any site to be selected for hosting a new nuclear generation facility must undergo rigorous evaluations at different stages of the development and investment decision-making processes. Some of these items are described in Section 4.3. While these efforts are substantial, additional new nuclear and continuing nuclear power generation for the state of Michigan (Palisades restart, license extensions, power uprates, and new generation) will be necessary to achieve the Michigan Clean Energy Future Bill's goals. While the costs to build new nuclear, particularly for FOAK installations, may be high, many of those associated costs will accrue to the local economy as economic benefits as well as flowing eventually to the state and local governments as tax payments. Nuclear power plants are long-term investments, with operational lives lasting 80+ years with proper maintenance and inspection programs in place. Electricity generation or other energy-related products will be available, free from the production of greenhouse gas emissions, for the duration of the operational lives of any nuclear power plants.

Michigan could benefit from partnering with other states to share some of the costs in incentivizing a FOAK nuclear installation. Substantial benefits are expected to be realized with subsequent new nuclear installations (NOAK) with reduced costs from the lessons learned on earlier installations. If new nuclear is pursued within the state of Michigan, the expected timelines of a project must be kept front of mind. The most recently completed nuclear projects in the United States and Europe have not been completed within quick timelines. If any new nuclear plant developer aspires to have a new plant ready to enter operation before the mid-2030s, substantial planning must begin today as opportunities to shorten full project timelines to less than nine or ten years are limited.

New nuclear power plants for the state of Michigan are certainly feasible, but pursuing new plants will neither be easy nor without costs. Benefits will include multi-generational clean energy production, providing desirable local employment and spill-over economic benefits.

REFERENCES

[1] Michigan Legislature, "Public Act 166 of 2022," 20 July 2022. [Online]. Available: https://www.legislature.mi.gov/documents/2021-2022/publicact/pdf/2022-PA-0166.pdf. [Accessed December 2023].

[2] Michigan Legislature, "Public Act 218 of 2022," 14 October 2022. [Online]. Available: https://www.legislature.mi.gov/documents/2021-2022/publicact/pdf/2022-PA-0218.pdf. [Accessed December 2023].

[3] Energy Information Administration, "Michigan Electricity Profile 2021," November 2022. [Online]. Available: https://www.eia.gov/electricity/state/michigan/. [Accessed August 2023].

[4] Michigan Public Service Commission, "Nuclear Feasibility Study," [Online]. Available: https://www.michigan.gov/mpsc/commission/workgroups/nuclear-feasibility-study. [Accessed August 2023].

[5] U.S. NRC, "About NRC," [Online]. Available: https://www.nrc.gov/about-nrc.html. [Accessed December 2023].

[6] C. G. Lawson and C. Krause, "Documenting history: Minutes of the New Piles Committee meetings," *Nuclear News,* pp. 36-38, November 2004.

[7] Wikimedia, [Online]. Available: https://commons.wikimedia.org/wiki/File:BWR_nuclear_power_plant_diagram.svg. [Accessed October 2023].

[8] Wikimedia, [Online]. Available: https://en.wikipedia.org/wiki/File:PWR_nuclear_power_plant_diagram.svg.

[9] Idaho National Laboratory, "Advanced Fuels Campaign Execution Plan," 2021.

[10] Nuclear Energy Institute, "U.S. Nuclear Industry Capacity Factors," March 2022. [Online]. Available: https://www.nei.org/resources/statistics/us-nuclear-industry-capacity-factors. [Accessed August 2023].

[11] Energy Information Administration, "U.S. nuclear electricity generation continues to decline as more reactors retire," april 2022. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=51978. [Accessed August].

[12] International Atomic Energy Agency, "The Resilience and Safety of Nuclear Power in the Face of Extreme Events," September 2020. [Online]. Available:

https://www.iaea.org/bulletin/the-resilience-and-safety-of-nuclear-power-in-the-face-of-extreme-events. [Accessed August 2023].

[13] American Nuclear Society, "U.S. nuclear capacity factors: Resiliency and new realities," May 2020. [Online]. Available: https://www.ans.org/news/article-183/us-nuclear-capacity-factors-resiliency-and-new-realities/. [Accessed August 2023].

[14] U.S. Energy Information Administration, "Capacity Factors for Utility Scale Generators Primarily Using Non-Fossil Fuels," [Online]. Available: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b. [Accessed October 2023].

[15] SolarSena, "Topaz Solar Farm (550 MW), California," april 2021. [Online]. Available: https://solarsena.com/topaz-solar-farm/. [Accessed July 2023].

[16] Solar Star Projects, "Fact Sheet," 2016. [Online]. Available: https://us.sunpower.com/sites/default/files/media-library/case-studies/cs-solar-star-projects-fact-sheet.pdf. [Accessed July 2023].

[17] U.S. Energy Information Administration, "Electricity Data Browser," [Online]. Available: https://www.eia.gov/electricity/data/browser/#/topic/0?agg=2,0,1&fuel=vtvv&geo=g&sec=g&linechart=ELEC.PLANT.GEN.58388-SUN-ALL.A&columnchart=ELEC.GEN.ALL-US-99.A~ELEC.GEN.COW-US-99.A~ELEC.GEN.NG-US-99.A~ELEC.GEN.NUC-US-99.A~ELEC.GEN.HYC-US-99.A~ELEC.GEN.WN. [Accessed July 2023].

[18] U.S. Emergy Information Administration, "Electricity Data Browser- Solar Star 2," [Online]. Available: https://www.eia.gov/electricity/data/browser/#/plant/58389?freq=A&start=2008&end=2019&ctype=linechart&ltype=pin&columnchart=ELEC.PLANT.GEN.58389-ALL-ALL.A&maptype=0&pin=ELEC.PLANT.GEN.58389-SUN-ALL.A&linechart=ELEC.PLANT.GEN.58389-SUN-ALL.A. [Accessed July 2023].

[19] National Renewable Energy Laboratory, "Crescent Dunes Solar Energy Project," October 2022. [Online]. Available: https://solarpaces.nrel.gov/project/crescent-dunes-solar-energy-project. [Accessed July 2023].

[20] USA BY #UNMBERS, "Top 12 Biggest Wind Farms in the US," January 2023. [Online]. Available: https://usabynumbers.com/wind-farms-in-the-us/#:~:text=Top%2012%20Biggest%20Wind%20Farms%20in%20the%20US,8.%20Capricorn%20Ridge%20Wind%20Farm%20...%20More%20items. [Accessed October 2023].

[21] NS ENERGY, "Top five biggest wind farms in the US," October 2018. [Online]. Available: https://www.nsenergybusiness.com/news/biggest-wind-farms-us/#:~:text=Featuring%2087%20Siemens%20SWT-2.3-108%20turbines%2C%20the%20200MW%20Los,spread%20over%20an%20area%20of%20approximately%2030%2C000%20acres.. [Accessed October 2023].

[22] NASA: Landsat Science, "Land Under Water: Estimating Hydropower's Land Use Impacts," March 2018. [Online]. Available: https://landsat.gsfc.nasa.gov/article/land-under-water-estimating-hydropowers-land-use-impacts/#:~:text=%E2%80%9CThe%20average%20land%20occupation%20in%20our%20study%20across,yr%2FkWh%20in%20the%20database%20for%20Switzerland%2C%E2%80%9D%20Dorber%20said.. [Accessed October 2023].

[23] U.S. Energy Information Administration, "Electricity Browser- Donald Cook," [Online]. Available: https://www.eia.gov/electricity/data/browser/#/plant/6000?freq=A&ctype=linechart&ltype=pin&columnchart=ELEC.PLANT.GEN.6000-ALL-ALL.A&linechart=ELEC.PLANT.GEN.6000-ALL-ALL.A&maptype=0&pin=. [Accessed July 2023].

[24] U.S. Energy Information Administration, "Palisades," [Online]. Available: https://www.eia.gov/electricity/data/browser/#/plant/1715/?freq=M&pin=. [Accessed October 2023].

[25] U.S. Energy Information Administration, "Electricity Data Browser-Fermi," [Online]. Available: https://www.eia.gov/electricity/data/browser/#/plant/1729?freq=A&ctype=linechart&ltype=pin&pin=&maptype=0&linechart=ELEC.PLANT.GEN.1729-ALL-ALL.A&columnchart=ELEC.PLANT.GEN.1729-ALL-ALL.A. [Accessed July 2023].

[26] Indiana Michigan Power: An AEP Company, "Cook Nuclear Plant," [Online]. Available: http://cookinfo.com/. [Accessed July 2023].

[27] ARCGIS, "Palisades Nuclear Plant," [Online]. Available: https://experience.arcgis.com/experience/5c8c212bf83a459a94824112224c500d/page/Palisades/. [Accessed October 2023].

[28] Nuclear Regulatory Comission, "Fermi 2 UFSAR," [Online]. Available: https://www.nrc.gov/docs/ML2105/ML21055A081.pdf. [Accessed July 2023].

[29] U.S. Department of Energy, "Pathways to Commercial Liftoff: Advanced Nuclear," March 2023. [Online]. Available: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf. [Accessed May 2023].

[30] Nuclear Regulatory Commission, "Emergency Planning Zones," [Online]. Available: https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html. [Accessed July 2023].

[31] Nuclear Regulatory Comission, "Backgrounder on Emergency Preparedness at Nuclear Power Plants," [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/emerg-plan-prep-nuc-power.html. [Accessed July 2023].

[32] R. Kelk, A. Murad, R. de Olivera and M. Jeltsov, "Emergency planning zones for small modular reactors," 2020. [Online]. Available: https://fermi.ee/wp-content/uploads/2021/03/epz-report-kbfi-20210211.pdf. [Accessed July 2023].

[33] U.S. Nuclear Regulatory Commission, "NRC to Issue Final Rule for Emergency Preparedness For Small Modular Reactors and Other New Technologies," [Online]. Available: https://www.nrc.gov/cdn/doc-collection-news/2023/23-048.pdf. [Accessed 2023 August].

[34] National Renewable Energy Laboratory, "Life Cycle Greenhouse Gas Emissions for Electricity Generation," 2021. [Online]. Available: https://www.nrel.gov/docs/fy21osti/80580.pdf. [Accessed August 2023].

[35] International Energy Agency, "Nuclear Power in a Clean Energy Sytem," May 2019. [Online]. Available: https://iea.blob.core.windows.net/assets/ad5a93ce-3a7f-461d-a441-8a05b7601887/Nuclear_Power_in_a_Clean_Energy_System.pdf. [Accessed August 2023].

[36] Energy Information Administration, "Electricity Generation, Capacity, and Sales in the United States," February 2023. [Online]. Available: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php. [Accessed August 2023].

[37] Nuclear Regulatory Commission, "Reevaluation of Station Blackout Risk at Nuclear Power Plants," December 2005. [Online]. Available: https://www.nrc.gov/docs/ML0602/ML060200479.pdf. [Accessed August 2023].

[38] Energy Information Administration, "Changes in coal sector led to less SO2 and NOx emissions from electric power industry," December 2018. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=37752. [Accessed August 2023].

[39] Enviormental Protection Agency, "Natural Gas Combustion," September 2020. [Online]. Available: https://www.epa.gov/sites/default/files/2020-09/documents/1.4_natural_gas_combustion.pdf. [Accessed August 2023].

[40] Energy Information Administration, "Michigan - Natural Gas 2021," 2021. [Online]. Available: https://www.eia.gov/naturalgas/annual/pdf/table_S24.pdf#:~:text=Industrial%207%2C325%20

7%2C076%206%2C729%206%2C589%206%2C392%20Average%20annual,575%20614%20Industrial%2023%2C234%2024%2C908%2025%2C801%2023%2C395%2024%2C820. [Accessed August 2023].

[41] Energy Information Administration, "Changes in coal sector led to less SO2 and NOx emissions from electric power industry," December 2018. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=37752. [Accessed August 2023].

[42] Electric Power Research Institute, "NUCLEAR PLANT RESILIENCE TO WEATHER-RELATED EVENTS BETWEEN 2011 TO 2020," 2022.

[43] U.S. Energy Information Administration, "Table 8.4. Average Power Plant Operating Expenses for Major U.S. Investor-Owned Electric Utilities, 2012 through 2022 (mills per kilowatthour)," [Online]. Available: https://www.eia.gov/electricity/annual/html/epa_08_04.html. [Accessed December 2023].

[44] World Nuclear Association, "Supply of Uranium," August 2023. [Online]. Available: https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx. [Accessed October 2023].

[45] World Nuclear Association, "Plutonium," [Online]. Available: https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx. [Accessed August 2023].

[46] B. Van Gosen and H. Tulsidas, "10 - Thorium as a nuclear fuel," in *Uranium for Nuclear Power*, Woodhead Publishing, 2016, pp. 253-296.

[47] Pacific Northwest National Laboratory, "Seawater yields first grams of yellowcake," June 2018. [Online]. Available: https://www.pnnl.gov/news/release.aspx?id=4514. [Accessed August 2023].

[48] Y. Yuan, Q. Yu, M. Cao and e. al., "Selective extraction of uranium from seawater with biofouling-resistant polymeric peptide.," *Nature Sustainability,* vol. 4, pp. 708-714, 2021.

[49] Nuclear Energy Institute, "Safe, Secure Transporation of Used Nuclear Fuel," September 2019. [Online]. Available: https://nei.org/resources/fact-sheets/safe-secure-transportation-used-nuclear-fuel. [Accessed August 2023].

[50] U.S. Nuclear Regulatory Commission, "Consolidated Interim Storage Facility," [Online]. Available: https://www.nrc.gov/waste/spent-fuel-storage/cis.html. [Accessed August 2023].

[51] Nuclear Regulatory Commission, "Backgrounder on Nuclear Insurance and Disaster Relief," April 2022. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/nuclear-insurance.html. [Accessed August 2023].

[52] Nuclear Electric Insurance Limited, "Who We Are," [Online]. Available: https://www.myneil.com/about-us. [Accessed August 2023].

[53] World Nuclear News, "Cook 1 restart September at the earliest," December 2008. [Online]. Available: https://world-nuclear-news.org/Articles/Cook-1-restart-September-at-the-earliest. [Accessed October 2023].

[54] Nuclear Energ Institute, "Nuclear Fuel," [Online]. Available: https://www.nei.org/fundamentals/nuclear-fuel. [Accessed August 2023].

[55] Energy Information Administration, "Nuclear Fuel Cycle," July 2022. [Online]. Available: https://www.eia.gov/energyexplained/nuclear/the-nuclear-fuel-cycle.php. [Accessed August 2023].

[56] Nuclear Regulatory Commission, "Module 3.0: Laser Enrichment Methods (AVLIS and MLIS)," [Online]. Available: https://www.nrc.gov/docs/ML1204/ML12045A051.pdf. [Accessed August 2023].

[57] U.S. Department of State, "THE NUCLEAR NON-PROLIFERATION TREATY: DISARMAMENT," July 2022. [Online]. Available: https://www.state.gov/wp-content/uploads/2022/07/Disarmament-Factsheet.pdf. [Accessed August 2023].

[58] Los Alamos National Laboratory, "Protecting Against Nuclear Threats," [Online]. Available: https://mission.lanl.gov/nuclear-threats/. [Accessed August 2023].

[59] International Atomic Energy Agency, "The IAEA and the Non-Proliferation Treaty," [Online]. Available: https://www.iaea.org/topics/non-proliferation-treaty. [Accessed December 2023].

[60] Energy Information Administration, "Megatons to Megawatts program will conclude at the end of 2013," September 2013. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=13091. [Accessed August 2023].

[61] World Nuclear News, "Megatons to Megawatts program concludes," 11 December 2013. [Online]. Available: https://www.world-nuclear-news.org/ENF-Megatons-to-Megawatts-program-concludes-1112134.html. [Accessed October 2023].

[62] International Atomic Energy Agency, "Genral Studies of Nuclear Reactors," International Nuclear Information System, Nuclear Energy Agency of OECD, 2018.

[63] B. Cohen, The Nuclear Energy Option, Plenum Press, 1990.

[64] J. R. Lovering, A. Yip and T. Nordhaus, "Historical construction costs of global nuclear power reactors," *Energy Policy,* vol. 91, no. 0301-4215, pp. 372-382, 2016.

[65] Nuclear Energy Institute, "Nuclear Costs in Context," October 2022. [Online]. Available: https://www.nei.org/resources/reports-briefs/nuclear-costs-in-context. [Accessed July 2023].

[66] W. R. &. S. K. Stewart, "Capital Cost Evaluation of Advanced Water-Cooled Reactor Designs With Consideration of Uncertainty and Risk," Center for Advanced Nuclear Energy Systems (CANES) at MIT, 2022.

[67] International Atomic Energy Agency, Advances in Small Modular Reactor Technology Developments, 2020.

[68] B. Mignacca and G. Locatelli, "Economics and finance of Small Modular Reactors: A systematic review and research agenda," *Renewable and Sustainable Energy Reviews,* vol. 118, 2020.

[69] G. A. Black, F. Aydogan and C. L. Koerner, "Economic viability of light water small modular nuclear reactors: General methodology and vendor data," *Renewable and Sustainable Energy Reviews,* vol. 103, no. 1364-0321, pp. 248-258, 2019.

[70] W. Stewart and K. Shirvan, "Capital cost estimation for advanced nuclear power plants," *Renewable and Sustainable Energy Reviews,* vol. 155, 2022.

[71] Institue for Energy Economics and Financial Analysis, "Eye-Popping new cost estimates released for NuScale small modular reactor.," January 2023. [Online]. Available: https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor. [Accessed July 2023].

[72] U.S. NRC, "Transportation of Spent Nuclear Fuel," [Online]. Available: https://www.nrc.gov/waste/spent-fuel-transp.html. [Accessed December 2023].

[73] Environmental Protection Agency, "Summary of the Nuclear Waste Policy Act," [Online]. Available: https://www.epa.gov/laws-regulations/summary-nuclear-waste-policy-act. [Accessed August 2023].

[74] U.S. Nuclear Regulatory Commission, "DOE's License Application for a High-Level Waste Geologic Repository at Yucca Mountain," 2008. [Online]. Available: https://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html. [Accessed October 2023].

[75] U.S. Nuclear Regulatory Commission, "NRC Staff's Safety Evaluation Report," [Online]. Available: https://www.nrc.gov/waste/hlw-disposal/key-documents.html#sers. [Accessed October 2023].

[76] U.S. DOE, "Spent Nuclear Fuel and Reprocessing Waste Inventory November 2021," 2021.

[77] HKA, "Spent Nuclear Fuel Verdicts & Settlements".

[78] Congressional Research Service, "Contract Liability Arising from the Nuclear Waste Policy Act (NWPA) of 1982," 2012.

[79] OECD Nuclear Energy Agency, "Technical and Economic Aspects of Load Following with Nuclear Power Plants," OECD NEA, 2011.

[80] PacifiCorp, "Integrated Resource Plan," June 2021. [Online]. Available: https://www.pacificorp.com/content/dam/pcorp/documents/en/pacificorp/energy/integrated-resource-plan/PacifiCorps_2021_IRP_PIM_June_25_2021.pdf. [Accessed October 2023].

[81] Energy Information Administration, "About 25% of U.S. power plants can start up within an hour," November 2020. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=45956. [Accessed November 2023].

[82] U.S. Nuclear Regulatory Commission, "Frequently Asked Questions (FAQ) About Radiation Protection," [Online]. Available: https://www.nrc.gov/about-nrc/radiation/related-info/faq.html#9. [Accessed October 2023].

[83] U.S. NRC, "Natural Background Sources," [Online]. Available: https://www.nrc.gov/about-nrc/radiation/around-us/sources/nat-bg-sources.html. [Accessed December 2023].

[84] U.S. Nuclear Regulatory Commission, "Backgrounder on the Three Mile Island Accident," [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html. [Accessed October 2023].

[85] Public Citizen, "Price-Anderson Act: The Billion Dollar Bailout for Nuclear Power Mishaps," [Online]. Available: https://www.citizen.org/wp-content/uploads/price_anderson_factsheet.pdf. [Accessed August 2023].

[86] Congressional Research Service, "Price-Anderson Act: Nuclear Power Industry Liability Limits and Compensation to the Public After Radioactive Releases," 2018.

[87] U.S. Nuclear Regulatory Commission, "Backgrounder on Nuclear Insurance and Disaster Relief," [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/nuclear-insurance.html. [Accessed October 2023].

[88] U.S. Nuclear Regulatory Commission, "Fermi Unit 1," [Online]. Available: https://www.nrc.gov/info-finder/decommissioning/power-reactor/enrico-fermi-atomic-power-plant-unit-1.html. [Accessed August 2023].

[89] J. Reindl, "Did we really 'almost lose Detroit' in Fermi 1 mishap 50 years ago?," *Detroit Free Press,* 9 October 2016.

[90] D. Lochbaum, "Nuclear Plant Accidents: Fermi Unit 1," Union of Concerned Scientists, 2016.

[91] D. Lochbaum, "Nuclear Plant Accidents: Sodium Reactor Experiment," Union of Concerned Scientists, 2016.

[92] "Emergency Preparedness at Nuclear Plants," Nuclear Energy Institute, 2016.

[93] D. H. Dorman, "SECY-22-0001, Final Rule: Emergency Preparedness for Small Modular Reactors and Other New Technologies," 3 January 2022. [Online]. Available: https://www.nrc.gov/docs/ML2120/ML21200A055.html. [Accessed 18 August 2023].

[94] Atomic Heritage Foundation, "Indian Nuclear Program," [Online]. Available: https://ahf.nuclearmuseum.org/ahf/history/indian-nuclear-program/. [Accessed August 2023].

[95] U.S. Nuclear Regulatory Commission, ""Too Cheap to Meter": A History of the Phrase," [Online]. Available: https://www.nrc.gov/reading-rm/basic-ref/students/history-101/too-cheap-to-meter.html. [Accessed August 2023].

[96] Michigan in the World and the Environmental Justice HistoryLab, projects of the U-M History Department, "Consumers Power Company - Midland, Big Rock," Ann Arbor, MI.

[97] D. Clark, "Midland Cogeneration facility purchased for $894 million," *Midland Daily News,* 13 July 2022.

[98] U.S. Department of Energy, "HALEU Demonstration Project Preps to Start First Domestic Production in U.S.," [Online]. Available: https://www.energy.gov/ne/articles/haleu-demonstration-project-preps-start-first-domestic-production-us. [Accessed August 2023].

[99] World Nuclear News, "HALEU fuel availability delays Natrium reactor project," [Online]. Available: https://world-nuclear-news.org/Articles/HALEU-fuel-availability-delays-Natrium-reactor-pro. [Accessed August 2023].

[100] World Nuclear Assocation , "Uranium Enrichment (Archived)," [Online]. Available: https://web.archive.org/web/20130701071520/http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/. [Accessed August 2023].

[101] U.S. Nuclear Regulatory Commission, "NRC Operator License Eligibility Requirements," [Online]. Available: https://www.nrc.gov/docs/ML1905/ML19053A433.pdf.

[102] Palisades Economic Recovery Initiative, "Economic Assessment of the Palisades Nuclear Power Plant Closure," Economic Growth Institute - University of Michigan, 2023.

[103] Holtec, "Holtec and Wolverine Ink Historic Power Purchase Agreement for the Palisades Power Plant," 2023.

[104] Office of Nuclear Energy, "These Accident Tolerant Fuels Could Boost the Performance of Today's Reactors," January 2020. [Online]. Available: https://www.energy.gov/ne/articles/these-accident-tolerant-fuels-could-boost-performance-todays-reactors#:~:text=Accident%20tolerant%20fuels%20are%20expected%20to%20last%20longer,1.5%20to%202%20years%20for%20pressurized%20water%20reactors.. [Accessed August 2023].

[105] U.S. NRC, "Accident Tolerant Fuel," [Online]. Available: https://www.nrc.gov/reactors/power/atf.html. [Accessed December 2023].

[106] "U.S. Nuclear Operating Plant Basic Information," [Online]. Available: https://www.nei.org/resources/statistics/us-nuclear-operating-plant-basic-information. [Accessed July 2023].

[107] Nuclear Regulatory Commission, "Fermi 2 UFSAR," February 2014. [Online]. Available: https://www.nrc.gov/docs/ML1616/ML16165A449.pdf. [Accessed August 2023].

[108] Nuclear Regulatory Commission, "Approved Power Uprate Application Information For Donald C. Cook Nuclear Plant Unit 1," 2002. [Online]. Available: https://www.nrc.gov/docs/ML0218/ML021840343.pdf. [Accessed August 2023].

[109] Nuclear Regulatory Commission, "Approved Power Uprate Application Information For Donald C. Cook Nuclear Plant Unit 2," 2002. [Online]. Available: https://www.nrc.gov/docs/ML0232/ML023250307.pdf. [Accessed August 2023].

[110] Nuclear Regulatory Commission, "Approved Power Uprate Application Information For Palisades Nuclear Plant," 2002. [Online]. Available: https://www.nrc.gov/docs/ML0316/ML031611053.pdf. [Accessed August 2023].

[111] Code of Federal Regulations Title 10 §50.75, "Reporting and recordkeeping for decommissioning planning".

[112] Code of Federal Regulations Title 10 §50.82, "Termination of License".

[113] Holtec Decommissioning International, LLC (HDI), *Report on Status of Decommissioning Funding for Reactors and Independent Spent Fuel Storage Installations – Holtec Decommissioning International, LLC (HDI),* March 31, 2023.

[114] American Nuclear Society, "NRC opens Palisades' decommissioning plans to public comment," September 2022. [Online]. Available: https://www.ans.org/news/article-4301/nrc-opens-palisades-decommissioning-plans-to-public-comment/. [Accessed August 2023].

[115] Nuclear Regulatory Commission, "US. Nuclear Regulatory Commisions analysis of Entergy Nuclear Operations," April 2021. [Online]. Available: https://www.nrc.gov/docs/ML2105/ML21054A132.pdf. [Accessed August 2023].

[116] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2 Decommissioning Funding Status Report," March 28, 2023.

[117] Nuclear Regulatory Commission, "Donald C. Cook Nuclear Plant Units 1 and 2 Decommissioning Funding Status Report," March 2023. [Online]. Available: https://www.nrc.gov/docs/ML2308/ML23087A116.pdf. [Accessed August 2023].

[118] DTE Electric Company, "Decommissioning Funding Status Report for Fermi 1," March 30, 2023.

[119] Nuclear Regulatory Commission, "Decommissioning Funding Status Report for Fermi 1," March 2021. [Online]. Available: https://www.nrc.gov/docs/ML2109/ML21090A027.pdf. [Accessed August 2023].

[120] DTE Electric Company, "Decommissioning Funding Status Report for Fermi 2," March 30, 2023.

[121] U. N. R. Commission, "Generic Environmental Impact Statement for License Renewal of Nuclear Plants (GEIS), Supplement 56 Regarding Fermi Nuclear Power Plant – Final Report, Chapters 1-8, NUREG-1437, Volume 1 September 2016. ADAMS Accession No. ML16259A103," 2016.

[122] DTE Energy Company, "Fermi 2 License Renewal Application Appendix D Technical Specification Changes and Appendix E Environmental Report. April 24, 2014. Accession Nos. ML14121A538, ML14121A539, and ML14121A540," 2014.

[123] Michigan Sea Grant, "Michigan Sea Grant Lake Erie," [Online]. Available: https://www.michiganseagrant.org/topics/great-lakes-fast-facts/lake-erie. [Accessed 22 August 2023].

[124] US Nuclear Regulatory Commission, "NUREG-1437 Supplement 20, GEIS for License Renewal of Nuclear Plants, Donald C. Cook Nuclear Plant, Units 1 and 2, Final Report, May 2005. ADAMS Accession No. ML051150556," 2005.

[125] US Nuclear Regulatory Commission, "Generic Environmental Impact Statement for License Renewal of Nuclear Plants (GEIS), Supplement 56 Regarding Fermi Nuclear Power Plant – Final Report, Chapters 1-8, NUREG-1437, Volume 1 September 2016. ADAMS Accession No. ML16259A103," 2016.

[126] U.S. Federal Reserve, "Detroit Edison Company; Environmental Assessment and Finding of No Significant Impact," 9 August 1994. [Online]. Available: https://www.govinfo.gov/content/pkg/FR-1994-08-09/html/94-19392.htm. [Accessed December 10 2023].

[127] DTE Energy Company, "Fermi 2 Power Plant, Operating License No. NPF – 43, - 2017 Annual Radioactive Effluent Release Report and 2017 Annual Radiological Environmental Operating Report. April 30, 2018. Accession No. ML18120A227," 2018.

[128] DTE Energy Company, "Fermi 2 Power Plant, Operating License No. NPF – 43, - 2018 Annual Radioactive Effluent Release Report and 2018 Annual Radiological Environmental Operating Report. April 30, 2019. Accession No. ML19120A513," 2019.

[129] DTE Energy Company, "Fermi 2 Power Plant, Operating License No. NPF – 43, - 2019 Annual Radioactive Effluent Release Report and 2019 Annual Radiological Environmental Operating Report. April 29, 2020. Accession No. ML20121A240," 2020.

[130] DTE Energy Company, "Fermi 2 Power Plant, Operating License No. NPF – 43, - 2020 Annual Radioactive Effluent Release Report and 2020 Annual Radiological Environmental Operating Report. April 28, 2021 Accession No. ML21118B032," 2021.

[131] DTE Energy Company, "Fermi 2 Power Plant, Operating License No. NPF – 43, - 2021 Annual Radioactive Effluent Release Report and 2021 Annual Radiological Environmental Operating Report. April 29, 2022. Accession No. ML22119A115," 2022.

[132] US Census, "US Census-Berrien County," 1 July 2022. [Online]. Available: https://www.census.gov/quickfacts/fact/table/berriencountymichigan/PST045222#PST045222. [Accessed 21 August 2023].

[133] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2021 Annual Radioactive Effluent Release Report. April 29, 2022. ADAMS Accession No. ML22119A256," 2022.

[134] Michigan Department of Environment, Great Lakes, and Energy, "Ozone Nonattainment," [Online]. Available: https://www.michigan.gov/egle/about/organization/air-quality/state-implementation-plan/ozone-nonattainment#:~:text=The%20Michigan%20counties%20designated%20as,Clair%2C%20Washtenaw%2C%20and%20Wayne. [Accessed 23 May 2023].

[135] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2017 Annual Radioactive Effluent Release Report. April 30, 2018. ADAMS Accession No. ML18123A348," 2018.

[136] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2018 Annual Radioactive Effluent Release Report. April 29, 2019. ADAMS Accession No. ML19122A388," 2019.

[137] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2019 Annual Radioactive Effluent Release Report. April 29, 2020. ADAMS Accession No. ML19122A388," 2020.

[138] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2020 Annual Radioactive Effluent Release Report. April 28, 2021. ADAMS Accession No. ML2118B086," 2021.

[139] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2017 Annual Radiological Environmental Operating Report. May 15, 2018. ADAMS Accession No. ML18137A203," 2018.

[140] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2018 Annual Radiological Environmental Operating Report. April 29, 2019. ADAMS Accession No. ML19122A094," 2019.

[141] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2019 Annual Radiological Environmental Operating Report. May 14, 2020. ADAMS Accession No. ML20143A247," 2020.

[142] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2020 Annual Radiological Environmental Operating Report. May 12, 2021. ADAMS Accession No. ML21133A000," 2021.

[143] Indiana Michigan Power, "Donald C. Cook Nuclear Plant Units 1 and 2, 2021 Annual Radiological Environmental Operating Report. May 13, 2022. ADAMS Accession No. ML22136A138," 2022.

[144] US Nuclear Regulatory Commission, NUREG-1437 Supplement 27, Generic Environmental Impact Statement for License Renewal of Nuclear Plants, Regarding Palisades Nuclear Plant, Final Report, October 2006. ADAMS Accession No. ML062710300, 2006.

[145] Holtect Decommissioning International, LLC & Comprehensive Decommissioning International, LLC , "Palisades Nuclear Plant, Post-Shutdown Decommissioning Activities Report and Site-SPecific Decommissioning Cost Estimate for Palisades Nuclear Plant. December 23, 2020. ADAMS Accession No. ML20358A232," 2020.

[146] Entergy Nuclear Operations, Inc., "2021 Annual Radiological Environmental Operating Report. May 12, 2022. ADAMS Accession No. ML 22132A110," 2022.

[147] Entergy Nuclear Operations, Inc., "2017 Annual Radioactive Effluent Release Report. April 20, 2018. Accession No. ML18113A246," 2018.

[148] Entergy Nuclear Opeations, Inc., "2018 Annual Radioactive Effluent Release Report. April 24, 2019. Accession No. ML19114A042," 2019.

[149] Entergy Nuclear Opeations, Inc., "2019 Annual Radioactive Effluent Release Report. April 15, 2020. Accession No. ML20107G158," 2020.

[150] Entergy Nuclear Operations, Inc., "2020 Annual Radioactive Effluent Release Report. April 21, 2021. Accession No. ML21111A179," 2021.

[151] Entergy Nuclear Operations, Inc., "2021 Annual Radioactive Effluent Release Report. April 25, 2022. Accession No. ML 22115A111," 2022.

[152] Entergy Nuclear Operations, Inc., "2017 Annual Radiological Environmental Operating Report. May 10, 2018. ADAMS Accession No. ML18130A813," 2018.

[153] Entergy Nuclear Operations, Inc., "2018 Annual Radiological Environmental Operating Report. May 2, 2019. ADAMS Accession No. ML18122A195," 2019.

[154] Entergy Nuclear Operations, Inc., "2019 Annual Radiological Environmental Operating Report. April 15, 2020. ADAMS Accession No. ML20108E575," 2020.

[155] Entergy Nuclear Operations, Inc., "2020 Annual Radiological Environmental Operating Report. May 12, 2021. ADAMS Accession No. ML 22132A068," 2021.

[156] U.S. Environmental Protection Agency, "Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act," 2023. [Online]. Available: https://www.epa.gov/climate-change/endangerment-and-cause-or-contribute-findings-greenhouse-gases-under-section-202a. [Accessed 8 December 2023].

[157] US Environmental Protection Agency, "Climate Change Indicators: Great Lakes Water Levels and Temperatures," [Online]. Available: https://www.epa.gov/climate-indicators/great-lakes. [Accessed 20 October 2023].

[158] US Nuclear Regulatory Commission, "Environmental Impact Statement for the Combined License (COL) for Enrico Fermi Unit 3, Final Report. Washington, DC: NRC. NUREG–2105, Volumes 1 and 2. January 2013. ADAMS Nos. ML12307A172 and ML12307A176.," NRC, 2013.

[159] National Oceanic and Atmospheric Administration, "NOAA Research - Climate-driven shifts in deep Lake Michigan water temperatures signal the loss of winter," [Online]. Available: https://research.noaa.gov/2021/03/16/climate-driven-shifts-in-deep-lake-michigan-water-temperatures-signal-the-loss-of-winter/#:~:text=%E2%80%9CWe%20found%20that%20this%20long,Anderson%2C%20the%20study's%20lead%20author.. [Accessed 20 October 2023].

[160] US Climate Resilience Toolkit , "US Climate Resilience Toolkit -Regions, Great Lakes," [Online]. Available: https://toolkit.climate.gov/regions/great-lakes. [Accessed 20 October 2023].

[161] Nuclear Energy Institute, "What Every Governor Needs to Know About Nuclear Energy," June 2023. [Online]. Available: https://www.nei.org/resources/fact-sheets/what-every-governor-needs-to-know-about-nuclear. [Accessed 16 June 2023].

[162] Intergovernmental Panel on Climate Change, "Climate Change 2023 Synthesis Report," 2023. [Online]. Available: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf. [Accessed 8 December 2023].

[163] World Nuclear Association, "World Nuclear Associate-How Can Nuclear Combat Climate Change," [Online]. Available: https://world-nuclear.org/nuclear-essentials/how-can-nuclear-combat-climate-change.aspx. [Accessed 26 May 2023].

[164] Nuclear Energy Institute, "Climate-Nuclear energy provides more than half of America's carbon-free electricity.," [Online]. Available: https://www.nei.org/advantages/climate. [Accessed 16 June 2023].

[165] US Nuclear Regulatory Commission, "Generic Environmental Impact Statement for License Renewal of Nuclear Plants, Appendices, Final Report, NUREG-1437, Volume 3, Revision 1. ADAMS Accession No. ML13106A244," 2013.

[166] Detroit Free Press, "Opinion: Michigan Should expand nuclear energy. It’s clean, safe and reliable. April 11, 2023," 11 April 2023. [Online]. Available: https://www.freep.com/story/opinion/contributors/2023/04/11/opinion-michigan-should-expand-clean-safe-reliable-nuclear-energy/70100336007/#:~:text=It%20is%20worth%20noting%2C%20too,to%20operate%20nuclear%20power%20plants. [Accessed 21 August 2023].

[167] Weather US, "The Climate of Michigan," [Online]. Available: https://www.weather-us.com/en/michigan-usa-climate. [Accessed 21 August 2023].

[168] Nuclear Regulatory Commission, "Generic Aging Lessons Learned (GALL) Report (NUREG-1801)," March 2021. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1801/index.html. [Accessed August 2023].

[169] Nuclear Regulatory Commission, "Status of Subsequent License Renewal Applications," July 2023. [Online]. Available: https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html#received. [Accessed August 2023].

[170] Nuclear Energy Institute, "Initial License Renewal Application Updates for U.S. Nuclear Power Plants," August 2022. [Online]. Available: https://www.nei.org/resources/statistics/us-nuclear-license-renewal-filings#:~:text=Nuclear%20Regulatory%20Commission%20has%20approved%20Initial%20License%20Renewal,Palisades%2C%20Pilgrim%2C%20Three%20Mile%20Island%2C%20and%20Vermont%20Yankee.. [Accessed August 2023].

[171] EPRI, "Nuclear Plant Life Cycle Management Implementation Guide, TR106109," 1998. [Online]. Available: https://www.osti.gov/biblio/354971. [Accessed August 2023].

[172] EPRI, "Users Guide for the Development of Life Cycle management plans, TR1025260".

[173] Nuclear Regulatory Commission, "Design Certification Application Review - AP1000 Amendment," [Online]. Available: https://www.nrc.gov/reactors/new-reactors/large-lwr/design-cert/amended-ap1000.html. [Accessed July 2023].

[174] Nuclear Energy Institute, "Advanced Nuclear Energy," [Online]. Available: https://www.nei.org/advanced-nuclear-energy. [Accessed August 2023].

[175] Nuclear Regulatory Commission, "NRC Authorizes Fuel Loading and Operation at Vogtle Unit 4," July 2023. [Online]. Available: https://www.nrc.gov/cdn/doc-collection-news/2023/23-047.pdf. [Accessed August 2023].

[176] Nuclear Regulatory Commission, "Locations of New Nuclear Power Reactor Applications," September 2022. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/large-lwr/col/new-reactor-map.html. [Accessed August 2023].

[177] Nuclear Regulatory Commission, "Final Safety Evaluations for Fermi, Unit 3 Application," [Online]. Available: https://www.nrc.gov/reactors/new-reactors/large-lwr/col/fermi/documents/ser-final.html. [Accessed August 2023].

[178] GEN IV International Forum, "Welcome to Generation IV International forum," [Online]. Available: https://www.gen-4.org/gif/. [Accessed August 2023].

[179] Gen IV International Forum, "Generation IV Goals," [Online]. Available: https://www.gen-4.org/gif/jcms/c_9502/generation-iv-goals. [Accessed August 2023].

[180] Gen IV International Forum, "Generation IV Systems," [Online]. Available: https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems. [Accessed August 2023].

[181] OECD Nuclear Energy Agency, "The NEA Small Modular Reactor Dashboard," OECD Publishing, Paris, 2023.

[182] OECD Nuclear Energy Agency, "The NEA Small Modular Reactor Dashboard: Volume II," OECD Publishing, Paris, 2023.

[183] Nuclear Regulatory Commission, "Issues Early Site Permit - Clinche River Nuclear Site," September 2022. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/large-lwr/esp/clinch-river.html. [Accessed May 2023].

[184] Nuclear Regulatory Commission, "Early Site Permit Applications for New Reactors," September 2022. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/large-lwr/esp.html. [Accessed May 2023].

[185] TerraPower, "Natrium: Carbon-Free Power for the Clean Energy Transition," [Online]. Available: https://natriumpower.com/. [Accessed August 2023].

[186] X-Energy, "Advanced Nuclear Reactor Project in Seadrift, Texas," [Online]. Available: https://x-energy.com/seadrift. [Accessed August 2023].

[187] U.S. Department of Energy, "What is a Nuclear Microreactor?," [Online]. Available: http://energy.gov/ne/articles/what-nuclear-microreactor. [Accessed August 2023].

[188] J. Lovering, "A Techno-Economic Evaluation of Microreactors for Off-Grid and Microgrid Applications," *Sustainable Cities and Society,* vol. 95, 2023.

[189] L. Wodrich, A. J. H. Lee, T. Kozlowski and C. S. Brooks, "Modeling of an Energy-Diverse Embedded Grid for Microreactor Integration," *Nuclear Technology,* vol. 209, no. 6, pp. 809-834, 2023.

[190] Oklo, "News Details," July 2023. [Online]. Available: https://oklo.com/newsroom/news-details/2023/Oklo-an-Advanced-Fission-Technology-Company-to-Go-Public-via-Merger-with-AltC-Acquisition-Corp/default.aspx. [Accessed August 2023].

[191] Last Energy, "Freeing the Potential of Nuclear Energy," [Online]. Available: https://drive.google.com/file/d/1L6tMES6dwN0kBV-ZsXl98tEOeE5x9Nce/view. [Accessed August 2023].

[192] GTTSI, "U.S. – Based Last Energy Secures PPA’s For 34 PWR-20 SMR’s," May 2023. [Online]. Available: https://gttsi.com/2023/05/u-s-based-last-energy-secures-ppas-for-34-pwr-20-smrs/. [Accessed August 2023].

[193] Ultra Safe Nuclear Corporation, "Projects: North America's First GEN IV Demonstrators," March 2023. [Online]. Available: https://www.usnc.com/projects/. [Accessed August 2023].

[194] Ultra Safe Nuclear Corporation, "MMR Energy System," 2023. [Online]. Available: August.

[195] Westinghouse, "eVinci Microreactor," 2023. [Online]. Available: https://www.westinghousenuclear.com/energy-systems/evinci-microreactor. [Accessed August 2023].

[196] Westinghouse Nuclear, "Westinghouse Launches eVinci™ Microreactor Accelerator Hub," 24 October 2023. [Online]. Available: https://info.westinghousenuclear.com/news/westinghouse-launches-evinci-microreactor-accelerator-hub. [Accessed December 2023].

[197] BWX Technologies Inc., "BWXT to Build First Advanced Microreactor in United States," June 2022. [Online]. Available: https://www.bwxt.com/news/2022/06/09/BWXT-to-Build-First-Advanced-Microreactor-in-United-States. [Accessed August 2023].

[198] World Nuclear News, "Wyoming to consider microreactors as SMR plans continue," August 2023. [Online]. Available: https://www.world-nuclear-news.org/Articles/Wyoming-to-consider-microreactors-as-SMR-plans-con. [Accessed August 2023].

[199] Radiant, "Kaleidos Home Page," 2022. [Online]. Available: https://www.radiantnuclear.com/. [Accessed August 2023].

[200] Global News Wire, "Former SpaceX Engineers Raise $1.2M and Launch Radiant," September 2020. [Online]. Available: https://www.globenewswire.com/news-release/2020/09/22/2097339/0/en/Former-SpaceX-Engineers-Raise-1-2M-and-Launch-Radiant-Which-Is-Developing-the-First-Portable-Zero-Emissions-Power-Source-That-Works-Anywhere.html. [Accessed August 2023].

[201] World Nuclear Association, "Small Nuclear Power Reactors," July 2023. [Online]. Available: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx. [Accessed August 2023].

[202] R. Testoni, A. Bersano and S. Segantin, "Review of nuclear microreactors: Status, potentialities and challenges," *Progress in Nuclear Energy,* vol. 138, 2021.

[203] J. Bayly, "How to start Homesteading in Michigan," November 2019. [Online]. Available: https://hellohomestead.com/how-to-start-homesteading-in-michigan/#:~:text=There%20were%2047%2C000%20farms%20in%20Michigan%20in%202017%2C,total%20farmed%20acreage%20in%202017%20was%209.8%20million.. [Accessed May 2023].

[204] E. Derr, "Nuclear Needs Small Amounts of Land to Deliver Big Amounts of Energy," Nuclear Energy Institute, April 2022. [Online]. [Accessed May 2023].

[205] U.S. Energy Information Administration, "Michigan State Energy Profile," August 2022. [Online]. Available: https://www.eia.gov/state/print.php?sid=mi#:~:text=In%202021%2C%20coal%20provided%20the%20largest%20share%20of,nuclear%20energy%20%2830%25%29%20and%20natural%20gas-fired%20power%20%2827%25%29.. [Accessed May 2023].

[206] A. F. S. Finder, "Alternative Fuels Data Center," U.S. Department of Energy, 2022.

[207] J. Modak, "Haber Process for Ammonia Synthesis," *Renosance,* vol. 7, pp. 69-77, 2002.

[208] J. Schenk and D. Spreitzer, "Reduction of Iron Oxides with Hydrogen- A review," *Steel Research International,* vol. 90, no. 10, 2019.

[209] R. El-Emam, H. Ozcan and C. Zamifirescu, "Updates on promising thermochemical cycles for clean hydrogen production using nuclear energy," *Journal of Clearn Production,* vol. 262, 2020.

[210] Worl Nuclear News, "Nucleoeléctrica contracted to complete CAREM-25," July 2021. [Online]. Available: https://www.world-nuclear-news.org/Articles/Nucleoelectrica-contracted-to-complete-CAREM-25#:~:text=The%20contract%20specifies%20construction%20of%20the%20small,modular%20reactor%20will%20be%20completed%20within%20three%20years.. [Accessed October 2023].

[211] U.S. Nuclear Regulatory Commission, "Design Certification - NuScale US600," [Online]. Available: https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/nuscale.html. [Accessed August 2023].

[212] U.S. Nuclear Regulatory Commission, "NuScale US460 Standard Design Approval Application Review," [Online]. Available: https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/current-licensing-reviews/nuscale-us460.html. [Accessed August 2023].

[213] NuScale, "Q2 2023 Investor Presentation," [Online]. Available: https://www.nuscalepower.com/-/media/nuscale/pdf/investors/2023/smr-2q23-presentation.pdf. [Accessed August 2023].

[214] NuScale, "NuScale Investor FAQs," [Online]. Available: https://www.nuscalepower.com/en/investors/resources/investor-faqs. [Accessed August 2023].

[215] CFPP LLC, "Carbon Free Power Project," [Online]. Available: https://www.cfppllc.com/. [Accessed August 2023].

[216] CFPP LLC, "Carbon Free Power Project Timeline," [Online]. Available: https://www.cfppllc.com/cfpp-timeline. [Accessed August 2023].

[217] U.S. Nuclear Regulatory Commission, "Issued Early Site Permit - Clinch River Nuclear Site," [Online]. Available: https://www.nrc.gov/reactors/new-reactors/large-lwr/esp/clinch-river.html. [Accessed August 2023].

[218] U.S. Nuclear Regulatory Commission, "Letter regarding ACRS Review of Construction Permit Application," [Online]. Available: https://www.nrc.gov/docs/ML2313/ML23130A183.pdf. [Accessed August 2023].

[219] Tennessee Valley Authority, "Kairos Power and TVA to Collaborate on Low-Power Demonstration Reactor," [Online]. Available: https://www.tva.com/newsroom/press-releases/kairos-power-and-tva-to-collaborate-on-low-power-demonstration-reactor. [Accessed August 2023].

[220] Electric Power Research Institute, "Advanced Nuclear Technology: Owner-Operator Reactor Technology Assesment Guide - 2022 Version," December 2022. [Online]. Available: https://www.epri.com/research/programs/065093/results/3002025344. [Accessed August 2023].

[221] Electric Power Research Institute, "Advanced Nuclear Technlogy: Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities (Siting Guide) - 2022 Revision," November 2022. [Online]. Available: https://www.epri.com/research/products/000000003002023910. [Accessed August 2023].

[222] Nuclear Regulatory Commission , "Industry Guideline for Developing a Plant Parameter Envelope in Support of an Early Site Permit," March 2010. [Online]. Available: https://www.nrc.gov/docs/ML1010/ML101050329.pdf. [Accessed August 2023].

[223] NOAA National Centers for Enviormental Information , "State Climate Summaries 2022 - Michigan," 2022. [Online]. Available: https://statesummaries.ncics.org/chapter/mi/. [Accessed August 2023].

[224] Nuclear Energy Institute Small Modular Reactor Licensing Task Force, "Physical Security For Small Modular Reactors," Nuclear Energy Institute, 2012.

[225] Nuclear Regulatory Commission, "Part 53 -Risk Informed, Technology inclusive Regulatory Framework for Advanced Reactors," March 2023. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/advanced/rulemaking-and-guidance/part-53.html. [Accessed August 2023].

[226] Nuclear Regulatory Commission, "SECY-23-0021: Proposed Rule: Risk Informaed, Technology-Inclusive Regulatory Framework for Advanced Reactors (RIN 3150-AK31)," March 2023. [Online]. Available: https://www.nrc.gov/docs/ML2116/ML21162A093.html. [Accessed August 2023].

[227] M. R. J. James T. Wiggins, "SECY-11-0184," Nuclear Regulatory Comission, 2011.

[228] U.S. Nuclear Regulatory Commission, "Regulatory Guide 4.7 General Site Suitability Criteria for Nuclear Power Stations," 1998.

[229] EPRI, "Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities (Siting Guide)," 2022.

[230] Federal Emergency Management Agency, "Earthquake Hazard Maps," 2020. [Online]. Available: https://www.fema.gov/emergency-managers/risk-management/earthquake/hazard-maps. [Accessed 16 August 2023].

[231] National Centers for Environmental Information, "Climate At A Glance Statewide Time Series," 2023. [Online]. Available: https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series/20/tavg/all/1/1895-2023?. [Accessed 28 August 2023].

[232] Michigan Department of Environment, Great Lakes, and Energy, "Flood Risk Areas," 2023. [Online]. Available: https://www.michigan.gov/egle/about/organization/water-resources/shoreland-management/flood-risk-areas. [Accessed 28 August 2023].

[233] Michigan Department of Environment, Great Lakes, and Energy, "Floodplain Management/National Flood Insurance," 2023. [Online]. Available: https://www.michigan.gov/egle/about/organization/water-resources/floodplain-management. [Accessed 30 August 2023].

[234] Farmland Information Center, "Michigan Data and Statistics," 2017. [Online]. Available: https://farmlandinfo.org/statistics/michigan-statistics/. [Accessed 30 August 2023].

[235] Michigan State University Extension, "Facing The Facts," 5 September 2019. [Online]. Available: https://www.canr.msu.edu/news/facing-the-facts. [Accessed 30 August 2023].

[236] National Weather Service, "Southeast Michigan Tornado Climatology," 2023. [Online]. Available: https://www.weather.gov/dtx/torclimateinfo. [Accessed 30 August 2023].

[237] Michigan Department of Environment, Great Lakes, and Energy, "2021 Water Use Category Chart," 2021. [Online]. Available: https://www.michigan.gov/egle/-/media/Project/Websites/egle/Documents/Programs/WRD/Water-Use/Report-data/2021-water-use-category-chart.pdf. [Accessed 30 August 2023].

[238] Michigan Department of Health and Human Services, "Michigan Drinking Water Sources," 2023. [Online]. Available: https://www.michigan.gov/mdhhs/safety-injury-prev/environmental-health/topics/care-for-mi-drinking-water/sources. [Accessed 30 August 2023].

[239] Michigan Department of Environmental Quality, "State of Michigan National Pollutant Discharge Elimination System Permit Application for Discharges to Surface Waters," 2015.

[Online]. Available: https://www.energy.gov/sites/prod/files/2015/06/f22/NPDES.pdf. [Accessed 7 December 2023].

[240] U.S. Environmental Protection Agency, "Thermal Discharges in NPDES Permits," 2023. [Online]. Available: https://www.epa.gov/system/files/documents/2023-07/Thermal-Discharges-Report.pdf. [Accessed 7 December 2023].

[241] Department of Enviorment, Great Lakes, and Energy, "MiEJScreen: Enviormental Justice Screening Tool," [Online]. Available: https://www.michigan.gov/egle/maps-data/miejscreen. [Accessed November 2023].

[242] NuScale, "Standard Power Chooses NuScale's Approved SMR Technology and ENTRA1 Energy to Energize Data Centers," October 2023. [Online]. Available: https://www.nuscalepower.com/en/news/press-releases/2023/standard-power-chooses-nuscales-approved-smr-technology-and-entra1-energy-to-energize-data-centers. [Accessed October 2023].

[243] TerraPower, "TerraPower Purchases Land in Kemmerer, Wyoming for Natrium Reactor Demonstration Project," August 2023. [Online]. Available: https://www.terrapower.com/terrapower-purchases-land-in-kemmerer-wyoming-for-natrium-reactor-demonstration-project/. [Accessed October 2023].

[244] NRC, "NRC to Issue Final Rule for Emergency Preparedness For Small Modular Reactors and Other Technolgies," August 2023. [Online]. Available: https://www.nrc.gov/cdn/doc-collection-news/2023/23-048.pdf. [Accessed October 2023].

[245] WBBJ Eyewitness News, "TVA moving forward with plans for smaller nuclear reactors," August 2023. [Online]. Available: https://www.wbbjtv.com/2022/08/08/tva-moving-forward-with-plans-for-smaller-nuclear-reactors-2/. [Accessed October 2023].

[246] The Verge, "Microsoft is going nuclear to power its AI ambitions," September 2023. [Online]. Available: https://www.theverge.com/2023/9/26/23889956/microsoft-next-generation-nuclear-energy-smr-job-hiring. [Accessed October 2023].

[247] Office of Nuclear Energy, "U.S. Department of Energy Restores Key Safety Test for Nuclear Fuel," October 2023. [Online]. Available: https://www.energy.gov/ne/articles/us-department-energy-restores-key-safety-test-nuclear-fuel. [Accessed October 2023].

[248] DOE Office of Nuclear Energy, "Centrus Produces Nations First Amounts of HALEU," November 2023. [Online]. Available: https://www.energy.gov/ne/articles/centrus-produces-nations-first-amounts-haleu. [Accessed November 2023].

[249] Nuclear Energy Institute, "Advanced Nuclear Energy: Oklahoma Senate Energy and Telecomunications Meeting," October 2023. [Online]. Available: https://oksenate.gov/sites/default/files/2023-11/NEI%20-%20Advanced%20Reactors%20-%20OK%20%282023-10-31%29_1.pdf. [Accessed November 2023].

[250] The Detroit News, "Palisades owner plans for two more reactors at shuttered nuclear plant on Lake Michigan," *The Detroit News,* 4 December 2023.

[251] Emirates Nuclear Energy Corporation, "ENEC and GE Hitachi sign MoU for potential investment and deployment of Small Modular Technology as part of ENEC ADVANCE Program," Decemeber 2023. [Online]. Available: https://www.enec.gov.ae/news/latest-news/enec-and-ge-hitachi-sign-mou-for-potential-investment-and-deployment-of-small-modular-technology/.

[252] Emirates Nuclear Energy Corporation, "ENEC and Westinghouse Sign MOU for Advanced Nuclear Reactor Technologies at COP 28," December 2023. [Online]. Available: https://www.enec.gov.ae/news/latest-news/enec-and-westinghouse-sign-mou-for-advanced-nuclear-reactor-technologies-at-cop-28-/.

[253] Emirates Nuclear Energy Corporation, "ENEC and TerraPower sign agreement to accelerate nuclear technology implementation," December 2023. [Online]. Available: https://www.enec.gov.ae/news/latest-news/enec-and-terrapower-sign-agreement-to-accelerate-nuclear-technology-implementation-/.

[254] Energy Information Adiministration, "First new U.S. nuclear reactor since 2016 is now in operation," August 2023. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=57280. [Accessed August 2023].

[255] Statista, "Median construction time required for nuclear reactors worldwide from 1981 to 2021," December 2022. [Online]. Available: https://www.statista.com/statistics/712841/median-construction-time-for-reactors-since-1981/. [Accessed August 2023].

[256] U.S. Nuclear Regulatory Commission, "Notice of Meeting with Holtec Decommissioning International, LLC," [Online]. Available: https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML23235A240. [Accessed August 2023].

[257] Energy Central, "Nuclear Regulatory Commission Approves License for DTE ESBWR at FERMI III," May 2015. [Online]. Available: https://energycentral.com/c/ec/nuclear-regulatory-commission-approves-license-dte-esbwr-fermi-iii. [Accessed August 2023].

[258] U.S. NRC, "Fermi License," 18 May 2015. [Online]. Available: https://www.nrc.gov/docs/ML1513/ML15138A151.html. [Accessed December 2023].

[259] World Nuclear News, "Fieldwork completed in milestone for UAMPS SMR," February 2022. [Online]. Available: https://www.world-nuclear-news.org/Articles/Fieldwork-completed-in-milestone-for-UAMPS-SMR. [Accessed August 2023].

[260] American Public Power Association, "Small Modular Reactor Project Being Developed by UAMPS Moves Forward," February 2023. [Online]. Available: https://www.publicpower.org/periodical/article/small-modular-reactor-project-being-developed-uamps-moves-forward. [Accessed August 2023].

[261] Utah Associated Municipal Power Systems, "Utah Associated Municipal Power Systems (UAMPS) and NuScale Power Agree to Terminate the Carbon Free Power Project (CFPP)," 8 November 2023. [Online]. Available: https://www.uamps.com/file/0f96e06f-9cd9-4cec-8fd3-0dbc753c6ea0. [Accessed December 2023].

[262] X-Energy, "Dow’s Seadrift, Texas location selected for X-energy advanced SMR nuclear project to deliver safe, reliable, zero carbon emissions power and steam production," May 2023. [Online]. Available: https://x-energy.com/media/news-releases/dows-seadrift-texas-location-selected-for-x-energy-advanced-smr-nuclear-project-to-deliver-safe-reliable-zero-carbon-emissions-power-and-steam-production#:~:text=Dow%20and%20X-energy%20will%20now%20prepare%20and%20. [Accessed August 2023].

[263] World Nuclear News, "TerraPower circles 2023 for Natrium construction permit," [Online]. Available: https://world-nuclear-news.org/Articles/TerraPower-eyes-Natrium-construction-permit-in-202. [Accessed August 2023].

[264] U.S. Code of Federal Regulations, "Part 50 - Domestic Licensing of Production and Utilization Facilities," [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/index.html. [Accessed August 2023].

[265] Terra Power, "Frequuntly Asked Questions," 2023. [Online]. Available: https://natriumpower.com/frequently-asked-questions/#:~:text=TerraPower%20anticipates%20submitting%20the%20demonstration%20plant%E2%80%99s%20construction%20permit,2025%20with%20completion%20of%20the%20plant%20this%20decade.. [Accessed August 2023].

[266] Voix du Nucleaire, "History of the construction times of the world's nuclear reactors," [Online]. Available: https://www.voix-du-nucleaire.org/technologie/historique-des-durees-de-construction-des-reacteurs-nucleaires-mondiaux-2/#pll_switcher. [Accessed August 2023].

[267] International Atomic Energy Agency, "The Database on Nuclear Power Reactors," August 2023. [Online]. Available: https://pris.iaea.org/pris/. [Accessed August 2023].

[268] J. Hansen, W. Jenson, A. Wrobel and e. al., "Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants," September 2022. [Online]. Available: https://fuelcycleoptions.inl.gov/SiteAssets/SitePages/Home/C2N2022Report.pdf. [Accessed June 2023].

[269] Idaho National Laboratory, "Transitioning Coal Power Plant to Nuclear Power Plants," December 2021. [Online]. Available: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_54812.pdf.

[270] Power Engineering, "DTE Energy to accelarate coal retirements," November 2022. [Online]. Available: https://www.power-eng.com/coal/dte-energy-to-accelerate-coal-retirements/. [Accessed August 2023].

[271] Gloabal Energy Monitoring Wiki, "Campbell Generating Plant," [Online]. Available: https://www.gem.wiki/Campbell_Generating_Plant#:~:text=In%20June%202021%2C%20Consumers%20Energyannounced%20plans%20to%20speed,close%2015%20years%20earliers%20then%20previously%20planned.%20. [Accessed July 2023].

[272] Global Energy Monitor Wiki, "Karn Generating Plant," [Online]. Available: https://www.gem.wiki/Karn_Generating_Plant#:~:text=The%20plant%27s%20two%20coal-fired%20units%20are%20planned%20for,Karn%2C%20which%20run%20on%20oil%20and%20gas.%20. [Accessed August 2023].

[273] Google Earth, "Map showing location of DTE Energy - Belle River Power Plant," [Online]. Available: https://earth.google.com/web/search/Belle+river+power+plant/@42.76941481,-82.51748112,175.04960108a,19568.60905915d,35y,0.00050264h,0t,0r/data=CigiJgokCSBSmN_o-URAEcIJ_BPo60RAGZG5vcb4zVTAIZEdguqR4FTA. [Accessed August 2023].

[274] Google Earth, "Map showing location of DTE Energy - Monroe Power Plant," [Online]. Available: https://earth.google.com/web/search/Monroe+power+plant/@41.8924891,-83.3463202,181.44184246a,762.38932187d,35y,0h,45t,0r/data=Cn0aUxJNCiUweDg4M2I2ZTFiYzJiOTk0NDU6MHhlYjRmNTE0MzU1NzQ0MjU0GatENBU98kRAIW08Mxwq1lTAKhJNb25yb2UgcG93ZXIgcGxhbnQYAiABIiYKJAn32-XEp.

[275] Google earth, "Map showing location of Consumers Energy J.H. Campbell Generating Complex," [Online]. Available: https://earth.google.com/web/search/cAMPBELL+Generating+Plant/@42.9120675,-86.2024125,182.60071188a,748.98658239d,35y,0h,45t,0r/data=CoQBGloSVAolMHg4ODE5ODkxYmI1NGY4Yzg1OjB4ZDE2N2VhMjI0Zjc0MmRmYxlLH7qgvnRFQCFN845T9IxVwCoZY0FNUEJFTEwgR2VuZXJhdGluZyBQbGFudB. [Accessed August 2023].

[276] Google Earth , "Map showing location of Consumers Energy Dan E. Karn Power Plant," [Online]. Available: https://earth.google.com/web/search/Karn+Generating+Plant/@43.63741877,-83.83691539,179.66586214a,4178.05524945d,35y,0h,0t,0r/data=CigiJgokCUQsP5YudkVAEal_IHQ7dEVAGQStffT3i1XAIdZZhPFRjVXA.

[277] TerraPraxis, "JOIN THE CLEAN ENERGY TRANSITION AND REPOWER YOUR COAL PLANT FOR $2,000/KWE IN JUST FIVE YEARS," [Online]. Available: https://www.terrapraxisrepower.com/Repower-Coal/Why-Repower/. [Accessed August 2023].

[278] TerraPraxis, "The Global REPOWER Consortium," [Online]. Available: https://www.terrapraxis.org/projects/repower/global-consortium. [Accessed August 2023].

[279] TerraPraxis, "DRAWING ON PUBLIC SOURCES, WE HAVE AGGREGATED A GLOBAL DATA SET THAT ALLOWS YOU TO EXPLORE INFORMATION ABOUT COAL PLANTS ACROSS THE GLOBE," [Online]. Available: https://www.terrapraxisrepower.com/The-Platform/Global-Plant-Data/. [Accessed August 2023].

[280] Office of Energy Efficiency & Renewable Energy, "Hydrogen Shot," [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-shot. [Accessed August 2023].

[281] Department of Energy, "Biden-Harris Administration Announces Historic $7 Billion Funding Oppurtunity to Jump-Start America's Clean Hydrogen Economy," September 2022. [Online]. Available: https://www.energy.gov/articles/biden-harris-administration-announces-historic-7-billion-funding-opportunity-jump-start. [Accessed August 2023].

[282] Govenor Gretchen Whitmer, "Gov. Whitmer Announces Michigan Wins Funding for Clean Hydrogen Hub, Creating Thousands of Good-Paying Jobs and Building a Brighter, Cleaner Future," October 2023. [Online]. Available: https://www.michigan.gov/whitmer/news/press-releases/2023/10/13/whitmer-announces-michigan-wins-funding-for-clean-hydrogen-hub. [Accessed November 2023].

[283] Financial Post, May 2023. [Online]. Available: https://financialpost.com/pmn/business-pmn/billion-dollar-pink-hydrogen-plan-on-hold-as-us-weighs-rules . [Accessed June 2023].

[284] IAEA, "Hydrogen Production Using Nuclear Energy," International Atomic Energy Agency, Vienna, 2013.

[285] G. Thomas and G. Parks, "Potential Roles of Ammonia in a Hydrogen Economy," U.S. Department of Energy, 2006.

[286] J. McDermott, "Going Green: Nel Hydrogen to Build in Michigan, Work with GM," ABC News, May 2023. [Online]. Available: https://abcnews.go.com/US/wireStory/green-nel-hydrogen-build-michigan-work-gm-99047226. [Accessed May 2023].

[287] Associated Press, "Going green: Nel Hydrogen to build in Michigan, work with GM," [Online]. Available: https://apnews.com/article/nel-green-hydrogen-factory-general-motors-michigan-57c90cd27e3d7c06dc5b60b6fcf6813d. [Accessed August 2023].

[288] FarmWeekNow, "Nitrogen Calculations Made Easy," 2022. [Online]. Available: https://www.farmweeknow.com/general/nitrogen-calculations-made-easy/article_572565f6-5a24-11ed-a4fb-dfd04100fcd9.html#:~:text=Anhydrous%20ammonia%20%2882-0-0%20or%2082%25%20N%29%3A%20Divide%20140,pounds%20by%200.82%20%3D%20171%20pounds%20per%20acre.. [Accessed July 2023].

[289] M. Rivarolo, G. Riveros-Godoy, L. Magistri and A. Massardo, "Clean Hydrogen and Ammonia Synthesis in Paraguar from the Itaipu 14 GW Hydroelectric Plant," *ChemEngineering,* vol. 87, no. 3, 2019.

[290] Idaho National Laboratory, "HTGR-Integrated Hydrogen Production Via Steam Methane Reforming (SMR) Process Analysis," September 2010. [Online]. Available: https://art.inl.gov/NGNP/INL%20Documents/Year%202010/HTGR-Integrated%20Hydrogen%20Production%20via%20Steam%20Methane%20Reforming%20(SMR)%20Process%20Analysis%20rev%200.pdf. [Accessed May 2023].

[291] M. Aminudin, S. Kamarudin, B. Lim, E. Majilan, M. Masdar and N. Shaari, "An overview: Current progress on hydrogen fuel cell vehicles," *International Journal of Hydrogen Energy,* vol. 48, no. 11, pp. 4371-4388, 2023.

[292] Nuclear Energy Agency, "The Role of Nuclear Power in the Hydrogen Economy," OECD, 2022.

[293] Enviormental Protection Agency, "EPA Report: U.S. Cars Achieve Record High Fuel Economy and Low Emission Levels as Companies Fully Comply with Standards," November 2021. [Online]. [Accessed May 2023].

[294] AAA, "National Average Gas Prices," 2023. [Online]. Available: https://gasprices.aaa.com/. [Accessed May 2023].

[295] Policy Genius, "Average Miles Driven by State," February 2022. [Online]. Available: https://www.policygenius.com/auto-insurance/average-miles-driven-by-state/. [Accessed May 2023].

[296] Statista, "Automobile Registrations in the United States in 2021, by State," 2021. [Online]. Available: https://www.statista.com/statistics/196010/total-number-of-registered-automobiles-in-the-us-by-state/. [Accessed May 2023].

[297] U.S. Enviormental Protection Agency, "Tailpipe Greenhouse Gas Emissions from a Typical Passenger Vehicle," [Online]. Available: https://www.epa.gov/greenvehicles/tailpipe-greenhouse-gas-emissions-typical-passenger-vehicle. [Accessed August 2023].

[298] U.S. Energy Information Administration, "Energy-Related CO2 Emission Data Tables," July 2023. [Online]. Available: https://www.eia.gov/environment/emissions/state/. [Accessed August 2023].

[299] S. Kasahara, N. Tankaka, H. noguchi, J. Iwatsuki, H. Takegami, X. L. Yan and S. Kubo, "JAEA's R&D on the Thermochemical Hydrogen Production IS Process," Japan Atomic Energy Agency, 2014.

[300] International District Energy Association, "Map of District Energy in North America," [Online]. Available: https://www.districtenergy.org/resources/resources/system-maps. [Accessed August 2023].

[301] D. Scripps and K. Peretick, "MPSC: Michigan Steam Supply Cost Recovery Report," May 2023. [Online]. Available: https://www.michigan.gov/lara/-/media/Project/Websites/lara/about/Legislative-Reports/Statutory-Required-Reports/FY2023/MPSC---2023-Michigan-Steam-Supply-Cost-Recovery-Report.pdf?rev=8b5eb03556584bb8b701337ca1213e71&hash=75EFFE503DAD548057321197C065C411. [Accessed November 2023].

[302] NOAA, "Global Monitoring Laboratory," [Online]. Available: https://gml.noaa.gov/ccgg/trends/. [Accessed August 2023].

[303] NASA, "The Atmosphere: Getting a Handle on Carbon Dioxide," [Online]. Available: https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/#:~:text=The%20concentration%20of%20carbon%20dioxide,it%20was%20near%20370%20ppm.. [Accessed August 2023].

[304] Department of Energy, "Regional Direct Air Capture Hubs," [Online]. Available: https://www.energy.gov/oced/regional-direct-air-capture-hubs. [Accessed August 2023].

[305] F. Galluci, "Chapter 18 - Inorganic Membrane Reactors for Methanol Synthesis," in *Methanol*, Elsevier, 2018, pp. 493-518.

[306] R. Javadli and A. Klerk, "Desulfurization of heavy oil," *Applied Petrochemical Resarch,* vol. 1, 2012.

[307] Enviormental Protection Agency, "5.1 Petroleum Refining," September 2020. [Online]. Available: https://www.epa.gov/sites/default/files/2020-09/documents/5.1_petroleum_refining.pdf. [Accessed August 2023].

[308] Marathon, [Online]. Available: https://www.marathonpetroleum.com/Operations/Refining/Detroit-Refinery/. [Accessed August 2023].

[309] U.S. Environmental Protection Agency, "Summary of the Atomic Energy Act," [Online]. Available: https://www.epa.gov/laws-regulations/summary-atomic-energy-act. [Accessed August 2023].

[310] "United States Code, Title 42, Chapter 23," [Online]. Available: https://www.govinfo.gov/content/pkg/USCODE-2010-title42/html/USCODE-2010-title42-chap23-divsnA.htm. [Accessed August 2023].

[311] U.S. Nuclear Regulatory Commission, "Governing Legislation," [Online]. Available: https://www.nrc.gov/about-nrc/governing-laws.html. [Accessed August 2023].

[312] Forbes, "How Policy Saved America's Nuclear Power Plants," November 2023. [Online]. Available: https://www.forbes.com/sites/energyinnovation/2023/11/08/how-policy-saved-americas-nuclear-power-plants/?sh=26ae82ee190e. [Accessed November 2023].

[313] National Conference of State Legislatures, "States Restrictions on New Nuclear Power Facility Construction," September 2023. [Online]. Available: https://www.ncsl.org/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility-construction. [Accessed October 2023].

[314] Enviorment & Public Works, "Accelerating Deployment of Versatile Advanced Nuclear for Clean Energy Act of 2023," May 2023. [Online]. Available: https://www.epw.senate.gov/public/_cache/files/a/8/a804f8d7-0142-47c3-87e1-413259c13967/D5974E051150760B7CFFB2D2420F46E1.capito-advance-act-one-pager.pdf. [Accessed October 2023].

[315] Grid Deployment Office, "Civil Nuclear Credit Program," [Online]. Available: https://www.energy.gov/gdo/civil-nuclear-credit-program. [Accessed October 2023].

[316] Department of Energy, "Biden-Harris Administration Announces Major Investment to Preserve America’s Clean Nuclear Energy Infrastructure," November 2022. [Online]. Available:

https://www.energy.gov/articles/biden-harris-administration-announces-major-investment-preserve-americas-clean-nuclear. [Accessed October 2023].

[317] Kalamazoo, "Owner of nuclear power plant along Lake Michigan to try again at restarting," March 2022. [Online]. Available: https://www.mlive.com/news/kalamazoo/2022/12/owner-of-nuclear-power-plant-along-lake-michigan-to-try-again-at-restarting.html. [Accessed October 2023].

[318] The Herald Palladium, "DOE rejects Palisades application for funds to restart," November 2022. [Online]. Available: https://www.heraldpalladium.com/communities/covert/doe-rejects-palisades-application-for-funds-to-restart/article_7cc0faf7-2e79-5ea1-8a82-89fc2c8039af.html. [Accessed October 2023].

[319] South Haven Tribune, "REPOWERING THE PALISADES PLANT: A deep dive on how Holtec can restart the Palisades Nuclear Power Plant," June 2023. [Online]. Available: https://www.heraldpalladium.com/southhaventribune/localnews/a-deep-dive-on-how-holtec-can-restart-the-palisades-nuclear-power-plant/article_ca5c99e8-60b9-5e40-96c7-5fcd2367d874.html. [Accessed October 2023].

[320] Office of Nuclear Energy, "Inflation Reduction Act Keeps Momentum Building for Nuclear Power," September 2022. [Online]. Available: https://www.energy.gov/ne/articles/inflation-reduction-act-keeps-momentum-building-nuclear-power. [Accessed October 2023].

[321] Enviormental Protection Agency, "Summary of Inflation Reduction Act provisions related to renewable energy," June 2023. [Online]. Available: https://www.epa.gov/green-power-markets/summary-inflation-reduction-act-provisions-related-renewable-energy. [Accessed October 2023].

[322] LISC, "The Inflation Reduction Act's Climate Investments and What They Mean for Community Development," Septemeber 2022. [Online]. Available: https://www.lisc.org/our-stories/story/inflation-reduction-acts-climate-investments-for-community-development/#:~:text=The%20IRA%20is%20the%20most%20significant%20climate%20law,targeted%20to%20disadvantaged%20communities%20to%20support%20environmental%20j. [Accessed November 2023].

[323] Nuclear Energy Institute, "Long-term Extension of Price-Anderson Needed to Advance Clean Energy Tech," July 2023. [Online]. Available: https://www.nei.org/news/2023/long-term-extension-of-price-anderson-needed. [Accessed October 2023].

[324] American Nuclear Society, "The Price-Anderson Act," November 2005. [Online]. Available: https://wx1.ans.org/pi/ps/docs/ps54-bi.pdf. [Accessed October 2023].

[325] American Nuclear Society, "House panel advances raft of pro-nuclear bills," 31 October 2023. [Online]. Available: https://www.ans.org/news/article-5497/house-panel-advances-raft-of-pronuclear-bills/. [Accessed November 2023].

[326] U.S. House Energy & Commerce Committee, "Energy, Climate, and Grid Security Subcommittee Markup of 17 Bills to Secure Reliable, Clean, American Energy," 24 October 2023. [Online]. Available: https://energycommerce.house.gov/events/an-energy-climate-and-grid-security-subcommittee-markup-of-17-bills-to-secure-reliable-clean-american-energy. [Accessed November 2023].

[327] N. Portuondo, "Bipartisan nuclear legislation falls out of defense bill," 29 November 2023. [Online]. Available: https://subscriber.politicopro.com/article/eenews/2023/11/29/bipartisan-nuclear-legislation-falls-out-of-defense-bill-00128943. [Accessed December 2023].

[328] 115th Congress, "S.512 - Nuclear Energy Innovation and Modernization Act," January 2019. [Online]. Available: https://www.congress.gov/bill/115th-congress/senate-bill/512. [Accessed October 2023].

[329] Office of Nuclear Energy, "NRC Approves New Approach to Streamline Advanced Reactor Licensing Process," July 2020. [Online]. Available: https://www.energy.gov/ne/articles/nrc-approves-new-approach-streamline-advanced-reactor-licensing-process. [Accessed October 2023].

[330] Nuclear Regulatory Commission, "NEI 18-04 Rev 1 Risk-Informed Performance-Based Technology Guidance for Non-Light Water Reactors," August 2016. [Online]. Available: https://www.nrc.gov/docs/ML1924/ML19241A336.html. [Accessed October 2023].

[331] Congress of the United States, July 2023. [Online]. Available: https://d1dth6e84htgma.cloudfront.net/Chairman_Hanson_Commission_Review_of_Part_53_Rulemaking_Letter_FINAL_79792c48e7.pdf. [Accessed October 2023].

[332] M. O'Neill, "Foraging a clear path for advanced reactor licensing in the United States: Approaches to streamlining the NRC environmental review process," *Nuclear Law Bulletin,* vol. 2020, no. 105.

[333] World Nuclear News, "US regulator approves methodology for SMR emergency planning," October 2022. [Online]. Available: https://world-nuclear-news.org/Articles/US-regulator-approves-methodology-for-SMR-emergenc. [Accessed October 2023].

[334] The Herald Palladium, "Palisades plant awaits federal funding decision," July 2023. [Online]. Available: https://www.heraldpalladium.com/news/palisades-plant-awaits-federal-funding-decision/article_f04d688f-6310-56b1-b888-ceadbae03e0a.html. [Accessed October 2023].

[335] Michigan Live, "Palisades nuclear plant gets $150 million in Michigan budget," July 2023. [Online]. Available: https://www.mlive.com/public-interest/2023/07/palisades-nuclear-plant-gets-150-million-in-michigan-budget.html. [Accessed October 2023].

[336] C. H. a. A. Lobo, "Whitmer signs bills setting 100% clean energy standarad for Michigan," *Detroit Free Press,* 28 November 2023.

[337] Natural Resources Defense Council, "New Laws Make Michigan A National Leader in Clean Energy," 28 November 2023. [Online]. Available: https://www.nrdc.org/press-releases/new-laws-make-michigan-national-leader-clean-energy. [Accessed December 2023].

[338] Tennessee Office of the Governor, "Gov. Lee Issues Executive Order to Advance Nuclear Energy Innovation & Investment," May 2023. [Online]. Available: https://www.tn.gov/governor/news/2023/5/16/gov--lee-issues-executive-order-to-advance-nuclear-energy-innovation---investment.html. [Accessed October 2023].

[339] IndyStar, "A bill would pave the way for nuclear power in Indiana -- at a cost to consumers," January 2022. [Online]. Available: https://www.indystar.com/story/news/environment/2022/01/24/nuclear-power-plant-renewable-energy-reactor-technology-utilities-indiana-bill-sb-271/6561722001/. [Accessed October 2023].

[340] World-Energy, "Virginia Governor Signs Bills to Support SMR Development," March 2023. [Online]. Available: https://www.world-energy.org/article/30644.html. [Accessed October 2023].

[341] Associated Press, "California governor proposes extending nuclear plant’s life," August 2022. [Online]. Available: https://apnews.com/article/california-legislature-gavin-newsom-climate-and-environment-4968ee9da7fd1d10ad67bfdf03950873. [Accessed October 2023].

[342] Office of the Governor (California), "Governor Newsom Statement on Federal Funding for Diablo Canyon Extension," November 2022. [Online]. Available: https://www.gov.ca.gov/2022/11/21/governor-newsom-statement-on-federal-funding-for-diablo-canyon-extension/. [Accessed October 2023].

[343] Office of the Governor, "Tennessee Office of the Governor," May 2023. [Online]. Available: https://www.tn.gov/governor/news/2023/5/16/gov--lee-issues-executive-order-to-advance-nuclear-energy-innovation---investment.html. [Accessed September 2023].

[344] Department of Energy, "At COP28, Countries Launch Declaration to Triple Nuclear Energy Capacity by 2050, Recognizing the Key Role of Nuclear Energy in Reaching Net Zero,"

December 2023. [Online]. Available: https://www.energy.gov/articles/cop28-countries-launch-declaration-triple-nuclear-energy-capacity-2050-recognizing-key. [Accessed December 2023].

[345] The White House, "FACT SHEET: Biden-Harris Administration Leverages Historic U.S. Climate Leadership at Home and Abroad to Urge Countries to Accelerate Global Climate Action at U.N. Climate Conference (COP28)," December 2023. [Online]. Available: https://www.whitehouse.gov/briefing-room/statements-releases/2023/12/02/fact-sheet-biden-harris-administration-leverages-historic-u-s-climate-leadership-at-home-and-abroad-to-urge-countries-to-accelerate-global-climate-action-at-u-n-climate-conference-cop. [Accessed December 2023].

[346] E. Lyman, ""Advanced" Isn't Always Better: Assessing the Safety, Security, and Environmental Impactsof Non-Light-Water Nuclear Reactors," Union of Concerned Scientists, Cambridge, MA, 2021.

[347] J. Cavicchi and J. Franklin, "Economic and Environmental Benfits to Massachuessetts from the operation of the Seabrook Nuclear Plant," March 2023. [Online]. Available: https://www.analysisgroup.com/globalassets/insights/publishing/2023_seabrook_ag_phase_2_report.pdf. [Accessed May 2023].

[348] MIT Energy Initiative, "The Future of Nuclear Energy in a Carbon-Constrained World," 2018. [Online]. Available: https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf. [Accessed May 2023].

[349] U.S. Department of Energy, "Pathways to Commercial Liftoff: Clean Hydrogen," March 2023. [Online]. Available: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf. [Accessed May 2023].

[350] RePlanet, "The World Wants New Nuclear, Findings from a comprehensive evaluation of the world's understanding and support for advanced nuclear," Clear Path, Potential Energy Coalition, RePlanet, Third Way, May 2023. [Online]. Available: https://www.replanet.ngo/_files/ugd/5caaac_3a0c021c58464c0091de86a7ac1e1bc1.pdf. [Accessed June 2023].

[351] K. Shirvan, "Overnight Capital Cost of the Next AP1000," March 2022. [Online]. Available: http://canes.mit.edu/overnight-capital-cost-next-ap1000. [Accessed June 2023].

[352] Worl Nuclear News, "Fourth Chinese AP1000 enters commercial operation," January 2019. [Online]. Available: https://world-nuclear-news.org/Articles/Fourth-Chinese-AP1000-enters-commercial-operation. [Accessed October 2023].

[353] Nuclear Innovation Alliance, "Transforming the U.S. Department of Energy: Paving the Way to Commercialize Advanced Nuclear Energy," January 2023. [Online]. Available: https://nuclearinnovationalliance.org/transforming-us-department-energy-paving-way-commercialize-advanced-nuclear-energy. [Accessed June 2023].

[354] DOE Microreactor Program, "Microreactor Applications in U.S. Markets:Evaluation of State-Level Legal, Regulatory,Economic and Technology Implications," March 2023. [Online]. Available: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_65488.pdf. [Accessed June 2023].

[355] National Academy of Engineering, "Laying the Foundation for New and Advanced Reactors in the United States (Pre-publication)," p. 300, 2023.

[356] Canadians for Nuclear Energy, "The Case for CANDU: Why Ontario's Homegrown Nuclear Technology Is Its Best Option In A Time Of Rising Electricity Demand," May 2023.

[357] DTE, "IRP Executive Summary," DTE Electric, 2022.

[358] Purdue University and Duke Energy, "Small Modular Reactor and Advanced Reactor Feasibility Study Interim Report," 2023.

[359] TerraPower, "Natrium Fact Sheet," 2022. [Online]. Available: https://natriumpower.com/wp-content/uploads/2022/05/Natrium-Wyoming-Factsheet2.pdf. [Accessed June 2023].

[360] GE HITACHI Nuclear Energy, "BWRX-300," August 2021. [Online]. Available: https://nuclear.gepower.com/content/dam/gepower-nuclear/global/en_US/documents/product-fact-sheets/GE%20Hitachi_BWRX-300%20Fact%20Sheet.pdf. [Accessed July 2023].

[361] E. D. Browser, "Net Generation for all sectors," U.S. EIA, 2017-21.

[362] World Energy Data, "World Electricity Generation," July 2023. [Online]. Available: https://www.worldenergydata.org/world-electricity-generation/. [Accessed August 2023].

[363] Bechtel, "Bechtel: Commercial Operations at Vogtle Unit 3 is an Important Milestone for US Nuclear Industry," July 2023. [Online]. Available: https://www.bechtel.com/newsroom/press-releases/commercial-operations-vogtle-unit-3-georgia/. [Accessed August 2023].

[364] L. L. N. Laboratory, "Michigan Energy Consumption in 2019," 2019.

[365] Small Modular Reactors, "Oklo - Aurora," [Online]. Available: https://small-modular-reactors.org/oklo-aurora/. [Accessed August 2023].

[366] World Nuclear Association, "Mineral Requirements for Electricity Generation," August 2021. [Online]. Available: https://www.world-nuclear.org/information-library/energy-and-the-environment/mineral-requirements-for-electricity-generation.aspx. [Accessed August 2023].

[367] B. Terzic, "Is Power Ever Too Cheap tro Meter," EnergySource, 2018.

[368] J. Kang and M. Ramana, "Canadian Reactors that "recycle" plutonimum would create more problems than they solve," Bulletin of the Atomic Scientists, 2023.

[369] Union of Concerned Scientists, "NRC's Risky Rule Change Ignores History. More Nuclear Emergency Planning Needed, Not Less.," [Online]. Available: https://www.ucsusa.org/about/news/nrcs-risky-rule-change-ignores-history-more-nuclear-emergency-planning-needed-not-less.

[370] World Nuclear Association, "Safeguards to Prevent Nuclear Proliferation," [Online]. Available: https://world-nuclear.org/information-library/safety-and-security/non-proliferation/safeguards-to-prevent-nuclear-proliferation.aspx. [Accessed August 2023].

[371] Nuclear Threat Initiative, "Proliferation Risks of Nuclear Power Programs," [Online]. Available: https://www.nti.org/analysis/articles/risks-nuclear-power-programs/. [Accessed August 2023].

[372] Indiana Michigan Power, "Donald C. Cook Nuclear Plant. Applicant's Environmental Report Operating License Renewal Stage. October 2003. ADAMS Accession No. ML033070185," 2003.

[373] U.S. Global Change Research Program, "Global Climate Change Impacts in the United States. Cambridge University Press. June 2009. ADAMS No. ML100580077," 2009.

[374] Nuclear Energy Institute, "Climate Nuclear Energy and Global Warming.," [Online]. Available: https://www.nei.org/advantages/climate. [Accessed 23 May 2023].

[375] WSJM, "New state budget includes money to restart Palisades," June 2023. [Online]. Available: https://www.detroitnews.com/restricted/?return=https%3A%2F%2Fwww.detroitnews.com%2Fstory%2Fnews%2Flocal%2Fmichigan%2F2022%2F09%2F09%2Fpalisades-owner-seeks-federal-grant-keep-michigan-nuclear-plant-open%2F8036078001%2F. [Accessed August 2023].

[376] M. Boatman, "Palisades owner says 'number of hurdles' need to be cleared to reopen plant," September 2022. [Online]. Available: https://www.hollandsentinel.com/story/news/environment/2022/09/12/palisades-owner-

number-of-hurdles-to-clear-before-possible-reopening/69486660007/. [Accessed August 2023].

[377] J. Reindl, "Regulators OK Fermi 3, but DTE has no plans to build it," *Detroit Free Press,* 30 April 2015.

[378] U.S. Nuclear Regulatory Commission, "Generic Environmental Impact Statement for License Renewal of Nuclear Plants: Regarding Fermi 2 Nuclear Power Plant – Final Report, Appendices (NUREG-1437, Supplement 56, Volume 2)," 2016. [Online]. Available: https://www.nrc.gov/docs/ML1625/ML16259A103.pdf. [Accessed 18 August 2023].

[379] Nuclear Energy Institute, "Climate: Nuclear Energy and Global Warming," 2023. [Online]. Available: https://www.nei.org/advantages/climate. [Accessed 30 August 2023].

[380] Dominion Engineering, Inc., "SMR Site Feasibility Study for LENOWISCO," 2023. [Online]. Available: https://energy.virginia.gov/renewable-energy/documents/FINAL%20LENOWISCO%20SMR%20Feasibility%20Study%20-%20DEI%2020230520%20.pdf. [Accessed 30 August 2023].

[381] U.S. Nuclear Regulatory Commission, "About NRC," [Online]. Available: https://www.nrc.gov/about-nrc.html. [Accessed October 2023].

[382] Rocky Mountain Institute, "Hope in Michigan: One Policy, Big Impact," August 2023. [Online]. Available: https://rmi.org/hope-in-michigan-one-policy-big-impact/. [Accessed October 2023].

[383] Arms Control Center, "Fact Sheet: Uranium Enrichment: For Peace of for Weapons," [Online]. Available: https://armscontrolcenter.org/uranium-enrichment-for-peace-or-for-weapons/#:~:text=Highly%20enriched%20uranium%20(HEU)%20is,applications%20for%20this%20fuel%20too.. [Accessed October 2023].

[384] National Park Service, "National Register of Historic Places - What is the National Register of Historic Places?," [Online]. Available: https://www.nps.gov/subjects/nationalregister/what-is-the-national-register.htm. [Accessed 20 October 2023].

[385] National Park Service, "National Register of Historic Places - How to List a Property," [Online]. Available: https://www.nps.gov/subjects/nationalregister/how-to-list-a-property.htm. [Accessed 20 October 2023].

[386] U.S. Nuclear Regulatory Commission, "NRC Staff Review of the Yucca Mountain License Application," [Online]. Available: https://www.nrc.gov/docs/ML1525/ML15251A537.pdf. [Accessed October 2023].

[387] Tennessee Valley Authority, "Tennessee Valley Authority, Ontario Power Generation, and Synthos Green Energy Invest in Development of GE Hitachi Small Modular Reactor Technology," March 2023. [Online]. Available: https://www.tva.com/newsroom/press-releases/tennessee-valley-authority-ontario-power-generation-and-synthos-green-energy-invest-in-development-of-ge-hitachi-small-modular-reactor-technology. [Accessed October 2023].

[388] U.S. Department of Energy, "TRISO Particles: The Most Robust Nuclear Fuel on Earth," 2019. [Online]. Available: https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth. [Accessed October 2023].

[389] NIRS, "TRITIUM from Nuclear Power Plants: Its Biological Hazards," [Online]. Available: https://www.nirs.org/radiation/tritium/. [Accessed November 2023].

[390] Nuclear Regulatory Commission, "Standard Review Plans for Enviormental Reviews for Nuclear Power Plants, Supplement 1 Rev 1," March 2021. [Online]. Available: https://www.nrc.gov/docs/ML1310/ML13106A246.pdf. [Accessed November 2023].

[391] Solar Energy Industries Association, "What's in a Megawatt?," [Online]. Available: https://www.seia.org/initiatives/whats-megawatt. [Accessed November 2023].

[392] World Nuclear News, "Illinois to lift moratorium on nuclear construction," 13 November 2023. [Online]. Available: https://www.world-nuclear-news.org/Articles/Illinois-to-lift-moratorium-on-nuclear-constructio. [Accessed December 2023].

[393] U.S. NRC, "Combined Licenses for Virgil C. Summer Nuclear Station, Units 2 and 3," 2019. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/large-lwr/col/summer.html. [Accessed December 2023].

[394] C. Forsberg and B. Dale, "Replacing Crude Oil with Nuclear-Assisted Biofuels," in *American Nuclear Society 2022 Annual Meeting*, Anaheim, CA, 2022.

[395] Institute of Nuclear Power Operations, "Our History," [Online]. Available: https://www.inpo.info/history. [Accessed December 2023].

[396] Holtec International, "First Two SMR-300 Units Slated to be Built at Michigan’s Palisades Site for Commissioning by Mid-2030," 4 December 2023. [Online]. Available: https://holtecinternational.com/2023/12/04/first-two-smr-300-units-slated-to-be-built-at-michigans-palisades-site-for-commissioning-by-mid-2030/. [Accessed December 2023].

[397] U.S. NRC, "Nuclear Materials Control and Accounting," [Online]. Available: https://www.nrc.gov/materials/fuel-cycle-fac/nuclear-mat-ctrl-acctng.html. [Accessed December 2023].

Michigan Nuclear Plant Feasibility Evaluation: Supply Chain, Workforce, Economic, and Power System Impacts

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1. Executive Summary

This report evaluates the supply chain, workforce, economic, and power system impacts associated with developing new nuclear energy generation in Michigan. The evaluation considers the construction and operation of a hypothetical nuclear facility consisting of 12 small modular reactors (SMR), with each module rated at 60 MWe totaling 720 MWe. SMRs were selected for evaluation because of their smaller footprint relative to traditional nuclear power plants. This allows for the possibility of placing them at retired fossil fuel sites which has advantages in terms of land availability and transmission system connections. The number of modules evaluated was based on replacing a typically sized baseload coal-fired unit.

Although this study does not advocate for any specific location, modeling the economic and power system effects of a hypothetical nuclear plant requires specifying a location for the plant. The Monroe Power Plant, located in Monroe County and operated by DTE Electric, and the J. H. Campbell Generating Plant, located in Ottawa County and operated by Consumers Energy, are scheduled to retire within the next ten years. These locations provide potential utility operators, grid connections, and land availability making them useful locations to evaluate the economic and power system effects of a hypothetical nuclear plant. The analysis therefore considers two alternative hypothetical scenarios: constructing and operating a hypothetical nuclear plant in DTE Electric's service territory in Monroe County and constructing and operating a hypothetical nuclear plant in Consumers Energy's service territory in Ottawa County. The analysis is agnostic to the individual business impacts that a hypothetical nuclear plant would have for DTE Electric or Consumers Energy. These two locations are chosen simply to allow evaluating the impacts that a hypothetical nuclear power plant would have on the local economy and power system.

Tables 1.1 and 1.2 summarize the results of the economic impact modeling conducted to estimate the economic impacts of the hypothetical plant's construction and operation. Table 1.1 presents the results of constructing and operating a hypothetical nuclear plant in Monroe County, and Table 1.2 presents the results for Ottawa County. While direct impacts are the same for constructing and operating the hypothetical plant in the two counties, indirect and induced impacts vary from county to county based on the industries present in each county and parameters that link economic output, employment, and value-added changes across industries. Indirect effects of the hypothetical plant are higher in Monroe County, meaning inter-industry transactions are greater between the plant and supplying industries in Monroe County than Ottawa County. However, induced effects resulting from local spending in affected industry sectors are greater in Ottawa County than Monroe County.

Constructing and operating a hypothetical plant in Monroe County is estimated to generate 17,305 jobs, provide approximately $2.4 billion in Labor Income, and contribute approximately $3.7 billion to Michigan's economy over the plant's lifetime (presented as Value Added in Table 1.1). Constructing and operating a hypothetical plant in Ottawa County is estimated to generate 17,915 jobs, provide approximately $2.4 billion in Labor Income, and contribute approximately $3.6 billion to Michigan's economy over the plant's lifetime (Table 1.2).

Table 1.1
Total Economic Impacts of Construction and Lifetime Operation–Monroe County

Impact Type	Employment	Labor Income	Value Added
Direct Effect	8,360	$1,397M	$1,931M
Indirect Effect	6,111	$703M	$1,200M
Induced Effect	2,834	$304M	$579M
Total Effect	**17,305**	**$2,405M**	**$3,710M**

Table 1.2
Total Economic Impacts of Construction and Lifetime Operation–Ottawa County

Impact Type	Employment	Labor Income	Value Added
Direct Effect	8,360	$1,397M	$1,931M
Indirect Effect	6,025	$606M	$1,009M
Induced Effect	3,531	$354M	$662M
Total Effect	**17,915**	**$2,358M**	**$3,602M**

Table 1.3 summarizes the power system modeling results related to the potential implications that a hypothetical nuclear plant may have for CO_2 emissions. The power system modeling evaluates future Baseline conditions of electricity generation and emissions without the hypothetical nuclear plant's operation. It then evaluates Counterfactual conditions with the hypothetical nuclear plant operating. Differences in operation and emissions under the Baseline and Counterfactual conditions represent the estimated emission reductions predicted with the hypothetical nuclear plant's operation. The results are presented as reductions in CO_2 that are modeled to occur in 2036 as a result of the hypothetical plant's operation. These are system wide emission reductions resulting from the hypothetical nuclear plant's operation displacing other plants with higher emissions. The table also includes estimated reductions in SO_2 and NO_X.

Table 1.3
Air Emission Reductions with Operating a Hypothetical Nuclear Plant (Tons)

Service Territory	Emission	Annual Reduction in 2036
DTE Electric	Carbon dioxide (CO_2)	365.2K
	Sulfur dioxide (SO_2)	62.4
	Nitrogen oxide (NO_X)	140.5
Consumers Energy	Carbon dioxide (CO_2)	1.2M
	Sulfur dioxide (SO_2)	6.2
	Nitrogen oxide (NO_X)	197.2

As depicted in Table 1.3, CO_2 reductions are nearly three times higher for the Consumers Energy location relative to the DTE Electric location whereas SO_2 emissions are more than ten times higher when the plant is modeled in the DTE Electric system. This difference results from the modeled 2036 power system characteristics for each company. Both companies are pursuing aggressive decarbonization strategies that rely heavily on solar generation. However, DTE Electric has more electricity coming from wind whereas Consumers Energy is intending to rely more on natural gas to serve nighttime load. The Consumers Energy natural gas generation is replaced by nuclear generated electricity resulting in higher CO_2 offset. DTE Electric is also serving more peak load with SO_2 emitting diesel than Consumers Energy. Generation from the hypothetical nuclear plant reduces the operation of the diesel generators, resulting in higher SO_2 reductions when the nuclear plant is modeled within the DTE Electric system.

These emission reduction predictions are the result of a complex power system evaluation, and it is useful to provide context for the estimates. The maximum CO_2 reduction is 1.2 million tons per year, which occurs when the hypothetical nuclear unit is modeled as being in the Consumers Energy system. CO_2 emission factors vary by plant efficiency, and fuel type. However, according to the Energy Information Administration, in 2019 coal-fired generation produced 2,257 pounds of CO_2 per MWh. At this rate, siting the hypothetical nuclear plant in the Consumers Energy system results in a CO_2 reduction that is approximately equal to eliminating the output of a 140 MW coal plant running continuously.

2. Overview & Supply Chain Evaluation

This section provides an overview of the report and evaluates the supply chain operation and opportunities associated with developing nuclear generation in Michigan. Although this study does not advocate for any specific location, evaluating the economic and power system impacts of a new nuclear generation facility requires identifying a specific location where the hypothetical facility would be built and operate. Section 3 describes the process of identifying two potential locations for modeling the economic and power system impacts of a hypothetical nuclear facility. As Section 3 describes, other locations could be used in addition to the sites chosen for this evaluation. Section 4 then describes the economic impacts associated with constructing and operating a hypothetical nuclear generation facility, and Section 5 describes the power system impacts of operating a hypothetical facility.

2.1 Supply Chain Operations and Opportunities

The supply chain for nuclear energy generation consists of the systems of parts and people that come together to deploy, operate, and support nuclear energy plants. This section describes the nuclear energy supply chain with consideration of opportunities for Michigan businesses and citizens. The subsections include timeline and outlays, manufacturing, employment, Michigan implications, Michigan economic evaluation, and workforce opportunities.

2.1.1 Timeline and Outlays

This section provides information on project development activities including the timeline for developing, operating, and decommissioning a nuclear energy plant and relative financial outlays. Phases include project development, major component design and procurement, balance of plant sourcing, installation and commissioning, operations and maintenance, and decommissioning.

- Project Development—Project development tasks begin as soon as 12 years before commissioning of a nuclear energy plant and may account for about 5% of total expenditures (Shykinov, Rulko, and Mroz 2016; World Nuclear Association 2022a). Installing new nuclear technology on an existing site may reduce the time and expenditures needed for project development.

  During project development, a company intending to build a nuclear energy plant identifies the timeline for the project and conducts a feasibility study, detailed site survey, and environmental impact assessment. Preparing for licensing, the company produces a Preliminary Safety Analysis Report, which a regulatory body reviews. Potentially one year after project development begins, Authorization to Proceed can be issued so that the construction schedule can be maintained (Shykinov, Rulko, and Mroz 2016; International Atomic Energy Agency [IAEA] 2012).

- Major Component Design and Procurement—Designing and procuring the major components (nuclear power reactors, for example) may take seven to eight years (Figure 2, Shykinov, Rulko, and Mroz 2016). Design and procurement may account for about 7% of the capital costs (World Nuclear Association 2022a).
- Balance of Plant Sourcing—Balance of plant refers to the supporting and auxiliary components of an energy plant. Balance of plant systems help keep the plant running. Electrical balance of plant systems regulate, monitor, and protect energy plant components by using transformers, circuit breakers, switchgears, and other devices. Mechanical balance of plant systems are composed of non-electrical auxiliary systems, such as fire protection, compressed air systems, and other systems (DXP Enterprises | Integrated Flow Solutions 2019). Balance of plant may account for 18% of capital costs (World Nuclear Association 2022a).
- Installation and Commissioning—This phase includes testing of all plant components and systems. The commissioning period uses, “plant data to monitor, analyze, and address plant issues; implement and execute applicable operational processes, programs, procedures and protocols; and introduce and reinforce operational standards and expectations for plant personnel” (New Unit Assistance Working Group, Fisher, and Moutenot 2020). Installation and commissioning may take more than one year and, along with first fueling, may account for 5% of capital costs (Shykinov, Rulko, and Mroz 2016; World Nuclear Association 2022a).
- Operation and Maintenance—Operation and maintenance occurs over the 60 to 80-year life cycle of the nuclear energy plant (IAEA 2012). The Nuclear Energy Institute (2020) estimated generating costs as the sum of the fuel, capital expenditures, and operation and maintenance costs. The industry average is $30.41 per megawatt hour (2019 dollars), and operations and maintenance account for 61% of that cost (NEI 2020).
- Decommissioning—This is the process of retiring nuclear generating plants from service and terminating the operating licenses granted by the U.S. Nuclear Regulatory Commission (NRC). Decommissioning involves decontaminating the facility and reducing residual radioactivity, dismantling structures, removing contaminated materials to appropriate disposal facilities, storing used nuclear fuel until it can be removed from the site, and releasing the property for other uses if appropriate. The NRC requires companies operating nuclear generating plants, “to provide assurance that funds will be available to decommission the facility.” Such funds may only be used for legitimate decommissioning expenses (Nuclear Energy Institute 2016). Decommissioning can take seven years or longer (U.S. Energy Information Administration [EIA] 2017). The World Nuclear Association (2022a) estimated that decommissioning costs in the U.S. are approximately, “five percent of the cost of the electricity produced.”

The World Nuclear Association (2022a) estimated capital costs of building a nuclear energy plant by activity. Table 2.1 presents the estimated share of activities compared to the total capital costs.

Table 2.1
Percentage of Capital Costs by Activity for Building a Nuclear Energy Plant

Activities Related to Building a Nuclear Energy Plant	Percentage of Capital Cost
Design, architecture, engineering, and licensing	5
Project engineering, procurement, and construction management	7
Construction and installation works:	
Nuclear island	28
Conventional island	15
Balance of plant	18
Site development and civil works	20
Transportation	2
Commissioning and first fuel loading	5
Total	100

Source: World Nuclear Association (2022a)

2.1.2 Manufacturing

This section provides a generalized depiction of the nuclear plant lifecycle supply chain and the major components that make up each phase of the life-cycle. Figure 2.1 presents a generalized depiction of the lifecycle supply chain for a nuclear energy plant. Materials are used to create major components and subcomponents. Major components are created directly from materials and assembled from subcomponents. Main components include fuel, moderators, control rods or blades, coolant, pressure vessel or pressure tubes, steam generators, and containment (World Nuclear Association 2023). The foundation of a nuclear energy plant, the reactor containments, auxiliary buildings, turbine buildings, and spent fuel storage areas are constructed from concrete reinforced by steel bars (rebar) or steel plate reinforced concrete (NRC undated).

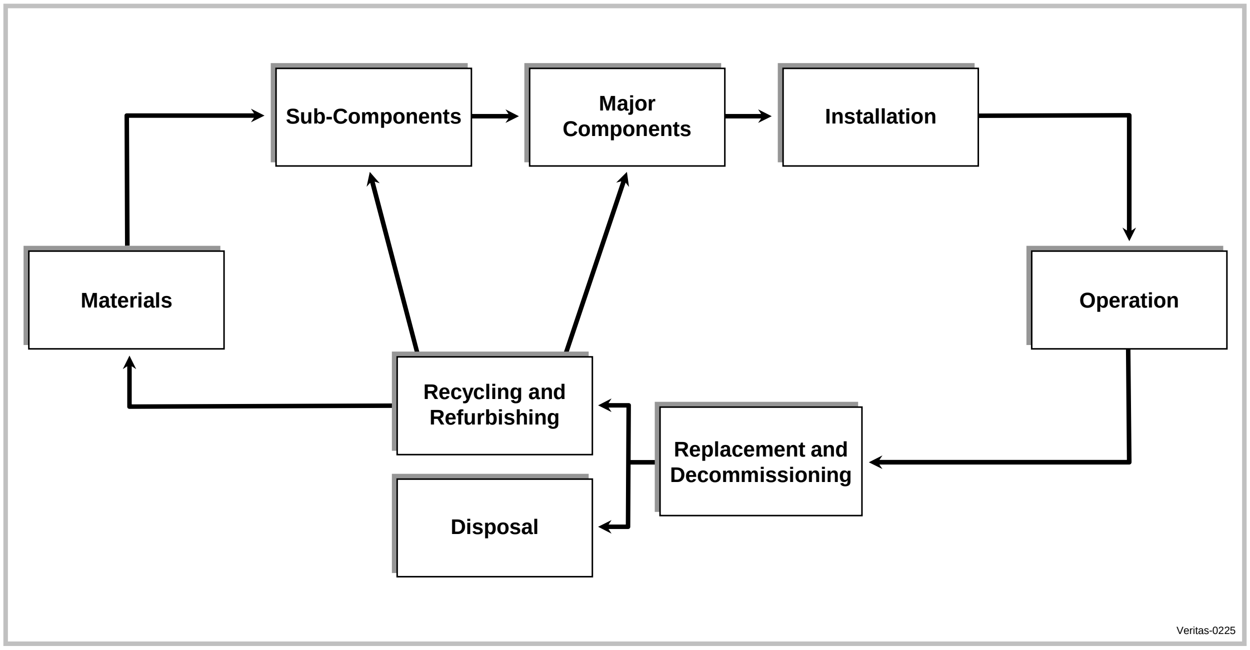

Figure 2.1: Nuclear Energy Plant Lifecycle Supply Chain

Subcomponents include electrical equipment, such as inverters, cables, transformers, and switchgear and additional turbine parts such as gearboxes, bearings, castings, and semiconductors.

The installation process comprises the placement and interconnection of system equipment, including the entire reactor vessels and turbogenerators, instrument tubing, and valves. Interconnections between equipment are generally made by piping, tubing, or duct work (World Nuclear Association 2023).

A nuclear energy plant can operate for 60–80 years (IAEA 2012). Safe, reliable, and economic nuclear energy plants use “careful, conservative operation and rigorous, well-planned maintenance” (IAEA 2023). Such maintenance includes preventive and corrective measures to ensure that structures, systems, and components can perform as designed (IAEA 2023). Nuclear energy plants typically refuel every 18-24 months. During a refueling outage, plants typically schedule facility upgrades, repairs, maintenance work, and other projects to improve reliability. While the average refueling outage is 34 days, nuclear power plants do not typically provide an approximate date of the outage’s completion for competitive reasons (U.S. EIA 2018; Entergy 2023).

Decommissioning a nuclear energy plant involves decontaminating the facility and reducing residual radioactivity, dismantling the structures, removing contaminated materials to appropriate disposal facilities, storing used nuclear fuel until it can be removed from the site, and releasing the property for other uses.

Refurbishing a nuclear energy plant modernizes and enhances major equipment and systems, as well as enhancing plant safety and reliability (IAEA 2015). Because “more than 90 percent of its potential energy still remains,” spent nuclear fuel can be recycled (IAEA 2015). The U.S. does not currently recycle spent nuclear fuel. The technology for recycling spent nuclear fuel and turning it into energy was proven in a U.S. Government research facility that operated from the 1960s through the 1990s. However, because of the economic cost and lack of political support, the technology was not developed commercially (U.S. DOE 2022b; Clifford 2022).

The World Nuclear Association (2022b) noted that “recycling materials from decommissioned nuclear facilities is constrained by the level of radioactivity.” Demolishing a nuclear energy plant results in large volumes of concrete and steel. The World Nuclear Association lists four categories of metal from a nuclear energy plant:

- Material that is essentially uncontaminated and can be released unconditionally.
- Material that can be melted in a regulated environment followed by metal recycled for consumer products (conditional clearance).
- Material with short half-life products that is melted and fabricated in a regulated environment and released for specific industrial applications (for example, used in a steel bridge).
- Material that cannot be released from regulatory control but may be recycled in the nuclear industry.

A variety of raw and processed materials are used in constructing nuclear energy plants. Metals used include steel, iron, copper, manganese, zirconium, chromium, nickel, Inconel, lead, aluminum, silver, cadmium, boron, indium, and brass/bronze alloys. Engineered or composite wood materials may be used, with wood sustainability harvested and tropical hardwoods avoided. Compound materials used include concrete, PVC, and insulation. Table 2.2 lists materials used in construction. The volume of materials needed for a plant with a pressurized water reactor, along with uranium, are listed in kilograms (kg) per kilowatt (kW) (U.S. Department of Energy [DOE] 2022a).

Table 2.2
Pressurized Water Reactor: Material Input Requirements (Kg per kW)

Material	KG per kW (Range)		
Concrete[1]	180.00	to	560.00
Carbon steel	10.00	to	65.00
Wood	4.70	to	5.60
Stainless steel	1.56	to	2.10
Galvanized iron	1.26		
Polyvinyl chloride (PVC)	0.80	to	1.27
Insulation	0.70	to	0.92
Copper	0.69	to	2.00
Uranium	0.40	to	0.62
Manganese	0.33	to	0.70
Zirconium	0.20	to	0.40
Chromium	0.15	to	0.55
Nickel	0.10	to	0.50
Inconel	0.10	to	0.12
Brass/bronze	0.04		
Lead	0.03	to	0.05
Aluminum	0.02	to	0.24
Silver	0.01		
Cadmium	0.01		
Boron	0.01		
Indium	0.01		
Total	195.00	to	635.00

Source: U.S. DOE (2022a)

The exact materials needed for building the next nuclear energy plant in the U.S. depends on the type of reactor. Based on reactor designs under development, the supply chain for constructing advanced nuclear plants is expected to include the primary materials and finished products listed in Table 2.3 (U.S. DOE 2022a).

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[1] The base slab of a containment building may consist of more than 4,000 m^3 of concrete (World Nuclear Association 2023).

Table 2.3
Reactor Types, Coolants, Fuels, Cladding, and Structural Materials for Advanced Nuclear Plants

Type of Reactor	Coolant	Fuel	Cladding	In-Core Structural Materials	Out-of-Core Structural Materials
Pressurized Water Reactor (PWR)	Water, single phase	Uranium oxide (UO_2) or mixed oxide (MOX) fuel	Zirconium alloy	Stainless steels, nickel-based alloys	Stainless steels, nickel-based alloys
Boiling Water Reactor (BWR)	Water, two phase	UO_2 or MOX	Zirconium alloy	Stainless steels, nickel-based alloys	Stainless steels, nickel-based alloys
Supercritical Water Reactor (SCWR)	Supercritical water	UO_2	Ferritic-Martensitic stainless steel (F-M), incoloy, oxide dispersion-strengthened steel (ODS), Inconel	Same as cladding options, as well as low-swelling stainless steel	F-M, low alloy steels
Very High Temperature Reactor (VHTR)	Helium	UO_2 or uranium oxycarbide (UCO)	Silicon carbide (SiC) or zirconium carbide (ZrC) coating and surrounding graphite	Graphites, pyro-carbon (PyC), SiC, ZrC; vessel: F-M	Nickel-based super-alloys, F-M with thermal barriers, low-alloy steels
Gas-Cooled Fast Reactor (GFR)	Helium or super-critical CO_2	Mixed carbide (MC), UO_2	Ceramic	Refractory metals and alloys, ceramics, oxide dispersion-strengthened steel (ODS); vessel: F-M	Nickel-based super-alloys, F-M with thermal barriers
Sodium-Cooled Fast Reactor (SFR)	Sodium	MOX, uranium-plutonium-zirconium (U-Pu-Zr) alloys, MC, or mixed nitride (MN)	F-M or F-M ODS	F-M ducts, 316 stainless steel grid plate	Ferritics, austenitic steel
Lead-Cooled Fast Reactor (LFR)	Lead or lead-bismuth	MN	High-silicon F-M or ODS, ceramics, or refractory alloys	Not applicable	High-silicon austenitic steel, ceramics, or refractory alloys
Molten Salt Reactor (MSR)	Molten salt (e.g., FLiNaK)	Salt, tri-structural isotropic (TRISO)	Not applicable	Ceramics, refractory metals, molybdenum (Mo), nickel-based alloys, graphite, Hastelloy® N alloy	High-Mo, nickel-based alloys

Source: U.S. DOE (2022a)

At least two U.S. companies, NuScale and TerraPower, are building small modular reactors (SMRs).[2] SMRs are less than one-third the size of current large reactors and can be made in factories and transported by truck or rail to energy plants. The advanced design SMRs range from 50–300 megawatts (MW) and may cost approximately $1 billion on the low end. By 2030, TerraPower plans to begin operating its first 345 MW sodium-cooled fast reactor with

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[2] On November 8, 2023, NuScale and Utah Associated Municipal Power Systems agreed to terminate the Carbon Free Power Project. NuScale stated that it “will continue to bring our American SMR technology to market and grow the U.S. nuclear manufacturing base” (NuScale 2023).

molten salt-based energy storage at a retiring coal plant site in Wyoming (Tan 2023; Gardner and Volcovici 2021; Carelli and Ingersoll 2015.).

U.S. DOE (2022a) assessed the supply chain risk for fuels and minerals needed for nuclear energy reactors. The assessment found that the U.S. relies on imports for several critical minerals needed for nuclear energy generation, as shown in Table 2.4. Critical minerals as defined in the Energy Act of 2020 have "a high risk of supply chain disruption" and serve "an essential function in one or more energy technologies." Critical minerals may also be defined by the U.S. Secretary of the Interior. Besides the energy technologies, other industries also use critical minerals (U.S. Department of Energy [DOE] 2023). In the near and medium term, the U.S. DOE classified the following minerals as critical:

- In the near term (2023–2025), the U.S. DOE classified several minerals that are used in energy and other industries as critical minerals: dysprosium, cobalt, gallium, graphite, iridium, neodymium, and terbium. Minerals classified as near critical are lithium, uranium, nickel, magnesium, platinum, silicon carbide, and electrical steel (U.S. DOE 2023).
- For the medium term (2025–2035), the U.S. DOE classified critical minerals as lithium, nickel, cobalt, graphite, gallium, platinum, magnesium, silicon carbide, dysprosium, iridium, neodymium, praseodymium, and terbium. Minerals classified as near critical for the medium term are uranium, copper, silicon, and electrical steel (U.S. DOE 2023).

The U.S. Government has instituted actions to address supply disruptions of critical minerals and near critical minerals (The White House 2023). U.S. industries, including the nuclear industry, and the U.S. Government continue to work on mitigating supply chain challenges (U.S. DOE 2022a, 2022c).

Table 2.4
Critical Minerals and U.S. Import Reliance

Mineral	U.S. Reliance on Imports	Countries and Share of Mineral Production
Graphite	100%	China, 75%
Yttrium	100%	China, 99%
Indium	100%	China, 40%; South Korea, 31%
Niobium	100%	Brazil, 88%
Chromium	75%	South Africa, Kazakhstan, more than 50%
Lithium	>50%	Australia, 58%
Nickel	50%	U.S., 50%; most other production comes from Indonesia, the Philippines, and Russia

Source: U.S. DOE (2022a)

Table 2.5 summarizes the key supply chain issues the U.S. DOE has noted for current U.S. reactors and advanced reactors. In addition, nickel is produced in the U.S. only at the Eagle Mine in Michigan. However, the domestic demand for nickel cannot be met solely by the Eagle Mine; the U.S. imports about 50% of the nickel needed to meet demand (Kinsey and Jessup 2018).

Table 2.5
Supply Chain Issues for Large Reactors and Advanced Reactors in the U.S.

Component or Product	Description
Current Large Reactors	
Uranium mining, milling, and conversion	Most uranium is imported and conversion is performed by foreign suppliers
Enriched lithium	Most lithium is imported; there is increased demand from other industries
Chromium and nickel	Current plants will replace various high alloy steel components (which use chromium and nickel); some steel components will be needed
Advanced Reactors	
High-assay low-enriched uranium (HALEU)	Most advanced reactors will require HALEU for fuel
Fuel fabrication	The U.S. has limited fuel fabrication facilities for advanced nuclear fuel
Nuclear graphite	The U.S. has no supplies of nuclear graphite; all graphite is imported
Lithium	Some molten salt reactors will need lithium, which will have increased demand from other industries; most lithium is imported
Lithium and chlorine enrichment	Lithium and chlorine will require enrichment to high purity levels for use in advanced reactors

Source: U.S. DOE (2022a)

As noted in U.S. DOE (2022a), the current fleet of pressurized water reactors (PWRs) in the U.S. “continually add lithium-7 (Li-7) for pH control throughout the plant lifetime.” About 300 kg per year (total) is needed for the PWR fleet in the U.S. “The enrichment of Li-7 is only performed in China and Russia,” which makes the dependability of the supply chain uncertain. The Electric Power Research Institute (EPRI) is studying the potential for replacing lithium-7 hydroxide with potassium hydroxide, which has several producers in the U.S. EPRI has completed more than half of the ten-year research program (U.S. DOE 2022a).

Many challenges in the supply chain for new nuclear projects in the U.S. are attributable to diminishing construction of nuclear energy plants. Less construction has resulted in a decreasing number of suppliers for nuclear plant equipment and fewer manufacturers maintaining the strict quality assurance programs needed (Kinsey and Jessup 2018).[3]

Kinsey and Jessup (2018) described the supply chain associated with installing AP1000® Pressurized Water Reactors (PWRs) at the V.C. Summer and Vogtle plant sites in South Carolina and Georgia, respectively. Table 2.6 lists components of the supply chain and the location of suppliers for the two projects.[4]

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[3] Holtec International is trying to reopen the Palisades Nuclear Power Plant in Michigan, which closed in 2022. Details about the type of reactor to be installed have not been disclosed (Wheaton 2023).

[4] Because of schedule delays, cost overruns, and other factors, the V.C. Summer project was eventually cancelled.

Table 2.6
Supply Chain for AP1000® PWR Installations in Georgia and South Carolina

AP1000® Component	Supplier	Location	Country
Condenser	BHI Company	Sacheon	South Korea
Containment vessel	IHI	Yokohama	Japan
Core barrel	Toshiba	Yokohama	Japan
Demineralizer	TSM Tech Company	Ansan City	South Korea
Heat exchanger	TSM Tech Company	Ansan City	South Korea
Main step-up transformers	Toshiba	Tokyo	Japan
Reactor vessel	Doosan	Changwon	South Korea
Steam generators	Doosan	Changwon	South Korea
Turbine generator	Toshiba	Tokyo	Japan
Valves	Samshin	Cheonan	South Korea
Accumulators	Mangiarottia SpA (subsidiary of Westinghouse)	Panellia	Italy
Class 1E battery chargers	Gutor Electronic	Westingen	Switzerland
Containment recirculation screens	CCI AG	Winterthur	Switzerland
Core make-up tanks	Mangiarottia SpA	Panellia	Italy
In-containment refueling water storage tank	CCI AG	Winterthur	Switzerland
Pressurizer	Mangiarottia SpA	Panellia	Italy
Passive RHR heat exchanger	Mangiarottia SpA	Panellia	Italy
Valves	CCI AG	Balterswil	Switzerland
AP1000 modules	Aecon	Cambridge, Ontario	Canada
	Chicago Bridge & Iron	Lake Charles, LA	U.S.
	Greenberry	Corvallis, OR	U.S.
	Specialty Maintenance and Construction	Lakeland, FL	U.S.
	Vigor Works	Clackamas, OR	U.S.
Automatic depressurization system squib valves	SPX Flow Control	McKean, PA	U.S.
Auxiliary relief valves	Farris Engineering	Brantford, Ontario	Canada
Class 1E batteries	EnerSys	Hays, KS	U.S.
Class 1E switchgear	Westinghouse	New Stanton, PA	U.S.
Control rod drive mechanisms	Westinghouse	Newington, NH	U.S.
Cranes	PaR Nuclear	Shoreview, MN	U.S.
Degasifiers	Val-Fab	Neenah, WI	U.S.
Fuel assemblies	Westinghouse	Columbia, SC	U.S.
Instrumentation valves	Swagelok	Solon, OH	U.S.
Integrated head package	Premier Technologies	Blackfoot, ID	U.S.
Liquid ring vacuum pump	Gardner Denver	Pittsburgh, PA	U.S.
Radiation monitoring systems	General Atomics Electro-magnetic Systems Group	San Diego, CA	U.S.

Table 2.6, continued

AP1000® Component	Supplier	Location	Country
Reactor coolant loop piping	Tioga	Philadelphia, PA	U.S.
Reactor coolant pumps	Curtiss-Wright	Cheswick, PA	U.S.
Reactor vessel flowskirt	Precision Custom Components	York, PA	U.S.
Reactor vessel internal lifting rig	Premier Technologies	Blackfoot, ID	U.S.
Recirculation heaters	Chromalox	Pittsburgh, PA	U.S.
Solenoid valves	ASCO	Pittsburgh, PA	U.S.
Steam generator recirculation and drain pumps	Hayward Tyler	Colchester, VT	U.S.
Shield building panels	Newport News Industrial	Newport News, VA	U.S.
Spent resin tank	Val-Fab	Neenah, WI	U.S.
Tank demineralizers	Sharpsville Container	Detroit, MI	U.S.
Unit auxiliary transformers	Efacec Power Transformers	Rincon, GA	U.S.
Valves	CCI	Rancho Santa Margarita, CA	U.S.
	Crane Valves	Bolingbrook, IL	U.S.
	Fisher Controls	Marshalltown, IA	U.S.
	Flowserve US	Raleigh, NC	U.S.
	Flowserve US	Springville, UT	U.S.
	Tyco Valves	Winchester, MA	U.S.
	Weir Valves	Ipswich, MA	U.S.
Variable frequency drives	Siemens	New Kensington, PA	U.S.
Cooling tower fans, V.C. Summer	Tecsis	Sao Paulo	Brazil

Source: Kinsey and Jessup (2018)

As of 2023, some components for the AP1000® PWR are manufactured in Michigan. Table 2.7 lists the products manufactured in Michigan that may be used for the AP1000® PWR. Michigan companies who do not yet have certification for manufacturing products used in nuclear plants may choose to apply for it from the American Society of Mechanical Engineers. In addition to the companies listed in Table 2.7, the following firms may potentially be able to manufacture additional components for nuclear plants based on information from company websites:[5]

- Crane Technologies in Rochester Hills, Michigan;
- Thermo Fisher Scientific plants in Ann Arbor, Kalamazoo, and Portage, Michigan;
- Emerson, which makes nuclear-quality auxiliary relief valves, has manufacturing plants in Michigan, but it is unclear how many products are used in nuclear energy plants; and

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[5] The companies listed in this section are established in the nuclear industry; however, this is not an exhaustive list, and other companies may be able to enter the nuclear parts supply chain in the future.

- Swagelok Michigan / Toledo, Farmington Hills, Michigan: currently, an Ohio Swagelok plant makes instrumentation valves and possibly other products for nuclear plants.

Table 2.7
Components for AP1000® PWR Manufactured in Michigan as of 2023

AP1000® Component	Company	Manufacturing Site in Michigan
Accumulators, heat exchangers, pumps, valves, specialty components	Energy Steel & Supply Co.	Rochester Hills
Fluid valves	MAC Valves, Inc.	Wixom
Instrumentation valves	Swagelok Michigan / Toledo	Farmington Hills
“Nuclear qualified valves”	Automatic Valve Nuclear	Novi
Severe service knife gate valves	DSS Valves	Niles
Solenoid valves	Automatic Valve Corporation	Novi
V66 series valves	Michigan Valve & Fitting, Inc.	Chesterfield
Liquid ring vacuum pump Reactor coolant pumps	Flowserve	Kalamazoo
Tank demineralizers	Sharpsville Container	Detroit

Sources: Company websites

Note: Besides the products listed in this table, concrete required for building a nuclear energy plant could be sourced from a concrete manufacturer, such as the Lafarge plant in Alpena, Michigan, which produces more than 2.4 million metric tons of concrete annually (Unit 202 Productions, Shanahan, and Beilstein 2022). Michigan has several other concrete manufacturers.

Shirvan (2022) estimated the construction time and overnight capital cost of the next AP1000® installed in the U.S. and compared those estimates with existing light water reactors in the U.S., both before and after the Three Mile Island (TMI) accident in 1979. Shirvan noted that the AP1000® uses less steel and concrete than historic reactor designs. Two AP1000® reactors have been installed at the Vogtle plant in Georgia and incurred additional cost because they are first of a kind reactors in the U.S. Table 2.8 lists the estimated engineering, procurement and construction overnight cost per kWe and construction time for a pressurized water reactor and the next AP1000® installed in the U.S.

Table 2.8
Historic Cost of a PWR Compared to AP1000®

Category	Overnight Cost: Engineering, Procurement, and Construction ($/kWe)	Approximate Construction Time (Months)
Historic PWR (before TMI)	$4,700	100
Historic PWR (after TMI)	$9,512	150
Vogtle Units 3 and 4 project (2021)	$7,956	120
Estimated Vogtle Units 3 and 4 (after TMI)	$9,200	130
Next AP1000® should cost[a]	$4,300	60
10th unit, AP1000® should cost[a]	$2,900	50
Next AP1000®, high-end estimate	$6,800	100
10th unit, AP1000®, high-end estimate	$4,500	60

[a] Based on a peer-reviewed study by researchers, Massachusetts Institute of Technology (Shirvan 2022)

Source: Shirvan (2022)

Shirvan (2022) also estimated the staff and cost data for operations and maintenance of the current fleet of reactors (Generation II) and the AP1000®. Table 2.9 lists Shirvan's estimates of staff and annual cost data.

Table 2.9
Staff and Cost Estimates for Current Reactor Fleet and AP1000®

Category	Generation II Staff	Generation II Cost ($ Millions)	AP1000® Staff	AP1000® Cost ($ Millions)
Engineering	68	$12.4	59	$10.8
Loss prevention	132	$21.8	72	$11.9
Materials and services	18	$3.2	18	$3.2
Fuel management	7	$1.0	7	$1.0
Operations	136	$27.4	86	$17.3
Training	31	$4.2	31	$4.2
Work management	158	$43.8	112	$31.1
Support services staff	49	$9.0	19	$3.5
Support services	—	$43.0	—	$30.1
Fixed fees (outages)	—	$15.0	—	$15.0
Total	599	$180.9	404	$128.0
Levelized ($MWhre)	—	$22.9	—	$14.1

Source: Shirvan (2022)

2.1.3 Employment

The Michigan Department of Technology, Management, & Budget (2023) published summary data for payroll jobs by industry. Table 2.10 lists the summary data.

Table 2.10
Michigan Payroll Jobs by Industry: April 2023

Industry	Number of Payroll Jobs
Total nonfarm	**4,420,000**
Total private	**3,815,300**
Mining, logging, and construction	198,600
Mining and logging	7,300
Construction	191,300
Manufacturing	607,500
Trade, transportation, and utilities	810,200
Information	56,500
Financial activities	228,400
Professional and business services	662,800
Education and health services	677,400
Leisure and hospitality	413,200
Other services	160,700
Government	604,700

Source: Michigan Department of Technology, Management & Budget (2023)

The Michigan Center for Data and Analytics reported the number of employees and wage range for key occupations in Michigan during 2021, including the Michigan Energy cluster (Table 2.11). The Energy cluster consists of industries that support the generation and utilization of energy sources. This includes five subclusters: energy efficiency; utilities; wholesale; electric manufacturing; and oil and gas exploration, extraction, and wholesaling. Across all occupations of the Energy cluster, the median hourly wage is $29.48 (Fuller 2023).

The Electric manufacturing subcluster employs 6.8% (8,100) of the Michigan Energy cluster and consists of various manufacturing industries. Annual salaries for these industries vary widely. Overall, the Electric manufacturing subcluster provides an annual average salary of $81,900 (Fuller 2023).

Development and operation of a nuclear energy plant requires a workforce during all stages of the plant's life cycle. Employment opportunities for a nuclear energy plant generally fall

Table 2.11
Key Occupations of the Michigan Energy Cluster, 2021

Key Occupation	Energy Cluster Employment	Michigan Employment, All Industries	Energy Cluster Wage Range: Hourly	Annual Openings	Typical Education and Training
Electricians	14,730	22,330	$19–$38	2,655	High school diploma or equivalent and apprenticeship
Plumbers, pipefitters, and steamfitters	9,440	12,650	$22–$38	1,420	High school diploma or equivalent and apprenticeship
HVAC and refrigeration mechanics and installers	7,500	9,480	$19–$29	970	Postsecondary nondegree award and long-term on-the-job training (OJT)
Electrical power-line installers and repairers	3,750	3,750	$38–$49	335	High school diploma or equivalent and long-term OJT
First-line supervisors of construction trades and extraction workers	3,290	14,680	$30–$47	1,615	High school diploma or equivalent
Electrical engineers	2,850	10,050	$38–$59	645	Bachelor’s degree
Construction laborers	2,770	26,080	$17–$28	3,555	Short-term OJT
Electrical, electronic, and electromechanical assemblers	2,430	8,670	$15–$22	1,315	High school diploma or equiv. and moderate-term OJT
Operating engineers	1,980	10,230	$23–$37	1,020	High school diploma or equiv. and moderate-term OJT
Sheet metal workers	1,830	3,470	$23–$37	340	High school diploma or equivalent and apprenticeship
First-line supervisors of mechanics, installers, and repairers	1,710	12,890	$37–$58	1,340	High school diploma or equivalent
Control and valve installers and repairers, except mechanical door	1,630	2,030	$37–$47	190	High school diploma or equiv. and moderate-term OJT
Construction managers	1,380	6,030	$38–$60	750	Bachelor’s degree and moderate-term OJT
Power plant operators	1,290	1,410	$37–$48	115	High school diploma or equivalent and long-term OJT
Electrical repairers, power, substation, and relay	1,090	1,190	$39–$49	85	Postsecondary nondegree award and moderate-term OJT
Cost estimators	870	5,620	$30–$48	550	Bachelor’s degree and moderate-term OJT
Electrical engineering technologists and technicians	830	2,620	$24–$38	185	Associate of applied science degree
Telecommunications line installers and repairers	670	2,270	$18–$25	215	High school diploma or equivalent and long-term OJT
Millwrights	480	2,520	$24–$37	310	High school diploma or equivalent and apprenticeship
Gas plant operators	440	490	$37–$48	30	High school diploma or equivalent and long-term OJT
Helpers: installation, maintenance, and repair workers	430	1,690	$17–$18	215	High school diploma or equivalent and short-term OJT
Helpers: pipelayers, plumbers, pipefitters, and steamfitters	380	430	$14–$19	95	High school diploma or equivalent and short-term OJT
Water and wastewater treatment plant operators	370	3,420	$19–$29	310	High school diploma or equivalent and long-term OJT
Nuclear engineers	320	380	$40–$62	25	Bachelor’s degree
Sales engineers	260	1,720	$38–$63	190	Bachelor’s degree and moderate-term OJT

Source: Fuller (2023)

into the following categories: construction, manufacturing, operations and maintenance, supply chain management, environmental oversight, and decommissioning.

Clean Energy Ministerial (2022) noted that "a new generation of smaller, MWe-scale power plants could help decentralize the benefits of nuclear energy to a local level… Smaller plants may be available in more communities." Constructing and operating a small nuclear energy plant requires expertise from many different occupations and will create diverse jobs: the percentage of direct, indirect, and induced jobs in the U.S. are expected in these categories:

- Business services, 40.7%
- Construction and production, 18.9%
- Transportation, 12.3%
- Service, 11.8%
- Maintenance and repair, 6.68%
- Engineering/technical, 4.57%

Other, 5.1% (Clean Energy Ministerial 2022).

The development phase of a nuclear energy plant includes detailed planning and employs project managers, cost estimators, and nuclear and electrical engineers. Supply chain management involves collaboration with suppliers and employs quality assurance managers or engineers (at both energy plant and suppliers) and supervision of manufacturing workers at the supplier site. Employment in the construction category includes construction managers and crews, as well as highly skilled technical workers who assemble and install the major components of a nuclear energy plant. The construction category also includes transportation operators who move components from the procurement site to the energy plant location. Common jobs in transportation include cargo handlers, water transportation workers, railroad engineers and brakemen, and truck drivers. The operations and maintenance category includes operating, electrical, and nuclear engineers; technologists; technicians, and others (Shykinov Rulko, and Mroz 2016; International Atomic Energy Agency 2016; Union Pacific undated; U.S. Bureau of Labor Statistics 2022, 2023).

2.2 Michigan Implications

The preceding review provides the backdrop for considering the employment implications of constructing nuclear energy plants in Michigan. This section provides additional considerations for the workforce in Michigan.

The Nuclear Energy Institute (2023) noted that "the U.S. nuclear energy sector directly employs nearly 100,000 people in high-quality, long-term jobs," as well as about 375,000 people in secondary jobs within diverse fields and educational backgrounds. Secondary jobs are other industry employees supported by the nuclear sector's transactions with the local economy, as well as its employees' spending. Table 2.12 lists many types of employment in those secondary jobs.

Table 2.12
Employment Provided by the Nuclear Energy Industry

Skilled Trades	Professions	Engineering, Technicians, and Radiologists
Carpenters	Accountants	Chemists
Electricians	Cybersecurity specialists	Chemical engineers
Operators of heavy equipment	Communicators	Radiation protection specialists
Masons	Health physicists	Reactor operators
Pipefitters	Lawyers	Scientists
Sheet metal workers	Subject matter experts	Nuclear engineers
Welders	Policy analysts	Safety and environmental impact specialists
Mechanics	Entrepreneurs	Civil engineers
Project Managers	Financial managers	Mechanical engineers

Source: Nuclear Energy Institute Inc. (2023)

Berkman and Murphy (2015) assessed the contribution of nuclear energy plants to the Michigan economy. The authors estimated direct and secondary employment at 3,200 full-time jobs in Michigan. Specific jobs were not identified in the assessment. However, the Nuclear Energy Institute (2023) estimated that "for every 100 nuclear power plant jobs, 66 more jobs are created in the local community." These additional jobs are referred to as indirect and induced jobs. These are jobs supported by the plant's transactions with other businesses within the supply chain and from household spending in the local economy generated by the plant's employees spending activity. Using that estimate, approximately 1,928 people worked in Michigan's nuclear generating plants during 2015. Because the Palisades Nuclear Generating Station (Palisades) closed during 2022, fewer people work in Michigan's nuclear generating plants now.

The University of Michigan "is home to one of the top nuclear engineering programs in the world" (Filler and Steckloff 2023). During a recent academic year, the University of Michigan awarded more than 50 degrees in nuclear engineering or engineering physics (University of

Michigan 2023). These skilled engineers can help expand nuclear generation projects in Michigan.

The University of Michigan (2020) has been working with Argonne National Lab, Idaho National Lab, and engineering firms Kairos Power and Curtiss Wright on developing "AI-enhanced 'digital twins' of nuclear reactors." This team seeks to improve "three drawbacks" of nuclear power which provides potential for building advanced nuclear generating plants in Michigan:

1) Reduce maintenance costs for nuclear power plants by "accurately predicting when components need replacing, rather than relying on overly cautious maintenance schedules."
2) Design "advanced nuclear power plants so that they would be less expensive to build and run."
3) Enable nuclear power "to ramp up and down according to demand, becoming a better complement to wind and solar energy" (University of Michigan 2020)

Monroe County Community College, located in Monroe, Michigan, offers an associate of applied science degree with specialization in nuclear engineering technology. Students earning this degree can be employed as nuclear engineering technicians (Monroe County Community College 2023).

To evaluate the economic impacts of constructing and operating a hypothetical nuclear plant, Section 3 specifies the development of a hypothetical nuclear plant to come online and begin producing electricity in 2036. Given this time period, and the expertise at the University of Michigan and community colleges such as Monroe County Community College, if the decision is made to pursue hypothetical nuclear plant development in Michigan, planning can begin with these institutions to begin developing the workforce needed to meet the employment requirements for the future plant construction and operation.

3. Location Screening

A hypothetical nuclear power plant in Michigan would ultimately be sited in a particular location. Although this study does not advocate for any specific location, modeling the local economic and power system effects of a hypothetical nuclear plant requires specifying a site. This section evaluates the power system in Michigan to identify potential locations for a hypothetical plant.

3.1 Michigan System Operators

The U.S.'s electrical system consists of large networks of power lines, generators, and supporting equipment that independently synchronize alternating current at 60 Hz. These grids are connected to one another by direct current which does not require synchronization. Within each synchronized grid, entities including system operators, regional transmission organizations (RTOs), and independent system operators oversee the system and coordinate electricity flow to balance electricity supply and demand.

Michigan is in the Eastern Interconnection. According to the U.S. DOE (2023b), "[t]he Eastern Interconnection reaches from Central Canada Eastward to the Atlantic coast (excluding Québec), South to Florida and West to the foot of the Rockies (excluding most of Texas)." Two of the Eastern Interconnection's largest system operators, the PJM Interconnection (PJM) and Midcontinent Independent System Operator (MISO), are in Michigan. PJM operates in all or parts of 13 states in the Mid-Atlantic and Midwest. MISO covers a large portion of the Midwest and parts of the South, serving 15 states. The PJM and MISO regions are depicted below.

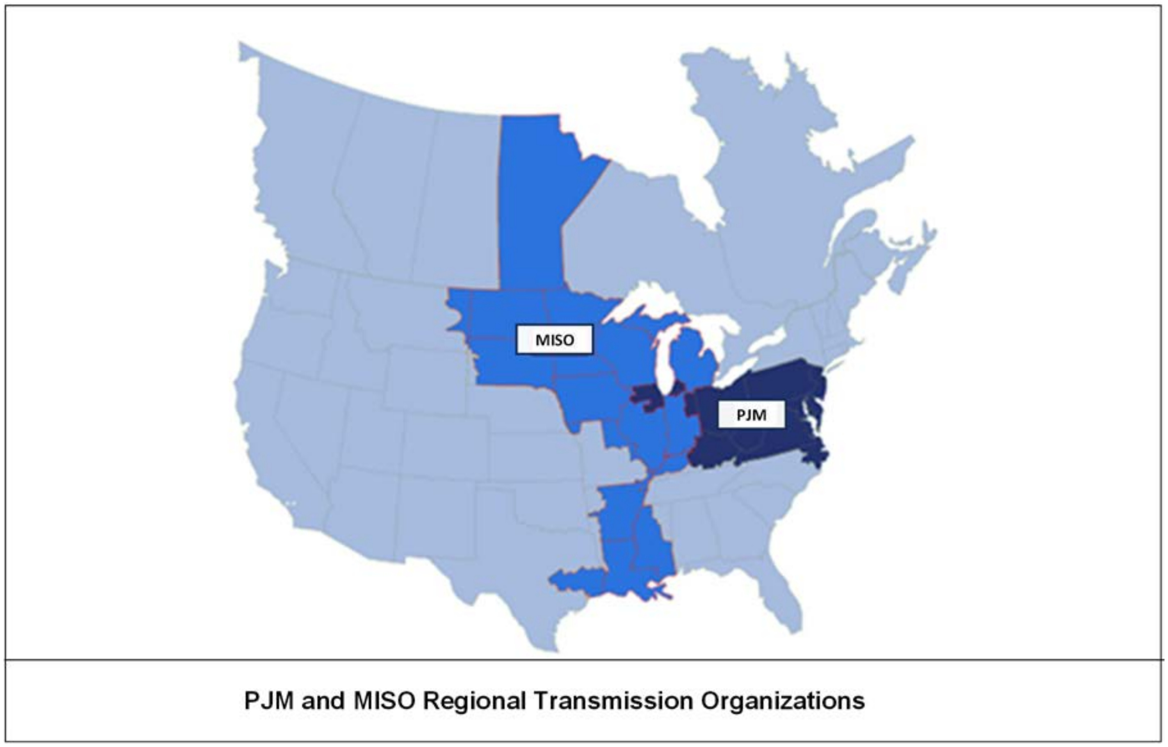

Figure 3.1: Michigan System Operators

As Figure 3.1 indicates, most of Michigan is served by MISO, with only the southwest corner being served by PJM. Both system operators provide reliability services and serve as marketplaces in which members buy and sell electricity.

3.2 Michigan Grid Connections

A hypothetical nuclear plant in Michigan would connect to the electrical grid at either an entirely new site or at an existing grid-tied generation location. The type of nuclear plant would dictate the capacity of transmission required. Potential reactor sizes range from the Westinghouse AP1000® Pressurized Water Reactors (PWRs) installed at the Vogtle Plant to small modular reactors (SMRs). The AP1000® reactors output up to 1,117 megawatts and would require a grid tie capable of absorbing that much electricity. However, advanced design SMRs can be as small as 50 megawatts, expanding the potential suitability of grid tie in locations.

The lower capacities of SMRs means that many sites with retiring coal or gas plants could have sufficient transmission to support them. Siting SMRs at sites with retiring units is a likely approach. TerraPower plans to launch its first 345 megawatt sodium-cooled fast reactor with molten salt-based energy storage at a retiring coal plant in Wyoming. In Michigan, a number of sites with aging and retired units are potentially available. Figure 3.2 presents a sample set of existing sites throughout Michigan.

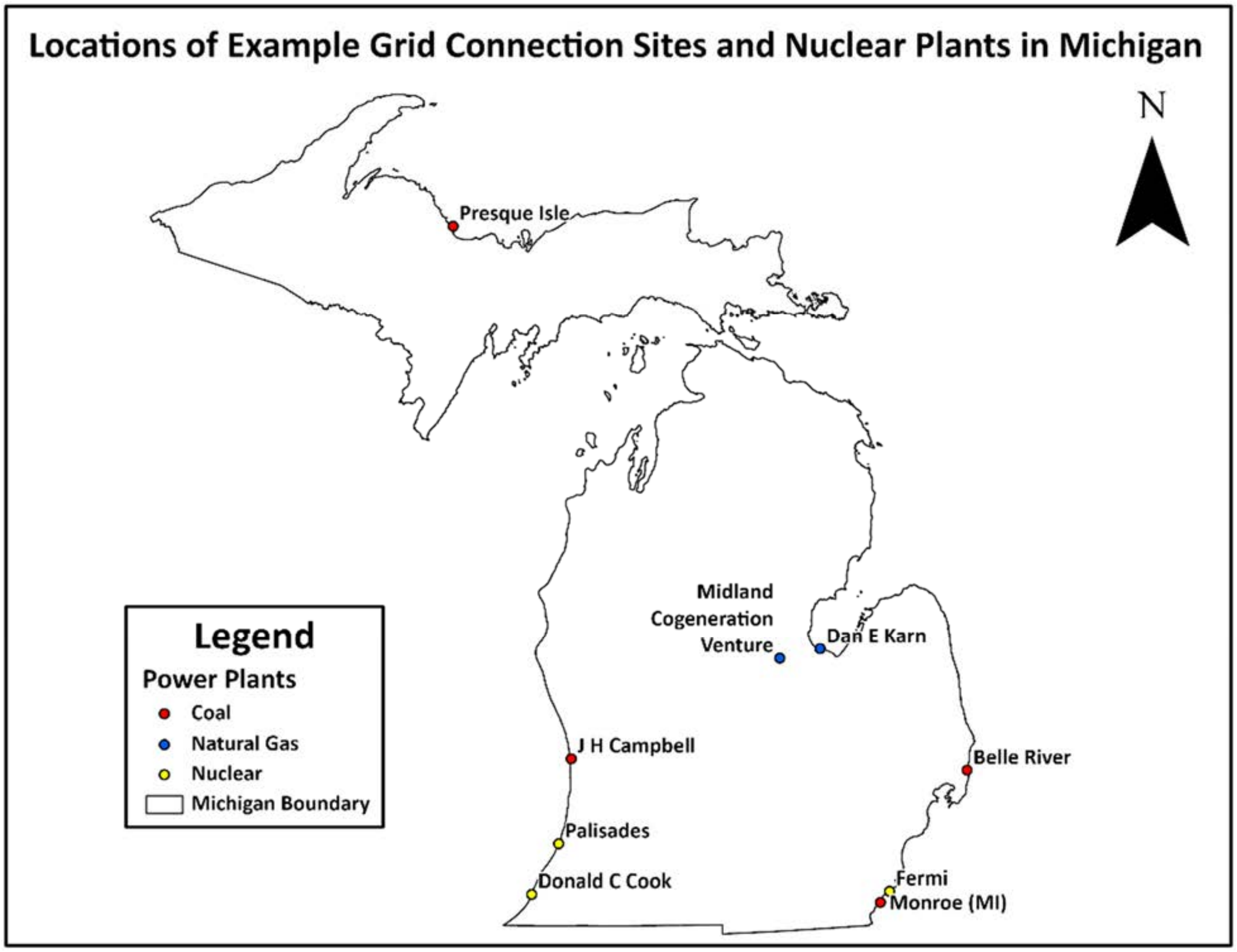

Figure 3.2: Evaluated Grid Connection Sites

The following text highlights each location:

- Presque Isle Power Plant is located in Marquette County and was operated by Wisconsin Energy. It consisted of five 90 megawatt coal-fueled units connected to the grid by several 138 kilovolt (kV) lines and a single 345 kV line. The plant was built in 1955 and retired in 2019.
- Dan E. Karn Generating Plant is located in Bay County and is operated by Consumers Energy. It consists of two 272 megawatt units fueled by coal and natural gas. The plant was built in 1959 and is expected to retire soon.
- Midland Cogeneration Venture (MCV) is located in Midland County and operated by Midland Cogeneration Venture Limited Partnership. MCV was originally planned to be a 2-Unit nuclear power plant, until the construction of the nuclear plant was abandoned in 1984 and subsequently converted to a natural gas-fired facility. It is currently an 1,849 megawatt natural gas combined cycle facility that consists of 12 gas turbines, two steam turbines, and one backpressure steam turbine.
- J. H. Campbell Generating Plant is located in Ottawa County and is operated by Consumers Energy. It consists of three units: a 265 megawatt unit, a 385 megawatt unit, and an 848 megawatt unit built in 1962, 1967, and 1980, respectively. It is fueled by sub-bituminous coal. The plant is scheduled to be retired in 2025.

- Belle River Power Plant is located in St. Clair County and operated by DTE Electric. It consists of two units, each of which is fueled by coal and generates 697.5 megawatts, and three gas-powered peaker units. Unit 1 was built in August of 1984, and Unit 2 was built in July of 1985. Several 345 kV power lines connect the plant to the grid. The plant is adjacent to the retired St. Clair Power Plant, which was also owned by DTE Electric. St. Clair was fueled by coal and consisted of seven units, which generated a total of 1,982 megawatts. The St. Clair Power Plant was shut down in 2022.
- Enrico Fermi Nuclear Plant is located in Monroe County and operated by DTE Electric. It currently consists of one operational unit, Unit 2, which was built in 1988. Unit 1 was built in 1966 and was shut down and decommissioned in 1972.
- Monroe Power Plant is located in Monroe County and is operated by DTE Electric. The plant consists of four coal-powered units—two 817.2 megawatt units (units 1 and 4) and two 822.6 megawatt units (units 2 and 3). Unit 1 was built in 1971, units 2 and 3 were built in 1973, and unit 4 was built in 1974. Units 3 and 4 are scheduled for closure in 2028, and Units 1 and 2 scheduled for closure in 2032.

This list is not exhaustive; rather, it is meant to illustrate the types of existing sites throughout the state where hypothetical nuclear units could be installed.

3.3 Michigan Utilities

Within Michigan, generation companies produce electricity and regulated utilities are responsible for delivering it. Michigan has areas that are covered by investor-owned utilities and cooperatives. Figure 3.3 depicts the electric utilities in Michigan. Areas in white are cooperatives.

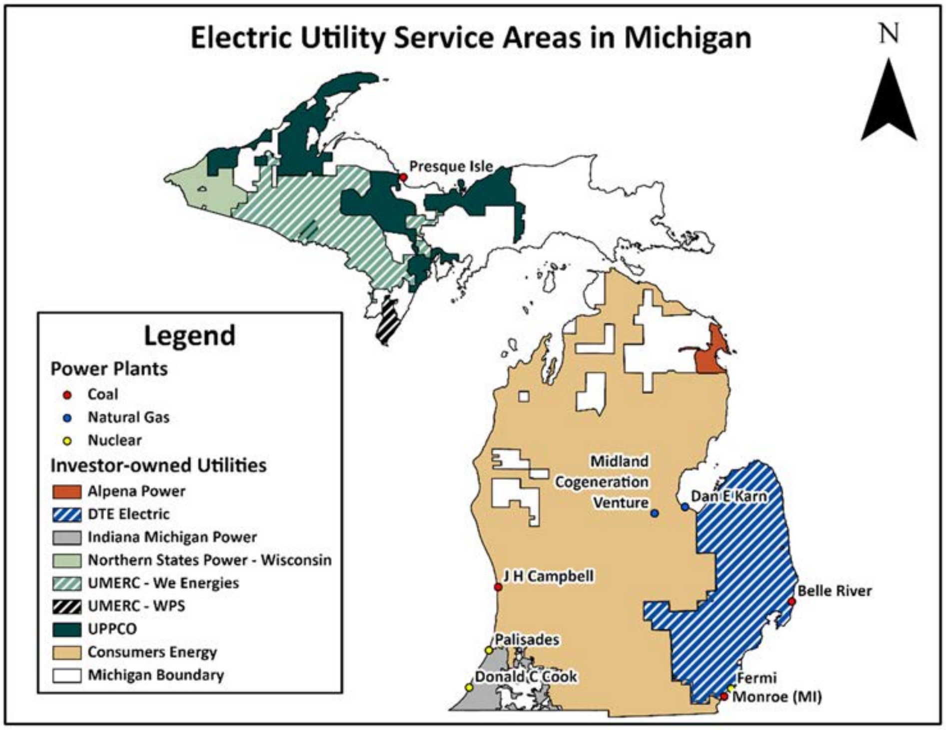

Figure 3.3: Michigan Utilities

As Figure 3.3 indicates, there are seven investor-owned utilities operating in Michigan. Of these utilities, DTE Electric, Consumers Energy, and Indiana Michigan Power Company (I&M) have operated nuclear power plants. Consumers Energy operated Palisades, DTE Electric currently operates Fermi 2, and I&M operates DC Cook.

3.4 Screening for Nuclear Plant Siting

A new nuclear power plant could conceivably be sited at many locations in Michigan. This study does not intend to suggest a location. However, modeling the economic impacts and power system effects of a new nuclear power plant requires specifying a physical location and utility power system. Important drivers in this include system operators, grid connections, utilities, and physical areas.

As indicated in Figures 3.2 and 3.3, public utilities serving Michigan's Upper Peninsula include Xcel Energy (Northern States Power), Upper Peninsula Power Company, and Upper Michigan Energy Resources Corporation, a subsidiary of the WEC Energy Group serving the former territories of Wisconsin Public Service Corporation and Wisconsin Electric Power Company. None of these companies are currently or have historically operated nuclear power plants. The only site identified as a potential grid connection in the Upper Peninsula is the Presque Isle site. The units at Presque Isle were closed in 2017. To replace the lost capacity in the Upper Peninsula, the F.D. Kuester and A.J. Mihm plants were constructed. There are a total of ten 18.9 megawatt units at these two sites for a total of 189 megawatts. Additional efforts to bring power to the Upper Peninsula potentially include two new 345 kV lines from Wisconsin. Based on the limited need for new power and the limited nuclear operation experience in the Upper Peninsula, locations and utilities in this region were screened out leaving lower Michigan for consideration.

As indicated in Figure 3.1, the great majority of Michigan is within MISO, but the southwest corner is in PJM. This area is operated by I&M and includes DC Cook nuclear plant, operating two Westinghouse pressurized water reactors. Unit 1 (1,120 megawatts) primarily serves Southwest Michigan, and Unit 2 (1,240 megawatts) serves Northwest and Central Indiana. Unit 1 began operating in 1975, and Unit 2 began operating in 1978. Both units were relicensed in 2005 extending Unit 1's license until 2034 and Unit 2's license until 2037. If DC Cook was granted a second renewal, the units would be operating into the 2050s. Given that the majority of Michigan is in MISO and DC Cook could potentially be relicensed, this assessment screens out the southwestern portion of Michigan, PJM, and I&M territory.

Sites that remain in consideration are within the Consumers Energy and DTE Electric territories. As depicted in Figure 3.2, Consumers Energy potentially has grid connections available at the Karn and Campbell sites and a Power Purchase Agreement (PPA) at MCV. DTE Electric potentially has grid connections available at the St. Clair, Monroe, and Fermi plants. The Consumers Energy and DTE Electric territories are depicted in Figure 3.4.

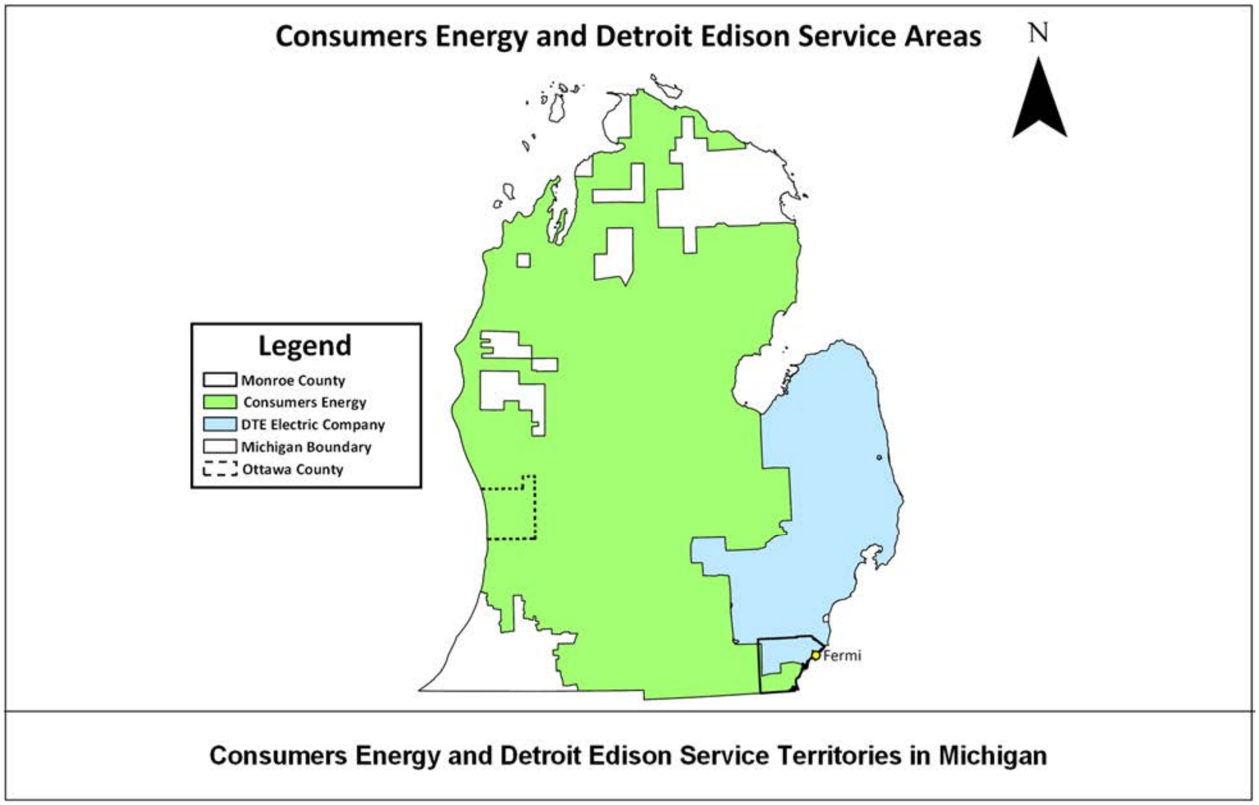

Figure 3.4: Selected Hypothetical Location

As major utilities, both DTE Electric and Consumers Energy produce Integrated Resource Plans (IRPs) that detail their intended approach for supporting generation and transmission needs for the future. Although neither of these companies explicitly model new nuclear generation in their IRP, DTE Electric does raise the possibility of using SMRs. DTE Electric is also currently operating the Fermi Nuclear Plant, and in 2015 DTE Electric received a license to construct a new nuclear unit at the Fermi location.[6]

Although there are a number of possible locations in Michigan to site a hypothetical nuclear plant, conducting economic impact and power system modeling requires specifying a county and power system. Based on this review, the Fermi and Monroe sites appear to be appropriate candidate locations for siting a hypothetical nuclear plant; therefore, the DTE Electric

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[6] The license expires at midnight on the date 40 years from when the NRC finds that the acceptance criteria in the combined license are met in accordance with 10 CFR 52.103(g).

system was used for power system modeling, and Monroe County was selected as a possible location and used for economic impact modeling.

Consumers Energy's service territory provides another option for evaluating the power system and economic impacts of a hypothetical nuclear plant in Michigan. Consumers Energy's J.H. Campbell facility is a coal-fired power plant located in Ottawa County that is scheduled to retire in 2025. For comparison with the Monroe County location, the analysis evaluates the power system and economic impacts of constructing and operating a hypothetical nuclear plant at J.H. Campbell.

4. Economic Impact Evaluation

This section describes the methods and results of estimating the economic impacts of constructing and operating a hypothetical nuclear plant in Michigan. The evaluation considers two alternative hypothetical scenarios: constructing and operating a hypothetical nuclear plant in DTE Electric's service territory in Monroe County and constructing and operating a hypothetical nuclear plant in Consumers Energy's service territory in Ottawa County. The hypothetical facility is specified to consist of 12 small modular reactors (SMR) with each module rated at 60 MWe totaling 720 MWe. SMRs were selected for evaluation because of their smaller footprint relative to traditional nuclear power plants. This allows for the possibility of placing them at retired fossil fuel sites which has advantages in terms of land availability and transmission system connections. The number of modules evaluated was based on replacing a typically sized baseload coal-fired unit. Capital costs are estimated to be approximately $2.5 billion, and construction activities are specified to occur from 2032 through the end of 2035. The plant is specified to come online in 2036 and run for 60 years.

4.1 Overview of Economic Impact Analysis

Identifying the contribution that expenditures resulting from nuclear plant development will have on the economic activity in the state of Michigan requires developing a predictive model that incorporates appropriate parameters across relevant sectors of the evaluated economy. Such an analysis is typically accomplished via a mathematical-economic technique called Input/Output Analysis (Leontief 1986) that assesses the effects of economic impacts in a particular economic system (e.g., town, county, state, region, or national level). Input-output (I/O) analysis measures the effects across the following three categories:

- *Direct effects* which represent the impacts from the industry being evaluated (e.g., wages paid to employees working at the nuclear plant).
- *Indirect effects* which are the inter-industry transactions between the supplying industries and the directly affected industries (e.g., production and sale of office supplies to the nuclear plant).
- *Induced effects* which reflect the local spending from the directly and indirectly affected industry sectors (e.g., purchases at local restaurants and grocery stores by employees working on the construction of the nuclear plant).

I/O analysis was developed to address policy issues with respect to income, sales, demand, and local infrastructure. I/O models specifically recognize that changes in final demand for one industry affect other industries within a specific economic area. Each industry's change in demand changes conditions in other industries, and so forth. In practice, the parameters that link demand changes across industries are called multipliers. The multipliers developed for I/O models include the following:

- *Output multipliers* that relate the changes in sales to final demand by one industry to total changes in output (gross sales) by all industries within the local area.
- *Income and employment multipliers* that relate the change in direct income and employment to changes in total income and total employment within the local economy.
- *Value added multipliers* that relate changes in value added in the industry experiencing the direct effect to total changes in value added for the local economy.

Calculating the impacts to final demand and specifying appropriate parameters provides the ability to estimate the total economic impacts expected to occur because of the nuclear plant's expenditures on employee compensation, operation and maintenance, and capital expenditures. Data requirements to conduct this evaluation include outputs and inputs from other sectors, value added, employment, wages and business taxes paid, imports and exports, final demand by households and government, capital investment, business inventories, marketing margins, and inflation factors (deflators).

To develop and conduct the I/O analysis, Veritas Economics (Veritas) used a software program called IMPLAN (IMpactPLANning), which is an economic impact planning model for conducting input-output analysis. IMPLAN contains detailed input-output information on more than 500 economic sectors at the national level. In addition, it captures the input-output relationships that are relevant at the ZIP Code, county, and state level using data compiled specifically for Michigan as well as all county codes within Michigan.

The analysis uses the expenditures associated with the development and construction of the hypothetical nuclear plant and its operations and maintenance costs. It includes expenditures and employment occurring in Michigan; it excludes expenditures and employment occurring outside Michigan. Veritas used the data found in publicly available sources to evaluate total impacts of the nuclear plant's expenditures. Veritas relied upon best professional judgement when estimating the distribution of expenditures between employee compensation, capital expenditures, and operations and maintenance, as well as the geographic area in which the expenditures are most likely to occur.

Veritas used the Analysis-by-Parts model in IMPLAN to evaluate the impacts of the nuclear plant's expenditures on each economy. Veritas' Analysis-by-Parts includes the following IMPLAN analysis types:

1. Industry Change,

2. Industry Spending Pattern, and
3. Labor Income Change.

In the Analysis-by-Parts model, Veritas specifies that the goods and services purchased for capital projects are classified as an Industry Change. An Industry Change includes effects of adding industries to the Study Area (e.g., the hypothetical nuclear plant) and changes in an industry's output, retail expenditures, and construction (e.g., development and construction of the hypothetical nuclear plant). The capital expenditures are direct effects because they represent the impacts from the industry being evaluated (e.g., the development and construction of the nuclear plant). IMPLAN calculates the indirect and induced effects of these expenditures.

Veritas specifies that the goods and services that are purchased for operation and maintenance purposes are classified as an Industry Spending Pattern. The Industry Spending Pattern estimates the indirect and induced effects of the plant's operation and maintenance expenditures. The input/output relationships within IMPLAN quantify the interrelationships between industries and other sectors within each economy—the indirect impacts. The induced impacts include purchases at local restaurants and grocery stores by employees of indirectly impacted electricity sector employees.

The third part of the Analysis-by-Parts is called a Labor Income Change. The Labor Income Change examines results of wages or compensation that an employer is paying to an employee. The impacts resulting from labor income are induced effects because the money received by an industry's employees is recirculated through the household spending patterns, causing additional economic activity.

The Analysis-by-Parts model identifies the following types of impacts:

- *Value-added impacts*—These represent income from labor, management, and ownership that are generated by the nuclear plant's construction and operation.
- *Employment impacts*—These represent the number of jobs that the plant's construction and operation contribute to the local economy, including plant employees and employees in related sectors.

Value-Added impacts account for the value of work, land, and capital. For example, businesses (e.g., nuclear power plants) purchase services (e.g., labor from hourly and salaried employees), raw materials (water and fuel), and intermediate products (e.g., construction equipment) and combine, repackage, or transform them into new products to be sold to consumers (e.g., electricity). The difference between the cost of the raw and intermediate goods and services (i.e., labor, construction equipment, and fuel) and the final product (i.e., electricity) is the amount by which businesses have added value in production, and, hence, to the economy. Therefore, a business that takes existing products and repackages them creates less added value for the economy than a business that takes inputs and utilizes labor services to creates something new.

Because Value-Added impacts represent the value of all final products and services, it is the metric that is most comparable to Michigan's Gross State Product ($621 billion in 2022). Gross State Product (GSP) is the value of final goods and services at the state level, and Gross Domestic Product or GDP is the value of final goods and services at the national level.

The Value Added category includes Labor Income which provides a monetary evaluation of the Employment Impacts. Labor Income includes all forms of employment income including employee compensation (wages, salaries, and benefits) and proprietor income (income received by local businesses and the self-employed).

4.2 Inputs to the Economic Impact Analysis

To evaluate the economic impacts of constructing and operating a hypothetical nuclear plant, the analysis has to specify construction and operation timing and costs. Costs associated with construction include labor, direct costs such as building materials, and indirect costs such as building design development. Costs associated with operation include labor and facility maintenance costs. Construction and operation costs are specified to occur in specific time periods in the future based on the projected project development plan.

Construction activities are specified to occur over a four-year period beginning in 2032. Cost estimates for the construction activities are based on the direct and indirect costs provided for manufacturing and constructing the NuScale 12-pack power plant as estimated in Black, Aydogan, and Koerner (2019). Table 4.1 summarizes the costs by category (costs presented in 2015 dollars). Table 4.1 also presents estimates of the amount of the costs that can potentially be sourced from Michigan. Given Michigan's robust historical manufacturing capabilities, it is anticipated that a portion of all direct costs will be sourced or originate from Michigan. Following the results of Black and Peterson (2019), 70% of the structure and improvement costs are specified to be sourced within Michigan. The more specialized equipment associated with the plant reactor, turbine, electrical, heat rejection systems, and other plant equipment are expected to have a lower portion sourced from Michigan, with 30% of costs specified to be sourced within Michigan.

Table 4.1
Total Non-Labor Construction Costs

Non-Labor Capital Cost Categories	Total Cost	Sourced From Michigan
Direct Costs		
Structures and Improvements	$612,136,797	$422,374,390
Reactor Plant Equipment	$869,360,876	$234,727,437
Turbine Plant Equipment	$196,121,808	$52,952,888
Electric Plant Equipment	$34,982,052	$9,445,154
Heat Rejection Systems	$62,934,255	$16,992,249
Miscellaneous Plant Equipment	$30,080,354	$8,121,696
Subtotal Direct Costs	$1,805,616,142	$744,613,814
Indirect Costs		
Design Services at Home Office	$130,978,572	$130,978,571
Field Construction Management	$60,906,859	$60,906,859
Field Construction Supervision	$246,930,385	$246,930,385
Field Indirect Costs	$224,894,794	$224,894,794
Subtotal Indirect Costs	$663,710,610	$663,710,609
Total	**$2,469,326,752**	**$1,408,324,423**

Table 4.2 presents the number of employees, employee compensation, and non-labor capital expenditures by year over the construction time period. Estimates of the number of employees and employee compensation are based on the results in Black and Peterson (2019), and the estimates of non-labor capital expenditures are the direct costs sourced from Michigan in Table 4.1 distributed by year and discounted at 3%. The first year of construction covers site improvement activities including major excavating work for all buildings, structures, and employee parking lots as well as a vast majority of the concrete work used in construction of foundations for building, structures, and onsite waste storage facilities. The second year of construction covers structural steel erection and exterior finishing for the primary buildings included on the site. The third year of construction covers interior finishing of the onsite buildings as well as physical security measures used to prevent thefts and sabotage relating to special nuclear material that will be housed at the site during the operation of the plant. The fourth year of construction is when the SMR reactor will be delivered and installed. The final year of construction covers materials and machinery used to finish the facility construction and functionality as it is tied into the grid.

Table 4.2
Direct Employment and Discounted Employee Compensation and Non-Labor Capital Expenditures Sourced in Michigan During the Construction Time Period

Category	2032	2033	2034	2035
Wage and Salary Employment	1815	908	2285	2992
Employee Compensation	$120,313,357	$60,156,678	$151,473,097	$198,315,032
Non-Labor Capital Expenditures	$129,485,920	$62,857,243	$153,663,159	$195,322,675

Notes: Employee Compensation and Non-Labor Capital Expenditures are discounted at 3% and presented in 2023 dollars.

4.3 Monroe County

Using IMPLAN's capabilities for evaluating the economic impacts of nuclear energy development, the Michigan module was employed to evaluate the economic impacts of a hypothetical nuclear plant located in DTE's service territory in Monroe County. The analysis assumes that the area will develop the supporting manufacturing capabilities before construction of a nuclear energy plant, which is specified to begin in 2032. Construction activities differ by year, resulting in varying direct effects across the construction time period. The analysis also specifies that all of the plant's maintenance labor is performed locally as well as the operation, management, and generation administration. Tables 4.3 through 4.6 present the direct, indirect, and induced effects for employment, total labor income, and value added for each year of construction.

Table 4.3
Discounted Economic Impacts of Construction, 2032

Impact Type	Employment	Labor Income	Value Added
Direct Effect	1,815	$120,313,357	$168,879,807
Indirect Effect	1,340	$82,481,691	$132,000,889
Induced Effect	607	$30,715,782	$58,389,199
Total Effect	**3,762**	**$233,510,830**	**$359,269,895**

Notes: Labor Income and Value-Added are discounted at 3% and presented in 2023 dollars.

Table 4.4
Discounted Economic Impacts of Construction, 2033

Impact Type	Employment	Labor Income	Value Added
Direct Effect	908	$60,156,678	$84,439,903
Indirect Effect	668	$41,230,333	$65,980,993
Induced Effect	302	$15,346,038	$29,179,412
Total Effect	**1,878**	**$116,733,049**	**$179,600,309**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars

Table 4.5
Discounted Economic Impacts of Construction, 2034

Impact Type	Employment	Labor Income	Value Added
Direct Effect	2,285	$151,473,097	$212,617,684
Indirect Effect	1,678	$103,796,363	$166,098,235
Induced Effect	758	$38,613,326	$73,438,711
Total Effect	**4,721**	**$293,882,786**	**$452,154,630**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.6
Discounted Economic Impacts of Construction, 2035

Impact Type	Employment	Labor Income	Value Added
Direct Effect	2,992	$198,315,032	$278,368,131
Indirect Effect	2,191	$135,864,750	$217,405,953
Induced Effect	988	$50,517,359	$96,102,859
Total Effect	**6,171**	**$384,697,141**	**$591,876,944**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Once construction is completed in 2035, the plant is specified to come online at the beginning of 2036 and operate for 60 years. The analysis specifies that the plant will employ 360 people throughout its normal operating life, all of whom are expected to live in Michigan. Table 4.7 presents the annual economic impact of plant operation, and Table 4.8 presents the total economic impacts of operation over the life of the plant.

Table 4.7
Annual Economic Impacts of Operation

Impact Type	Employment	Labor Income	Value Added
Direct Effect	360	$44,652,414	$61,114,442
Indirect Effect	234	$17,515,495	$31,876,145
Induced Effect	179	$8,703,455	$16,604,345
Total Effect	**773**	**$70,871,365**	**$109,594,931**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.8
Total Discounted Economic Impacts of Lifetime Operation

Impact Type	Employment	Labor Income	Value Added
Direct Effect	360	$866,751,738	$1,186,297,538
Indirect Effect	234	$339,994,746	$618,750,505
Induced Effect	179	$168,943,499	$322,308,325
Total Effect	**773**	**$1,375,689,983**	**$2,127,356,368**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.9 sums the total economic impacts of plant construction presented in Tables 4.3 through 4.6 and the total economic impacts of the plant's lifetime operation presented in Table 4.8 to produce the total economic impacts of the plant's construction and operation. As Table 4.9 shows, the hypothetical nuclear energy plant is estimated to generate 17,305 jobs, provide approximately $2.4 billion in Labor Income, and contribute approximately $3.7 billion to Michigan's economy over the plant's lifetime.

Table 4.9
Total Economic Impacts of Construction and Lifetime Operation

Impact Type	Employment	Labor Income	Value Added
Direct Effect	8,360	$1,397,009,902	$1,930,603,063
Indirect Effect	6,111	$703,367,883	$1,200,236,576
Induced Effect	2,834	$304,136,005	$579,418,507
Total Effect	**17,305**	**$2,404,513,789**	**$3,710,258,146**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

In addition to employment, labor income, and value-added impacts, annual increases in local, state, and federal taxes stemming from construction of the plant and its operation are shown in Tables 4.10 through 4.16. Tables 4.10 through 4.13 present the taxes associated with each year of construction, and Table 4.14 sums them to provide the total discounted taxes associated with construction activities. Table 4.15 presents the annual tax impacts from plant operation, and Table 4.16 is the total discounted tax impacts resulting from the plant's 60-year operation.

Table 4.10
Discounted Tax Impacts of Construction, 2032

Impact Type	County	State	Federal	Total
Direct Effect	$6,805,056	$32,951,497	$14,593,648	$74,637,196
Indirect Effect	$1,785,063	$10,376,122	$15,010,049	$32,729,241
Induced Effect	$648,471	$4,279,852	$5,794,175	$12,953,798
Total Effect	**$9,238,590**	**$47,607,471**	**$35,397,872**	**$120,320,236**

Table 4.11
Discounted Tax Impacts of Construction, 2033

Impact Type	County	State	Federal	Total
Direct Effect	$3,404,938	$16,487,421	$7,301,993	$37,345,036
Indirect Effect	$894,856	$5,201,001	$7,522,343	$16,404,276
Induced Effect	$324,571	$2,142,222	$2,900,268	$6,483,896
Total Effect	**$4,624,366**	**$23,830,644**	**$17,724,605**	**$60,233,209**

Table 4.12
Discounted Tax Impacts of Construction, 2034

Impact Type	County	State	Federal	Total
Direct Effect	$8,579,629	$41,544,347	$18,399,273	$94,100,537
Indirect Effect	$2,259,124	$13,128,972	$18,985,989	$41,407,328
Induced Effect	$818,138	$5,400,091	$7,311,199	$16,344,694
Total Effect	**$11,656,890**	**$60,073,410**	**$44,696,461**	**$151,852,559**

Table 4.13
Discounted Tax Impacts of Construction, 2035

Impact Type	County	State	Federal	Total
Direct Effect	$11,240,773	$54,430,163	$24,106,177	$123,287,713
Indirect Effect	$2,965,492	$17,232,248	$24,915,536	$54,345,099
Induced Effect	$1,072,273	$7,077,805	$9,582,933	$21,422,886
Total Effect	**$15,278,539**	**$78,740,216**	**$58,604,646**	**$199,055,698**

Table 4.14
Total Discounted Tax Impacts of Construction

Impact Type	County	State	Federal	Total
Direct Effect	$30,030,396	$145,413,428	$64,401,091	$329,370,482
Indirect Effect	$7,904,535	$45,938,342	$66,433,918	$144,885,944
Induced Effect	$2,863,453	$18,899,971	$25,588,575	$57,205,275
Total Effect	**$40,798,385**	**$210,251,741**	**$156,423,584**	**$531,461,701**

Table 4.15
Annual Tax Impacts of Operation

Impact Type	County	State	Federal	Total
Direct Effect	$2,291,288	$11,154,805	$5,671,541	$25,948,365
Indirect Effect	$488,628	$3,169,643	$2,877,790	$8,267,230
Induced Effect	$185,461	$1,207,430	$1,619,533	$3,644,488
Total Effect	**$2,965,377**	**$15,531,878**	**$10,168,864**	**$37,860,083**

Table 4.16
Total Discounted Tax Impacts of Lifetime Operation

Impact Type	County	State	Federal	Total
Direct Effect	$44,476,386	$216,526,851	$110,090,753	$503,685,889
Indirect Effect	$9,484,794	$61,526,201	$55,861,024	$160,475,889
Induced Effect	$3,600,007	$23,437,526	$31,436,891	$70,743,464
Total Effect	**$57,561,186**	**$301,490,577**	**$197,388,668**	**$734,905,243**

4.4 Ottawa County

The Michigan module within IMPLAN was also employed to evaluate the economic impacts of a hypothetical nuclear energy plant located in Consumers Energy's Service Territory in Ottawa County. The analysis assumes that the area will develop the supporting manufacturing capabilities before construction, which is scheduled to begin in 2032. Based on this, the nuclear energy plant is specified to have 100% of its maintenance conducted in Michigan. All the maintenance labor is specified to be performed locally as well as the operation, management, and generation administration. Tables 4.17 through 4.20 present the direct, indirect, and induced effects for employment, total labor income, and value added for each year of construction.

Table 4.17
Discounted Economic Impacts of Construction, 2032

Impact Type	Employment	Labor Income	Value Added
Direct Effect	1,815	$120,313,357	$168,879,807
Indirect Effect	1,334	$87,825,241	$145,848,465
Induced Effect	765	$40,383,072	$74,933,890
Total Effect	**3,914**	**$248,521,670**	**$389,662,162**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.18
Discounted Economic Impacts of Construction, 2033

Impact Type	Employment	Labor Income	Value Added
Direct Effect	908	$60,156,678	$84,439,903
Indirect Effect	665	$43,898,842	$72,896,389
Induced Effect	381	$20,177,615	$37,448,820
Total Effect	**1954**	**$124,233,136**	**$194,785,112**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.19
Discounted Economic Impacts of Construction, 2034

Impact Type	Employment	Labor Income	Value Added
Direct Effect	2,285	$151,473,097	$212,617,684
Indirect Effect	1,670	$110,509,792	$183,493,736
Induced Effect	956	$50,775,471	$94,256,275
Total Effect	**4,910**	**$312,758,360**	**$490,367,695**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.20
Discounted Economic Impacts of Construction, 2035

Impact Type	Employment	Labor Income	Value Added
Direct Effect	2,992	$198,315,032	$278,368,131
Indirect Effect	2,180	$144,645,652	$240,156,823
Induced Effect	1,246	$66,435,140	$123,350,879
Total Effect	**6,418**	**$409,395,823**	**$641,875,833**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Once construction is complete in 2035, the plant is expected to come online at the beginning of 2036 and operate for 60 years. The plant is specified to employ 360 people throughout its normal operating life, and all of the employes are specified to live in Michigan. Table 4.21 presents the annual economic impact of plant operation, and Table 4.22 presents the total economic impacts of operation over the plant's lifetime.

Table 4.21
Annual Economic Impacts of Operation

Impact Type	Employment	Labor Income	Value Added
Direct Effect	360	$44,652,414	$61,114,442
Indirect Effect	176	$11,290,032	$18,892,535
Induced Effect	183	$9,104,202	$17,115,934
Total Effect	**719**	**$65,046,648**	**$97,122,911**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.22
Total Discounted Economic Impacts of Lifetime Operation

Impact Type	Employment	Labor Income	Value Added
Direct Effect	360	$866,751,738	$1,186,297,538
Indirect Effect	176	$219,151,758	$366,724,581
Induced Effect	183	$176,722,425	$332,238,824
Total Effect	**719**	**$1,262,625,921**	**$1,885,260,943**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

Table 4.23 sums the total economic impacts of plant construction presented in Tables 4.17 through 4.20 and the economic impacts of the plant's lifetime operation presented in Table 4.22 to produce the total economic impacts of the plant's construction and operation. As Table 4.23 shows, the hypothetical nuclear energy plant is estimated to generate 17,915 jobs, provide approximately $2.4 billion in Labor Income, and contribute approximately $3.6 billion to Michigan's economy over the plant's lifetime.

Table 4.23
Total Economic Impacts of Construction and Lifetime Operation

Impact Type	Employment	Labor Income	Value Added
Direct Effect	8,360	$1,397,009,902	$1,930,603,063
Indirect Effect	6,025	$606,031,285	$1,009,119,994
Induced Effect	3,531	$354,493,722	$662,228,688
Total Effect	**17,915**	**$2,357,534,910**	**$3,601,951,745**

Notes: Labor Income and Value Added are discounted at 3% and presented in 2023 dollars.

In addition to employment, labor income, and value-added impacts, annual increases in local, state, and federal taxes stemming from construction of the plant and its operation are shown below in Tables 4.24–4.30. Tables 4.24 through 4.27 present the taxes associated with each year of construction, and Table 4.28 sums them to provide the total discounted taxes associated with construction activities. Table 4.29 presents the annual tax impacts from plant operation, and Table 4.30 is the total discounted tax impacts resulting from the plant's 60-year operation.

Table 4.24
Discounted Tax Impacts of Construction, 2032

Impact Type	County	State	Federal	Total
Direct Effect	$4,494,059	$33,899,239	$9,426,971	$69,563,733
Indirect Effect	$1,289,182	$11,064,447	$13,898,851	$32,444,892
Induced Effect	$621,618	$5,448,926	$7,037,449	$15,971,409
Total Effect	**$6,404,859**	**$50,412,613**	**$30,363,271**	**$117,980,034**

Table 4.25
Discounted Tax Impacts of Construction, 2033

Impact Type	County	State	Federal	Total
Direct Effect	$2,248,621	$16,961,627	$4,716,825	$34,806,507
Indirect Effect	$646,164	$5,545,429	$6,964,063	$16,259,450
Induced Effect	$311,144	$2,727,428	$3,522,701	$7,994,517
Total Effect	**$3,205,930**	**$25,234,484**	**$15,203,589**	**$59,060,474**

Table 4.26
Discounted Tax Impacts of Construction, 2034

Impact Type	County	State	Federal	Total
Direct Effect	$5,665,987	$42,739,234	$11,885,268	$87,704,053
Indirect Effect	$1,631,049	$13,997,171	$17,573,829	$41,036,736
Induced Effect	$784,347	$6,875,499	$8,880,738	$20,153,541
Total Effect	**$8,081,383**	**$63,611,904**	**$38,339,834**	**$148,894,330**

Table 4.27
Discounted Tax Impacts of Construction, 2035

Impact Type	County	State	Federal	Total
Direct Effect	$7,423,407	$55,995,669	$15,571,722.62	$114,907,231
Indirect Effect	$2,140,694	$18,369,911	$23,058,128.00	$53,851,591
Induced Effect	$1,028,047	$9,011,831	$11,640,680.05	$26,416,039
Total Effect	**$10,592,148**	**$83,377,411**	**$50,270,530.68**	**$195,174,862**

Table 4.28
Total Discounted Tax Impacts of Construction

Impact Type	County	State	Federal	Total
Direct Effect	$19,832,074	$149,595,770	$41,600,786	$306,981,525
Indirect Effect	$5,707,090	$48,976,958	$61,494,871	$143,592,669
Induced Effect	$2,745,157	$24,063,684	$31,081,568	$70,535,506
Total Effect	**$28,284,320**	**$222,636,412**	**$134,177,225**	**$521,109,700**

Table 4.29
Annual Tax Impacts of Operation

Impact Type	County	State	Federal	Total
Direct Effect	$1,513,166	$11,463,310	$3,780,576	$24,078,200
Indirect Effect	$176,241	$1,502,411	$1,747,379	$4,248,021
Induced Effect	$144,068	$1,249,572	$1,529,583	$3,592,609
Total Effect	**$1,833,475**	**$14,215,292**	**$7,057,539**	**$31,918,830**

Table 4.30
Total Discounted Tax Impacts of Lifetime Operation

Impact Type	County	State	Federal	Total
Direct Effect	$29,372,195	$222,515,259	$73,385,084	$467,383,948
Indirect Effect	$3,421,033	$29,163,430	$33,918,526	$82,458,695
Induced Effect	$2,796,514	$24,255,539	$29,690,866	$69,736,436
Total Effect	**$35,589,742**	**$275,934,228**	**$136,994,476**	**$619,579,079**

5. Power System Modeling

If new nuclear generation were constructed in Michigan, it would have implications for power system operations. Because nuclear plants operate nearly continuously, electricity from the hypothetical plant would replace electricity from other sources. Nuclear generated electricity is emission free, and a new nuclear plant is expected to reduce the emissions from the electrical system in which it operates.

As described in the screening evaluation, both the DTE Electric and Consumers Energy service territories potentially have locations for a new nuclear plant. To evaluate the emission reduction implications of a hypothetical new plant, power system modeling was conducted for each of these systems. The modeling was conducted using the Electricity Policy Simulation Model (EPSM). This model simulates the operation of power systems meeting hourly load at minimum cost using available power generating units. Results from operating the model include estimates of each unit's generation, fuel consumption, cost, and emissions.

To estimate emission reductions from the hypothetical nuclear plant, two cases are compared. The first is a Baseline case in which the available generators do not include the hypothetical nuclear plant. The second is a Counterfactual case in which a nuclear plant is added to the available generating units. Total annual emissions are calculated for each case. The difference in emissions between the Baseline and Counterfactual cases is the emission reduction expected from adding a nuclear plant to each system.

Developing a new nuclear plant takes years. This means the hypothetical nuclear plant would not begin operating until some point in the future. Both DTE Electric and Consumers Energy are transforming their electrical systems to reduce carbon emissions. Because of this decarbonization, both systems will be very different by the time a new nuclear plant could be constructed. This means that accurately estimating changes in emissions requires modeling the power systems of the future. Characteristics of these future power systems were identified by considering the timeline for commissioning a new nuclear plant in the context of publicly available planning documents for each system.

This section describes the methodology and results of the power system modeling. The section begins with a detailed description of the DTE Electric system, DTE Electric's plans for future power generation, the baseline model developed to forecast generation and emissions under DTE Electric's Future Baseline, and DTE Electric's predicted Baseline generation in 2036. The section then provides an overview of the same modeling process undertaken for Consumers

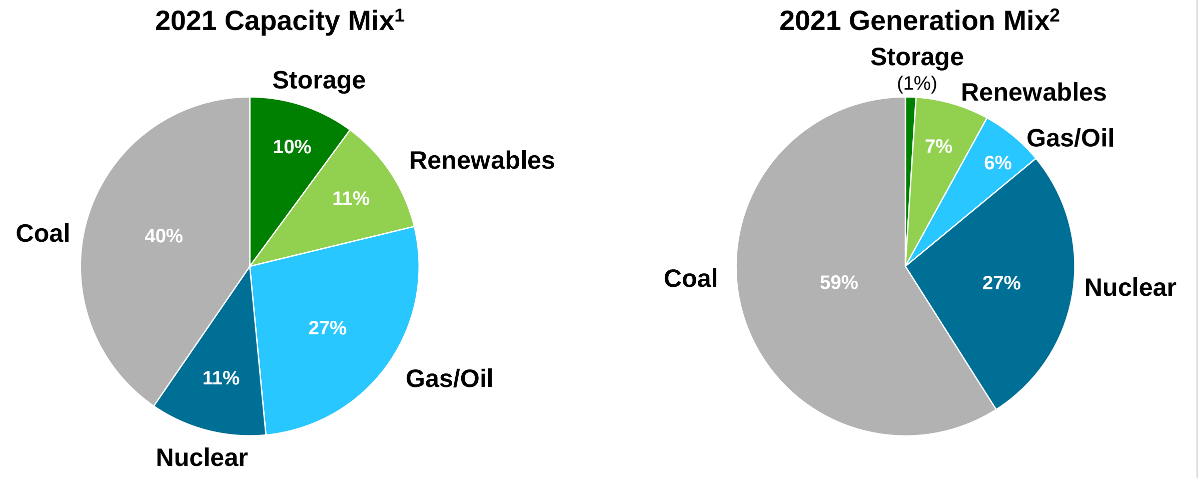
Energy. The section concludes with a description of the Counterfactual conditions and the estimated emission reductions associated with operating a new nuclear plant.

5.1 The DTE Electric System

DTE Electric serves 2.3 million residential, commercial, and industrial customers (DTE Electric 2023a). The company owns and operates an extensive network of distribution infrastructure, encompassing around 31,000 miles of overhead distribution lines and 16,000 miles of underground distribution lines. DTE Electric’s service territory spans across 7,600 square miles in the region.

DTE Electric utilizes a mix of energy sources including coal, nuclear fuel, natural gas, hydroelectric pumped storage, solar, and wind to generate electricity. Figure 5.1 depicts DTE Electric’s capacity and generation by resource type using the most recent complete annual data from the U.S. Environmental Protection Agency’s (EPA) Emissions & Generation Resource Integrated Database (eGRID) (eGRID 2023). The pie chart on the left side of Figure 5.1 represents capacity (i.e., how much electricity is available to be produced by each generating resource and resource type), and the pie chart on the right shows generation (i.e., the actual amount of electricity that was produced by each resource type in 2021—the year with the most recent complete annual data from eGRID).

Of the generating resources presented in Figure 5.1, certain units are dispatchable meaning that they can be flexibly operated or called upon to operate when needed (i.e., they can be operated when electricity demand is high and shut off when electricity demand decreases). Other generating units are not dispatched. They either run all the time, like nuclear power plants,



Data Source: eGRID (2023)
Notes
1. Percentages represent the total megawatts of nameplate capacity by resource type.
2. Percentages represent total megawatts generated by each resource type.

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Figure 5.1: DTE Electric's 2021 Capacity and Generation Mix

or they produce electricity when the sun is shining or the wind is blowing. Because nuclear and renewable sources do not meet all of its customers' electricity demand, DTE Electric operates its dispatchable units to cost effectively make up the difference between nuclear and renewable generation and customer demand.

5.1.1 The DTE Electric IRP

Under Michigan Public Service Commission (MPSC) regulations, regulated power companies must submit an Integrated Resource Plan (IRP) every five years. This plan is required to include projections of customer demand and strategies to ensure generation reliability. The 2022 DTE Electric IRP includes a long-term load forecast, plans for meeting energy and capacity needs, cost estimates for construction and major investments, information on existing resources, strategies for new generation, energy waste reduction, demand response, electric transmission options, compliance with environmental regulations, and an analysis of rate impacts (DTE Electric 2023b).

The primary objective of DTE Electric's IRP is to identify the most reasonable and prudent plan that ensures customer access to reliable and affordable electricity. The process of developing the plan included subjecting numerous alternatives to extensive modeling and analysis. Factors guiding the process included consideration of stakeholder input and compliance with state laws and clean energy goals, as well as consistency with DTE Electric's planning objectives. These objectives include affordability; ensuring the safety, reliability, and resilience of the electricity system; considering customer accessibility and community needs; and prioritizing clean energy sources.

The approach for prioritizing clean energy sources ultimately includes developing 6,500 MW of solar energy, 8,900 MW of wind energy, and 1,810 MW of battery storage in forthcoming decades. The IRP also incorporates the maximum achievable Energy Waste Reduction (EWR) potential identified in the Michigan EWR Statewide Potential Study, deploying conservation voltage reduction/volt-var optimization technology. Examples of these technologies include upgrading residential homes with more efficient appliances, insulating basements and attics, and upgrading commercial buildings with more efficient lighting and HVAC systems. In addition, the IRP also calls for demand programs such as time-of-use rates, peak time rebates, and smart appliance control.

The IRP also includes retiring existing coal fired units and replacing them with natural gas and renewables. DTE Electric intends to cease coal-fired generation operations at Belle River and convert the facility into a 1,270 MW natural gas resource by 2026. The retirement of Monroe Power Plant Units 3 and 4 is slated for 2028 with Units 1 and 2 scheduled for closure in 2032.

Although the initial phase of the 20-year IRP relies on commercially available technologies like renewable energy and lithium-ion batteries, the IRP recognizes that technologies and their costs will evolve over the modeled 20-year period. Emerging technologies, including small modular nuclear reactors, hydrogen, combustion gas turbines with carbon capture and sequestration, and various forms of mid- to long-duration energy storage are expected to play a crucial role in supporting the transition toward achieving net-zero emissions while ensuring reliability and affordability.

In considering this aspect of the generation portfolio, DTE Electric developed “technology readiness levels” that indicate the maturity level of different technologies. The nine levels are as follows: 1-3 basic research, 4-5 technology development, 6 technology demonstration, 7-8 system commissioning, and 9 commercialized.

Small modular nuclear reactors (SMR) offer carbon-free nuclear power generation. SMRs employ new technologies like factory-built modules and built-in safety features. SMRs provide 24/7 power generation and have the capability to follow load fluctuations. Although the DTE Electric IRP indicates a capacity limit of 300 MW, the Nuscale website markets one of its newest versions of their SMR options as generating up to 924 MW. Generation III SMRs use traditional light water cooling, while Generation IV utilizes molten salt, liquid metal, or high-temperature gas-cooled technology. DTE Electric rated Generation III SMRs from 4 to 6 and Generation IV from 1 to 5.

Hydrogen can serve as a low-carbon fuel and a means of long-duration chemical energy storage. Hydrogen can be produced through electrolysis using renewable resources or alternative methods fueled by natural gas with carbon sequestration or nuclear power. Hydrogen can be used in fuel cells or blended with natural gas to generate electricity. DTE Electric rated the capacity for 100% hydrogen generation from 1 to 5 and rated a 30% hydrogen blend from 6 to 8.

Carbon capture and sequestration captures 90% to 98.5% of CO_2 from flue gas emissions of power plants (e.g., combined cycle gas turbine) using chemical or physical solvents, sorbent materials, or other technologies. The CO_2 is then utilized for other purposes or stored in geologic formations. DTE Electric rates the first-generation technology for CO_2 capture at a 9 and second generation form 4 to 6.

Mid- to long-duration storage technologies provide grid flexibility to support intermittent energy resources. These technologies utilize thermal, mechanical, chemical, or electrochemical processes and employ storage materials such as salt, sand, iron, zinc, water, and air. Examples of storage systems include flow batteries; pumped hydro; and batteries utilizing iron, zinc, or sodium. DTE Electric rates the capability for long-duration storage from 1 to 5 and rates mid-duration storage from 6 to 9.

The IRP also includes a low or zero-carbon, dispatchable resource of 946 MW in 2035. This resource is currently planned to be a natural gas combined cycle turbine with carbon capture and sequestration (CCGT with CCS).

5.1.2 Power System Modeling Approach

Veritas evaluated the potential power system effects of new nuclear energy in Michigan using EPSM (Veritas Economics 2011). EPSM is a sophisticated electricity modeling system that has been applied in several national analyses and scores of peer-reviewed, plant-specific studies. EPSM is populated with data from eGRID which provides annual data on power plant generation and emissions and is available on the U.S. EPA website (eGRID 2023). The eGRID data is organized by year, state, and plant. EPSM uses the following two specific eGRID data sources:

- The most recent unit year data, which gives readings for individual units of a plant, and
- The most recent generator year data, which gives readings for generators in each plant.

The Unit dataset provides unit descriptors, the unit's operational status, the primary fuel type, annual readings of heat input in MMBtus, annual NO_x emissions in tons, annual SO_2

emissions in tons, and CO_2 emissions in tons. The Generator dataset provides the same descriptor variables, as well as the generator nameplate capacity in megawatts, generator capacity factor, and generator annual net generation in megawatt hours. EPSM solves at the hourly level by dispatching thermal units to most cost effectively meet the load anticipated for each hour of a year.

Operating EPSM to evaluate policy and strategy decisions requires specifying scenarios that represent possible generation systems: in this case, a Baseline scenario that represents expected units and operations in 2036 based on the DTE Electric IRP. It also includes a Counterfactual scenario in which a hypothetical nuclear plant becomes operational in 2036. Comparisons of system reliability and economic outcomes across the two scenarios are used to evaluate the power system implications of the hypothetical nuclear plant.

5.1.3 Baseline Power System Model

The Baseline power system model consists of a representation of demand and supply conditions over time. For this evaluation, the period selected for evaluation is 2036. This timing ensures sufficient time for a nuclear plant to be constructed and installed. This subsection describes the Baseline demand specification and the Baseline generation supply across generation categories of nuclear, renewable, and fossil-powered plants.

5.1.3.1 Baseline Demand

Baseline demand is hourly load for 2036. This is not available and therefore must be estimated. Estimation of the 2036 hourly load is based on projections from the most recent available hourly load. DTE Electric is in MISO Local Resource Zone 7 (LRZ 7) and hourly load from LRZ 7 is the best publicly available load shape data for DTE Electric. However, because LRZ 7 includes most of the lower peninsula, the load is greater than the DTE Electric load. To create the DTE Electric 2023 hourly load, the MISO LRZ 7 hourly load is scaled to reflect peak demand of 11,250 MW and total electric load of 45,230 GWh. Figure 5.2 presents the 2023 specified hourly load.

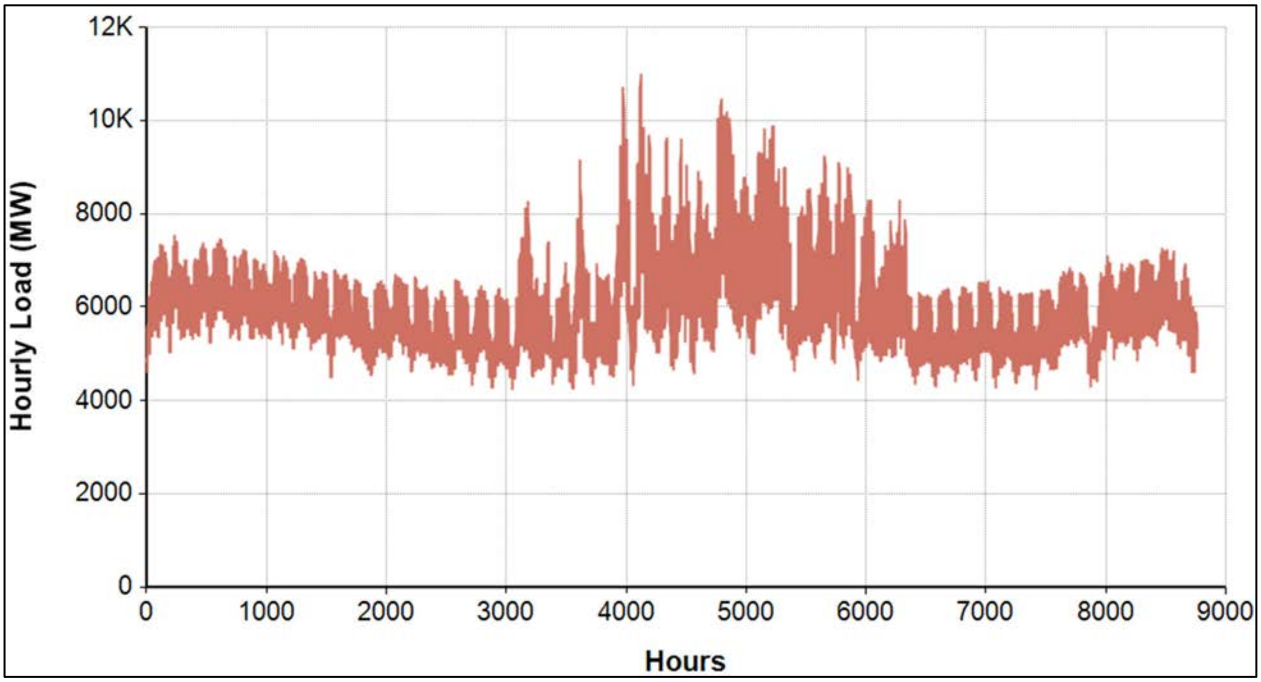

Figure 5.2: DTE Electric Modeled Hourly Load for 2023

The estimated 2036 hourly load is extrapolated from the 2023 hourly load based on expected electricity demand as described in DTE Electric's IRP. DTE Electric load projections include considerations of the Michigan Energy Waste Reduction (EWR) Statewide Potential Study. This study identifies a maximum 2% annual energy waste reduction in 2023 and then an average of 1.5% annual savings through 2027. The IRP also identifies innovative technologies that reduce energy waste in combined cycle systems, accounting for a 15 MW load reduction. Between 2027 and 2032, the DTE Electric IRP identifies 1.2% annual energy efficiency savings. These are again consistent with the maximum annual energy savings identified in the Statewide Potential Study. The IRP also identifies an additional incremental 23 MW of load reduction through innovative supply side activities.

Hourly load consistent with the most recent historical hourly patterns and the forecast of gross and peak load for the period 2023 to 2036 were developed. Figure 5.3 depicts modeled hourly load for 2036. As described in its IRP, DTE Electric is intending to integrate significant amounts of renewable generation by 2036. Because solar and wind generation sources cannot create electricity on demand, this introduces the importance of modeling net load – load with renewable generation subtracted away. Removing renewable generation to calculate net load results in changing load patterns and introduces uncertainty beyond what is already in the

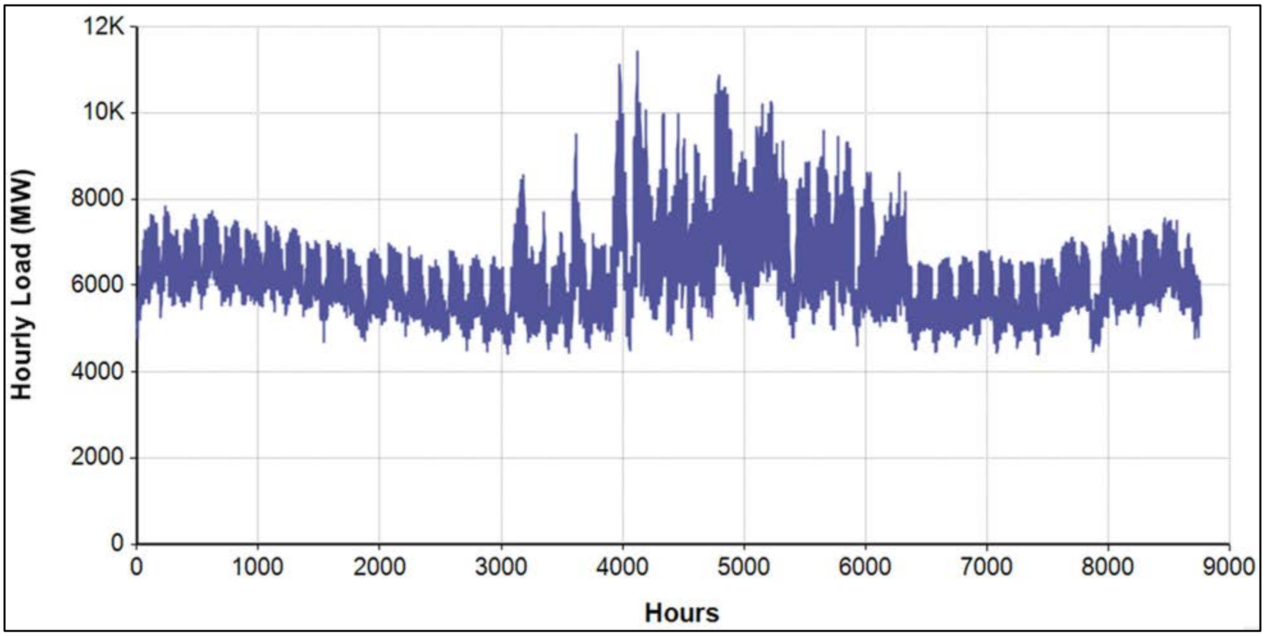

Figure 5.3: DTE Electric Modeled Hourly Load for 2036

demand-based load. The following subsections describe how we evaluated the baseline supply of solar and wind to model net load.

5.1.3.2 Baseline Supply—Solar

DTE Electric currently owns and operates 65 MW of solar assets in Huron, Lapeer, Livingston, Macomb, Monroe, Oakland, St. Clair, Tuscola, Washtenaw, and Wayne counties. According to the DTE Electric IRP, the company is planning to increase solar capacity by 6,000 MW by 2036 (MPSC 2022). Operating EPSM to identify power system emissions requires hourly estimates of output from renewables. Because this information is not publicly available, hourly generation from solar was estimated.

Factors that influence solar output including irradiance, clouding, and precipitation vary by location. To account for location effects, the power system modeling employs a geographic analysis that identifies potential solar locations and estimates their hourly generation. Figure 5.4 presents annual average horizontal solar irradiance estimates for Michigan's lower peninsula. As the figure shows, the southeast region of lower Michigan has a higher average annual solar irradiance than the rest of the state. Higher irradiance improves solar panel performance, meaning solar farms located in southeast Michigan will produce more electricity per unit of capacity than farms located in other parts of Michigan. Clouding and precipitation vary geographically and can also affect solar output. Figure 5.5 shows the Normal Annual Snowfall in Lower Michigan from 1991–2020.

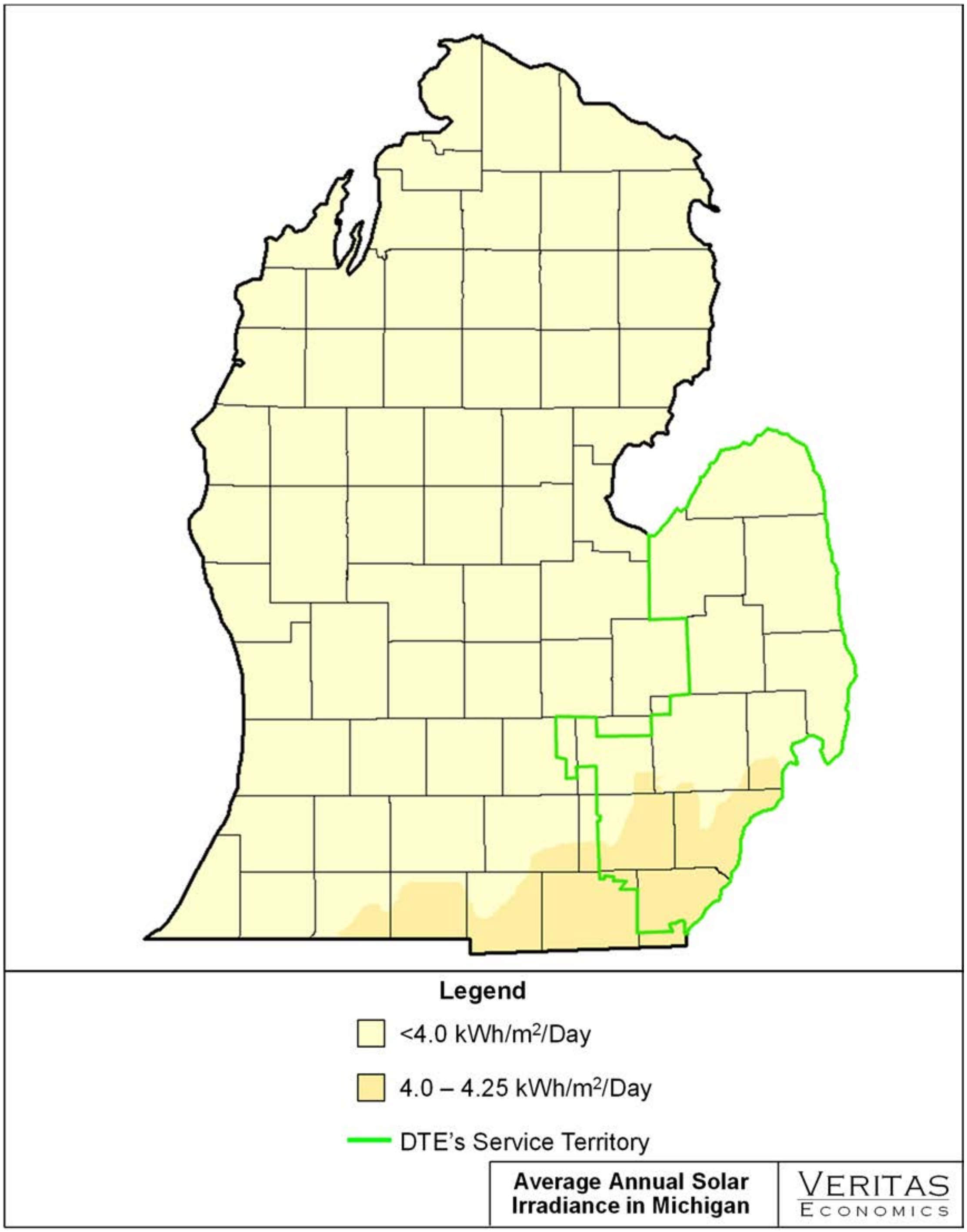

Figure 5.4: Michigan Annual Average Solar Irradiance

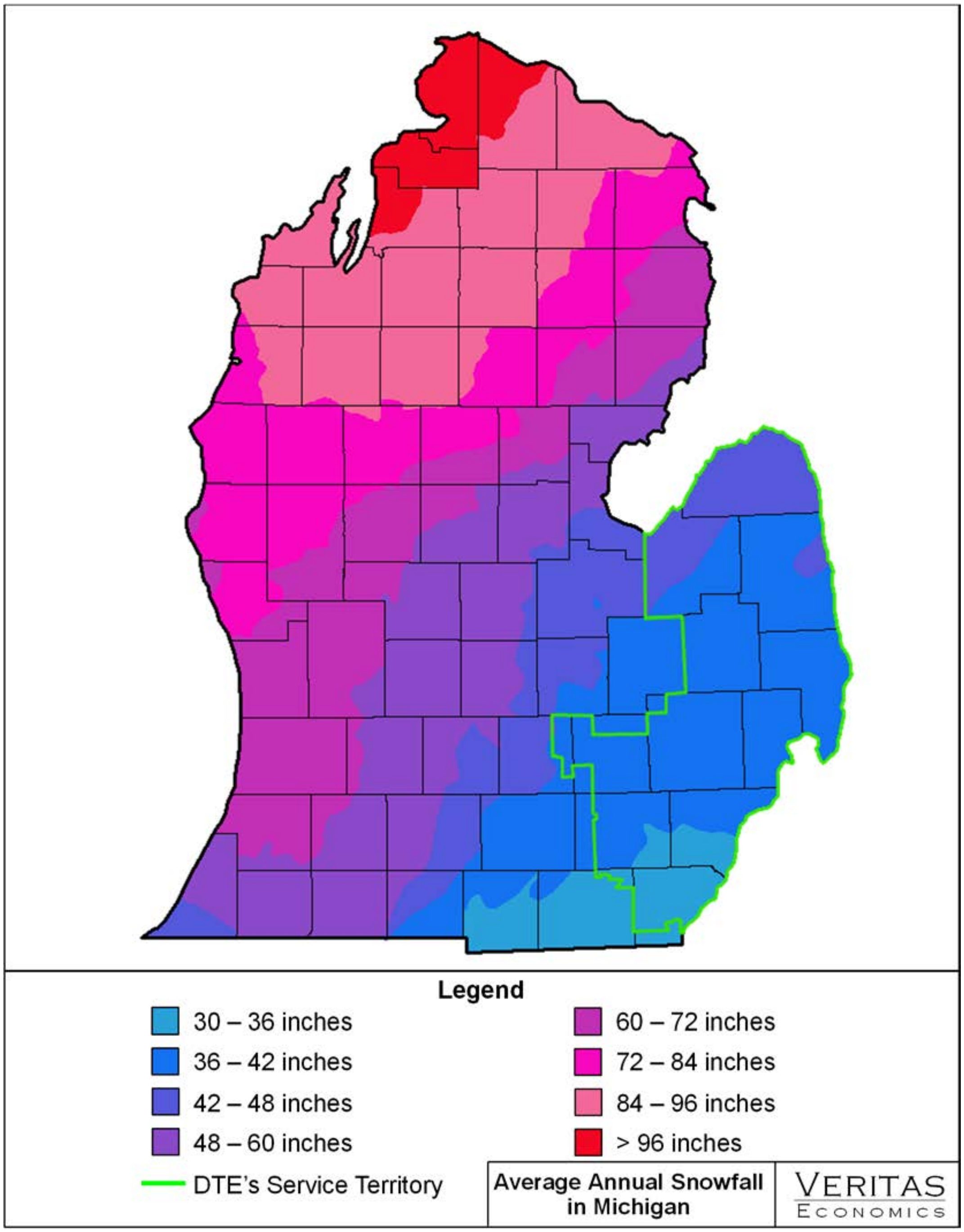

Figure 5.5: Annual Snowfall in the Midwestern United States

Snowstorms and snow accumulation affect solar panels' electricity output. Like all precipitation, snowstorms are accompanied by clouds that block the sun. After the storm passes, the snow must either be removed or melt before the solar panel can resume producing electricity. As Figure 5.5 indicates, annual snowfall varies widely across the lower peninsula of Michigan with the southeast corner receiving the least snowfall.

Based on irradiance and snowfall considerations, the most efficient location for solar efficiency is in southeastern Michigan. However, solar farms require 5-10 acres per megawatt of capacity (Michigan State University Extension & Graham Sustainability Institute University of Michigan 2021). Based on this requirement, DTE Electric's solar expansion will occupy between 26,200 and 52,400 acres by 2036. Although smaller solar farms may be located on capped landfills, brownfields, or rooftops of large buildings, the combination of these space requirements and geographically varying output highlight the importance of considering the availability of appropriate locations.

Figure 5.6 depicts solar potential in eastern Michigan from the Argonne National Lab Energy Zone Mapping Tool. The EZMT considers system performance, topographic limitations, and environmental and land-use constraints (EZMT 2023). As Figure 5.6 indicates, the highest solar potential is in the "thumb" portion of eastern Michigan where the solar farms are outside the snowbelt, maximizing the annual solar irradiance, and in areas with lower population densities where there is more available land.

Based on this evaluation, locations for the planned 6,000 MW of capacity increase were specified at the county level based on solar potential, and generation was modeled based on county-specific meteorological conditions (MPSC 2022). Considering solar potential, capacity by county was specified based on ratios of total acreage by county to potential, resulting in the specification in Table 5.1.[7]

Table 5.1
Specified DTE Electric's 2036 Solar Capacity by County

County	Capacity (MW)
Monroe	692
Wayne	497
Washtenaw	1063
St. Clair	1208
Lapeer	1003
Sanilac	784
Tuscola	609
Huron	144

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[7] Qualitative potential ratings were made numeric as follows: High = 1, Medium-High = 0.75, Medium = 0.5.

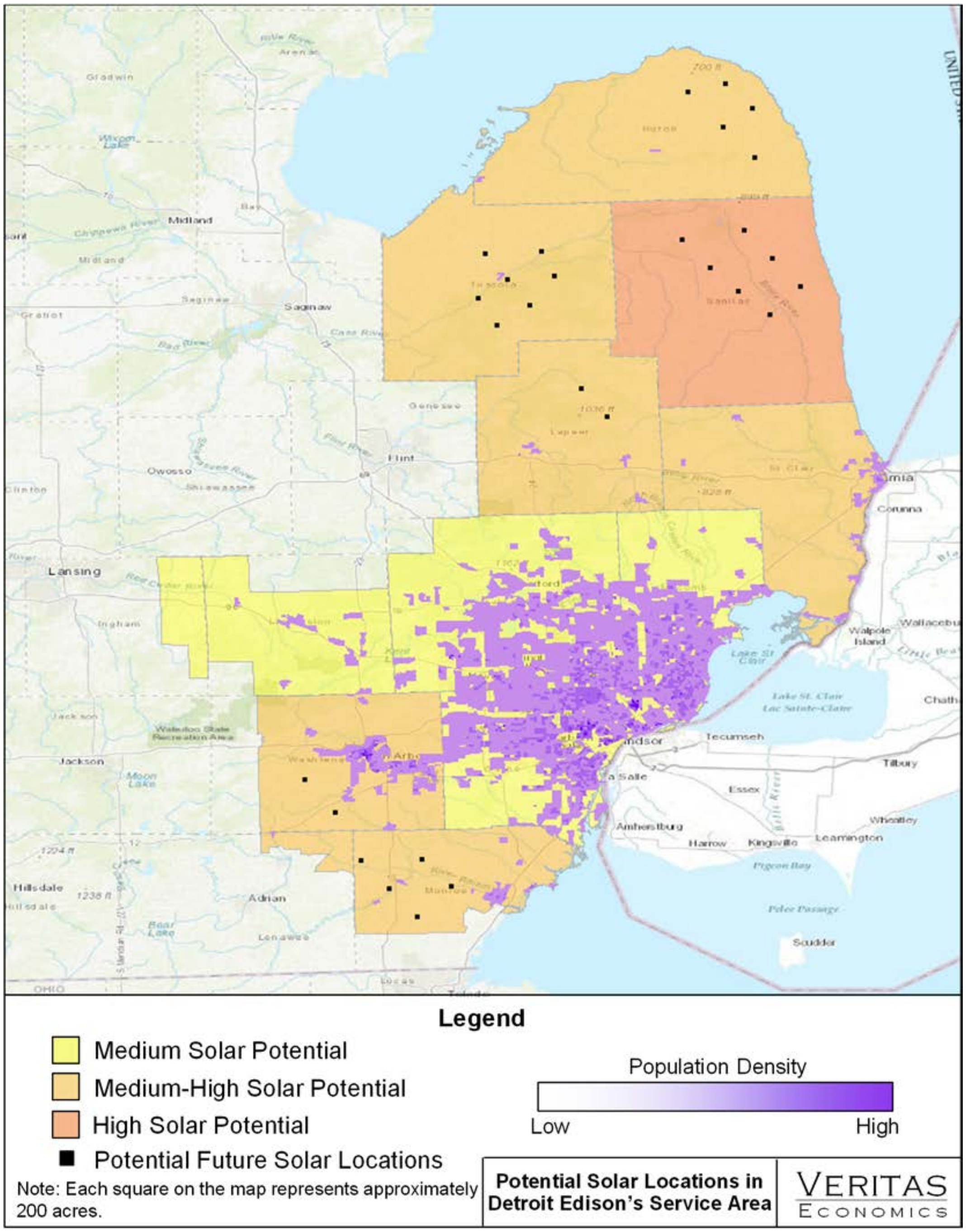


Figure 5.6: Eastern Michigan Solar Potential

To model baseline solar output, the analysis used location-specific Typical Meteorological Year (TMY) weather data from the National Renewable Energy Lab's National Solar Radiation Database (NSRDB) for each of the counties in Table 5.1. Hourly generation from each county was then summed to estimate hourly solar output as depicted in the figure below.

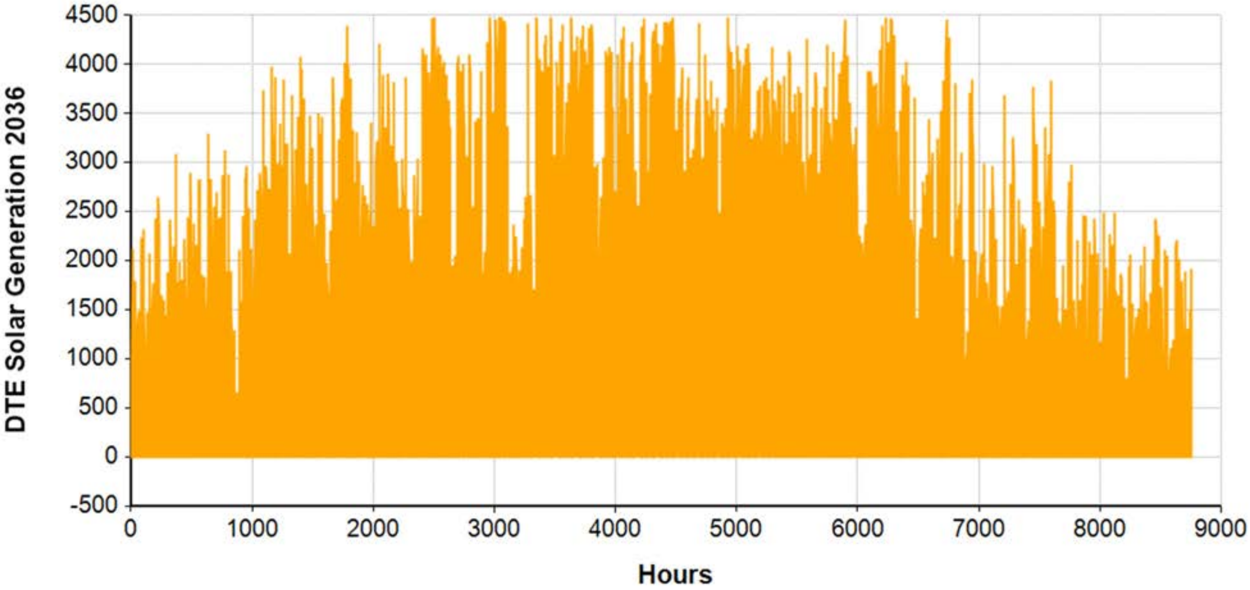


Figure 5.7: DTE Electric 2036 Solar Generation

5.1.3.3 Baseline Supply—Wind

DTE Electric currently utilizes 1,666 wind turbines to provide approximately 3,500 MW of wind generating capacity. These turbines are primarily located in the Lower Peninsula's "thumb" where wind resources are abundant, and land is available. Current wind farm locations are depicted in the Figure 5.8.

Generation from wind farms is determined by meteorological conditions and turbine characteristics. Generation from existing wind farms was predicted based on nearby average hourly wind speeds, blade length, and turbine efficiency. Blade length is used to calculate the swept area of each turbine. Combined with capacity limitations and hourly wind speed, this is used to estimate output from DTE's 1,666 turbines.

According to the DTE Electric IRP, DTE is intending to integrate an additional 3,400 MW of wind generated electrical capacity by 2036 (MPSC 2022). Because the turbine specifications and locations for this new generation are not yet known, their hourly generation is predicted based on an evaluation of evolving turbine characteristics and location-specific wind energy.

The amount of wind energy captured by a turbine is directly related to the area swept by its blades. Because this increases by the square of its radius, there are exponential returns to larger turbines, and manufacturers are producing increasingly longer turbine blades. The largest turbines with blades of up to 100 meters are being used for offshore wind. The Great Lakes region has a great deal of potential offshore wind energy; however, the narrow locks of the St. Lawrence Seaway and the Welland Canal limit the passage of large ocean vessels required for installing

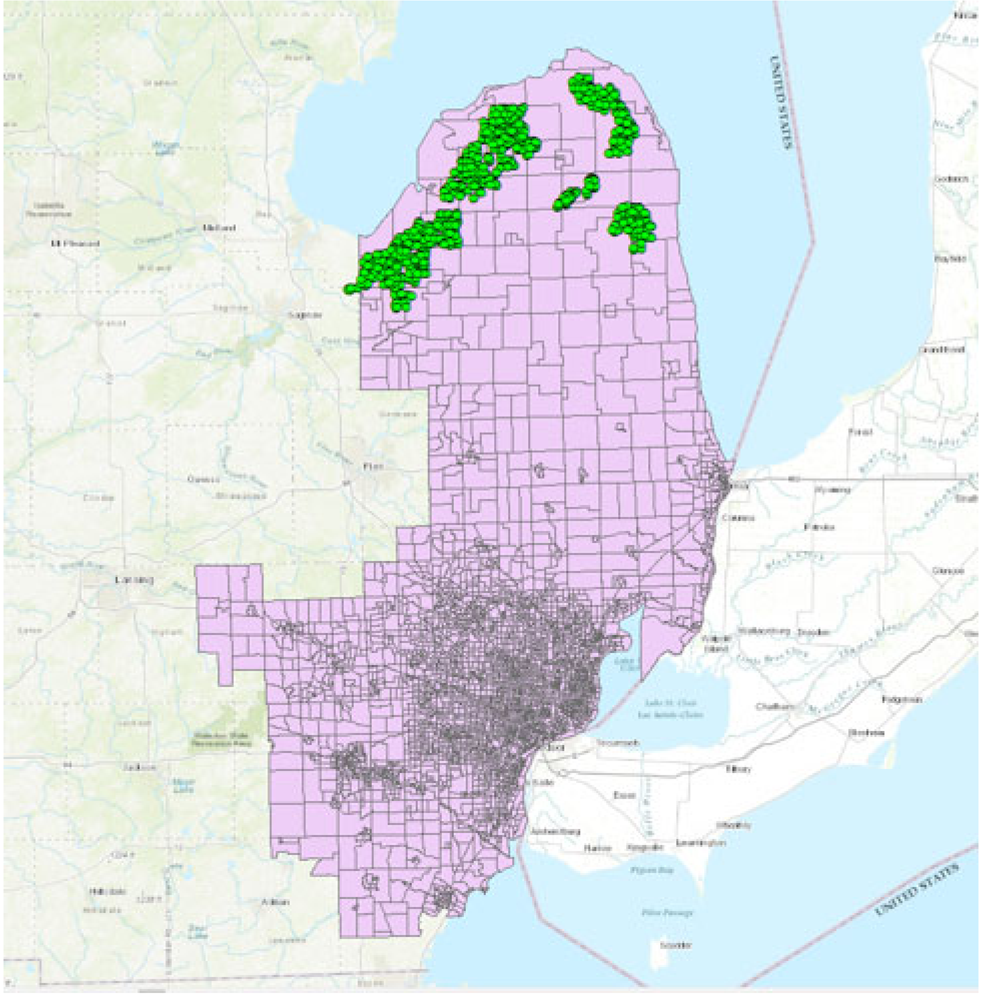


Figure 5.8: DTE Electric Territory and 2023 Windfarms

fixed bottom offshore wind turbines. Additional concerns include lakebed disruption, visibility from shore, icing, and wildlife-turbine interactions.

Given the timeline for this evaluation and the fact that the National Renewable Energy Lab has targeted 2035 for commercial viability of offshore wind in the Great Lakes, this analysis evaluates onshore wind. Under the assumption that the new turbines will be land based, the main size constraint is from transportation. The three main constraints are blade length, width, and height. In addition, each state has weight or length limitations (or both) for transporting freight on state roads (U.S. Federal Highway Administration 2019). Railroads also have rules for general dimension of freight and weight limitations (Norfolk Southern 2023; Union Pacific Railroad undated; U.S. Army undated). Because most land-based wind turbine blades are transported by road and rail, routes are analyzed to assure that the blade has the necessary clearance because access to certain areas can be limited.

Although turbines will continue to get larger as manufacturing efficiencies are harnessed to achieve lower levelized electricity costs, physical limitations for transportation will remain and are expected to limit turbine size. For this reason, forthcoming wind farms are modeled based on the dimensions of the largest turbines at DTE Electric’s most recent installation, the Meridian Wind Park. The largest turbines at this park are the Vestas V136 which have 66.7 meter blades and a capacity of 3.45 MW.

The implication of using turbines of similar size to achieve DTE Electric’s IRP goal of adding 3,400 MW of wind generating capacity is that there will be an additional 1,205 turbines (MPSC 2022). These turbines would be sited in locations with strong wind resources, low population density, and grid connections. A detailed study on the availability of suitable locations to site these turbines was not possible for this study. Turbine locations are specified based on professional judgement that considers wind resources and population density. The amount by county is depicted in the table below.

Table 5.2
Specified DTE Electric Future Wind Generation by County

County	Capacity (MW)
Huron	340
Isabella	1020
Delta	340
Gratiot	1020
Wexford	680

With information specified as described in Table 5.2 and per-turbine output calculated, the total hourly output from these wind farms is calculated, summed, and added to the appropriate year and hour of generation.

5.1.3.4 Baseline Supply—Net Load

Electric utilities traditionally endeavor to reliably meet electrical load at lowest cost. Because daily customer load in the DTE Electric region typically reaches its highest point in the early evening, this results in a consistent pattern of operations in which more expensive units are called upon over the afternoon until peak load is met in the early evening, and, once it has passed, these units are successively shut down.

However, unlike these traditional dispatchable resources that can be called upon when needed, the electrical output from wind and solar is not under direct utility control and can only be predicted. This means that as more renewables join the grid, the character of the load that must be met by dispatchable resources changes. As a result, load with renewable generation subtracted away or net load becomes the more relevant target. By 2036, DTE Electric's net load changes will result in a lower total amount of dispatched generation, a change in the timing of peak load, overall more variable load targets, and the potential for negative net load. Figure 5.9 depicts the modeled hourly net load for DTE Electric for 2036.

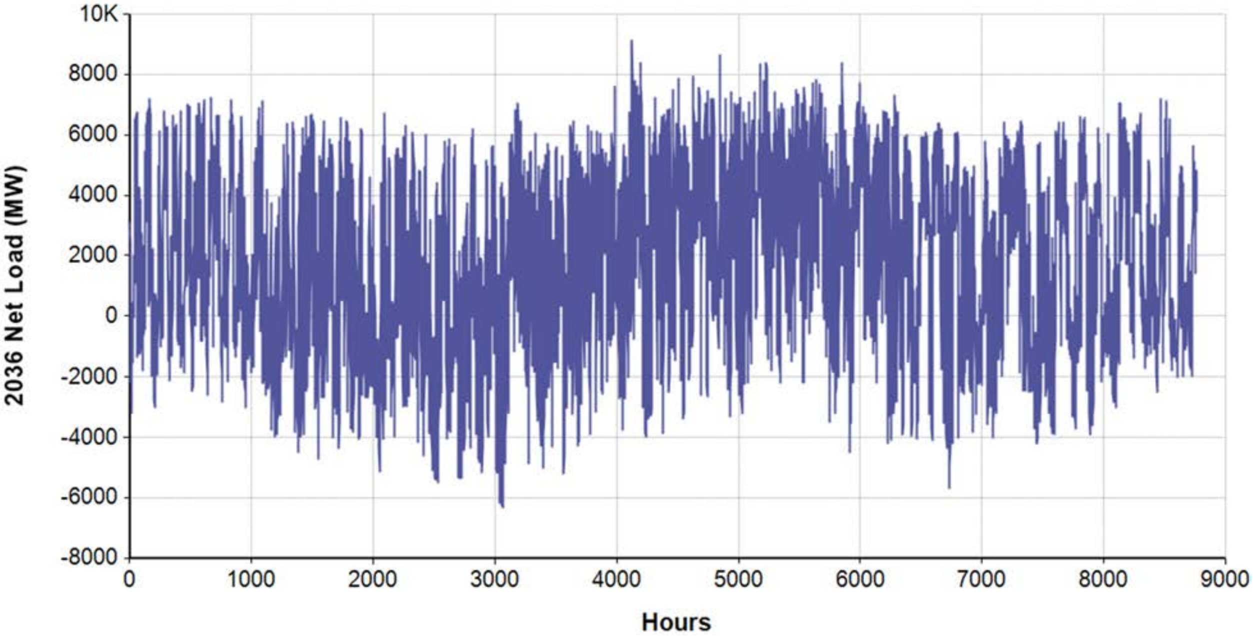


Figure 5.9: DTE Electric Modeled Net Load—2036

5.1.3.5 Baseline Supply—Storage

Integration of large amounts of renewable generation into DTE Electric's territory has implications for system operations because changes in DTE Electric's resource mix will alter the net load profile. Net load will be met using a combination of dispatched generation and storage. This section discusses storage. Storage and dispatchable units are similar in that both can offer electricity to the grid at the desire of the system operator. Storage differs in that it takes electricity from the grid and that it has a limit in terms of the amount of capacity that can be used in any given period.

Storage can potentially occur over different time frames, but because of the diurnal nature of electricity load, storage is often charged and discharged over a 24 hour period. The role of storage for meeting predictable peaks is best illustrated through an exposition of net load in a single 24 hour period. The figure below depicts specified hourly net load for a summer day in 2023. As this figure indicates, load currently tends to be lowest in the early morning hours and then increases over the day until six in the evening when it peaks and then begins to decrease again.

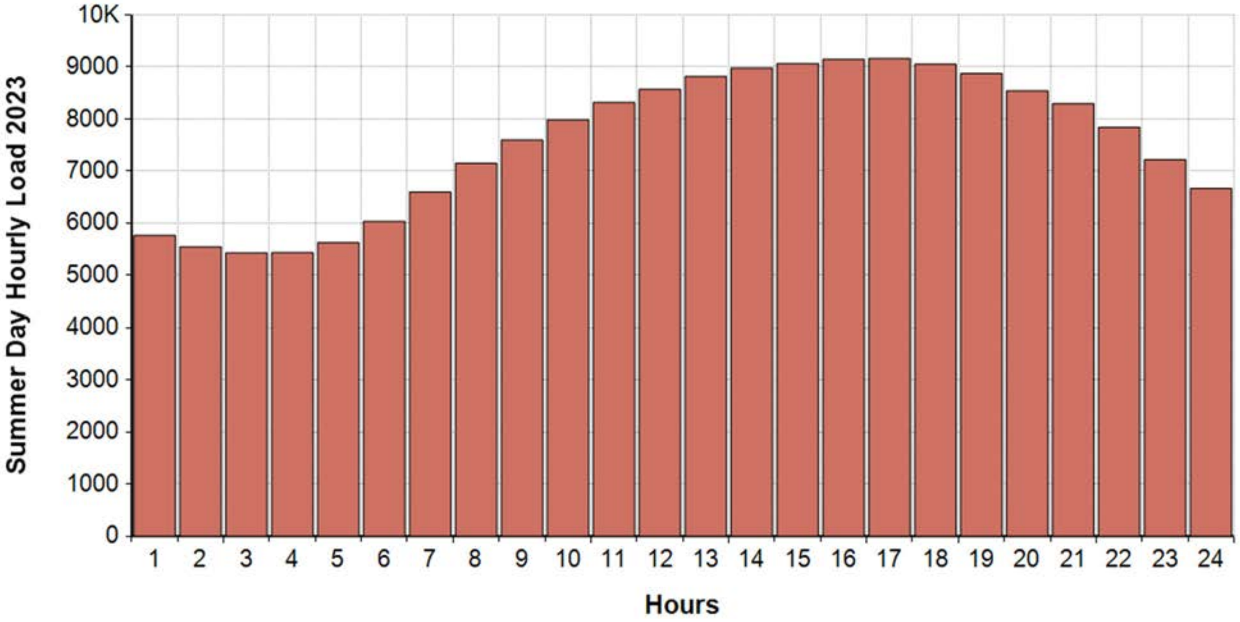


Figure 5.10: DTE Electric Summer Day Typical Load—2023

By 2036, DTE Electric plans to add an additional 3,400 MW of wind generation and 6,000 MW of solar generation (MPSC 2022). Consistent with the net load concept, DTE Electric will predict output and subtract it from load when planning system operation. Figure 5.11 depicts estimated wind output for a summer day in 2036, and Figure 5.12 depicts estimated additional solar output.

As these figures indicate, wind production varies throughout the day, whereas solar production tends to be highest around midday and early afternoon. When solar and wind generation are subtracted from the load to produce net load, the load becomes more variable and peak net load moves to the evening. Figure 5.13 depicts net load for a typical summer day in 2023 and 2036.

This difference will be met with some combination of storage and dispatched resources. DTE Electric co-owns the Ludington Pumped Storage Plant (Ludington) with Consumers Energy. This hydroelectric facility serves as long-duration storage. It consists of a man-made reservoir and turbines that can operate as pumps during times of excess energy and as generators during periods of high demand and limited renewable energy availability.

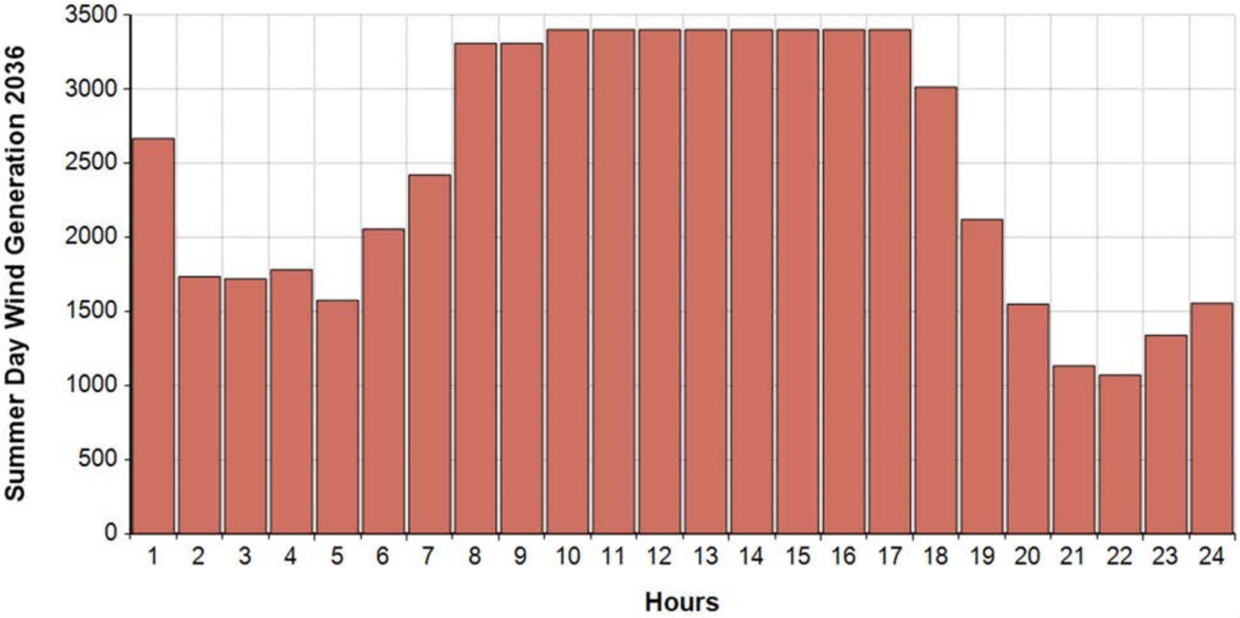


Figure 5.11: DTE Electric Summer Day Additional Wind Generation—2036

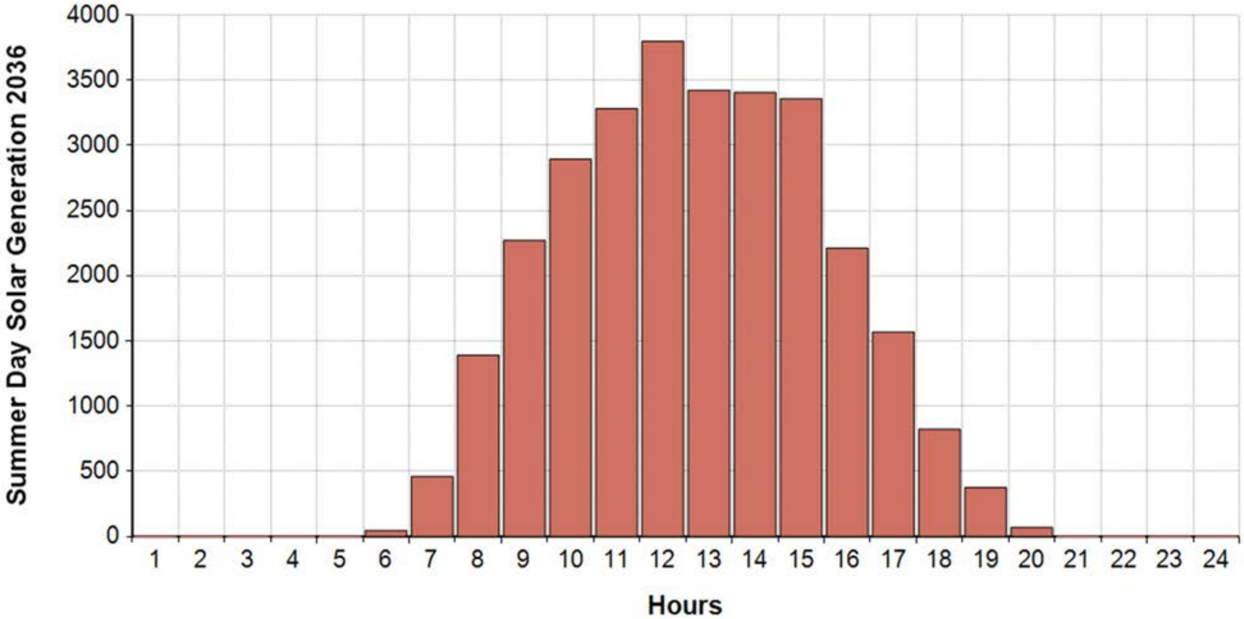


Figure 5.12: DTE Electric Summer Day Additional Solar Generation—2036

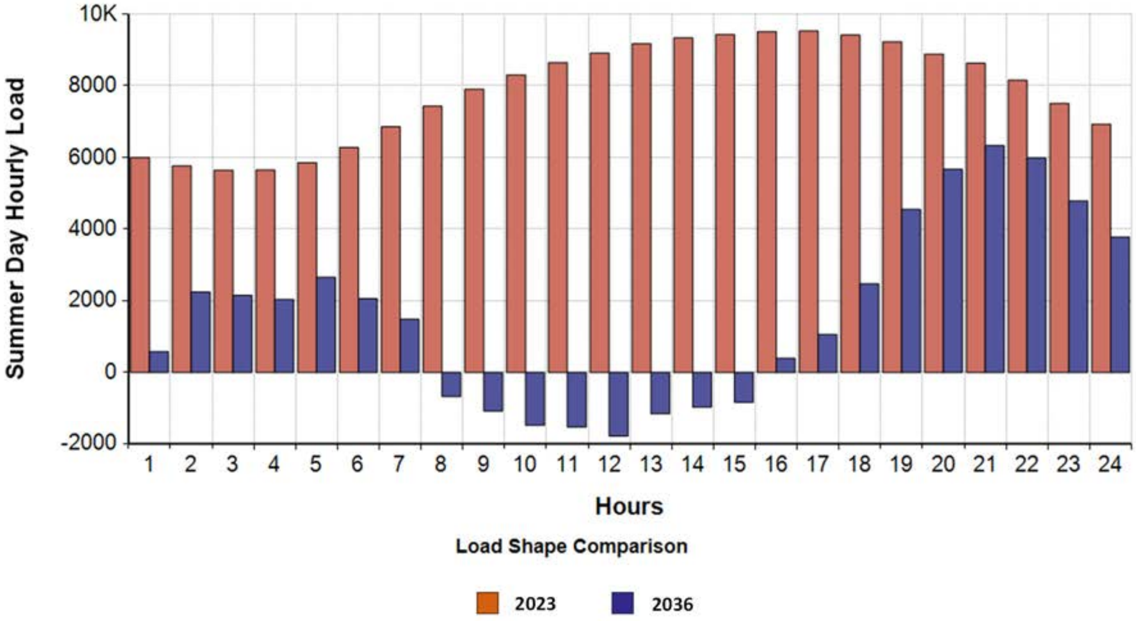


Figure 5.13: DTE Electric Modeled Net Load

DTE Electric is also planning significant capacity of new storage. The company's immediate focus is on lithium-ion batteries. The initial pilot battery energy storage project is a 14 MW lithium-ion battery at the Slocum peaker site. It aims to replace five diesel peaker engines. The Slocum battery energy storage pilot is slated for completion in 2024, with 56 MWh of storage capacity. In addition to this pilot project, the IRP includes an additional 360 MW in the first five years, and 1,200 MW in the second five years totaling 1,560 MW of additional storage prior to 2036 (MPSC 2022).

In traditional electrical systems served by dispatchable resources, energy storage systems such as Ludington typically reduce system costs by using electricity during periods of low demand when electricity is less expensive and generate electricity during peak periods when it is more expensive. Although storage systems use more electricity than they create, this strategy allows them to be cost-effective. As electric systems integrate large amounts of renewable electricity, electricity storage has an additional advantage in addressing the intermittency of renewable generation. Intermittency refers to difficult-to-predict, moment-to-moment variation in output. This occurs with solar due to precipitation and cloud cover and with wind electricity to due changes in wind velocity.

The degree of intermittency can be estimated by evaluating short term changes in renewable output. Figure 5.14 depicts hour-to-hour changes in wind generation that are calculated from the estimation of hourly wind generation..

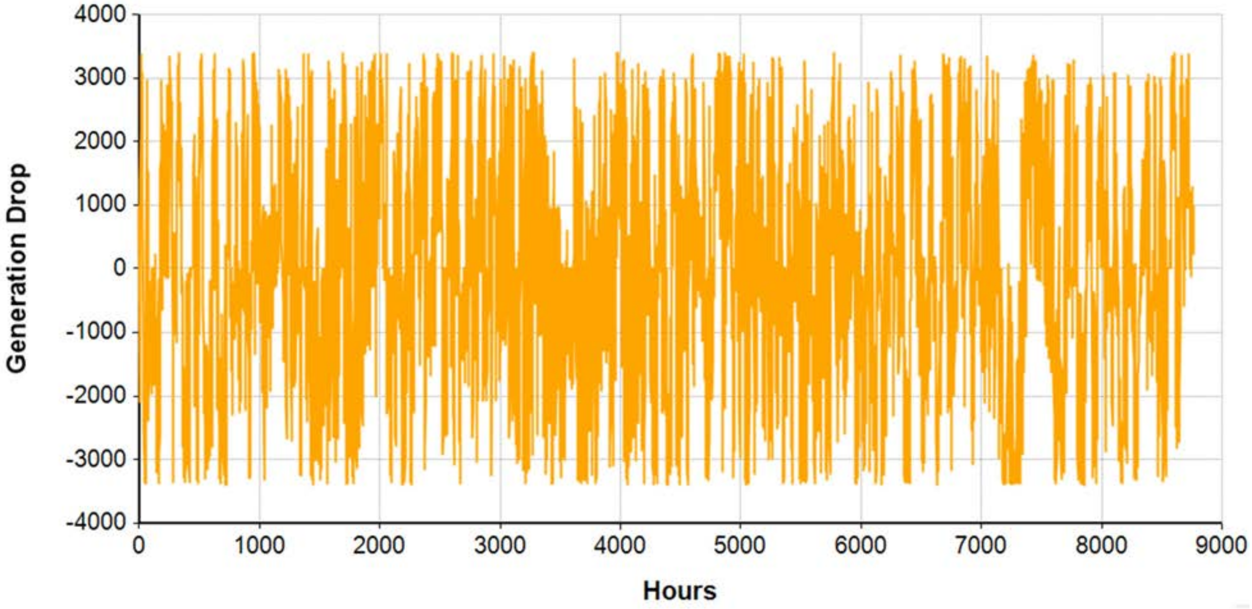
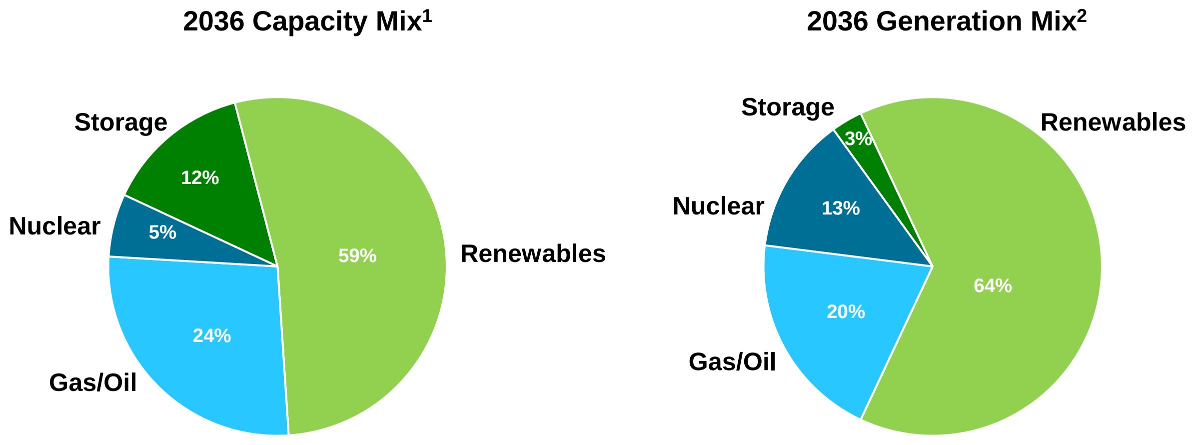


Figure 5.14: Hourly Wind Generation Differences

As Figure 5.14 indicates, there is the possibility of very large (e.g., over 3,000 MW) generation changes over an hour. This result is presented at the hourly scale over which the system modeling is conducted. However, this effect also occurs over shorter time frames (i.e., within hours). Intermittency is even more relevant over shorter time frames when ramping constraints are most severe. Because fossil power plants do not start instantly, traditional dispatchable resources must be kept in spinning reserve to meet this function. When fossil plants are in spinning reserve status, they are expected to bring generation online in minutes if called upon. To fulfill this function, plants are either outputting power, but not at full capacity, or they are spinning and ready to be synchronized and generating. There are incremental costs associated with a fossil fueled unit remaining in either of these states. Batteries are an excellent alternative because they output power on very small time scales and do not incur incremental costs when not operating.

5.1.3.6 Baseline Supply—Dispatchable Units

DTE Electric will operate its fossil and dispatchable capacity to meet load net of renewables (solar and wind) at lowest cost. Figure 5.15 presents the modeled capacity and generation for DTE Electric in 2036 using the results of the net load evaluation. The pie chart on the left depicts the planned capacity mix by generation type, and the pie chart on the right depicts DTE Electric’s expected generation mix for 2036.


2036 Capacity Mix[1]

2036 Generation Mix[2]

Data Source: eGRID (2023); MPSC (2022); EPSM (Veritas Economics 2011)

Notes

1. Percentages represent the total megawatts of nameplate capacity by resource type.
2. Percentages represent total megawatts generated by each resource type.

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Figure 5.15: DTE Electric’s 2036 Capacity and Generation Mix

Based on the results from EPSM, in 2036 approximately 24% of system capacity will be units that are dispatchable. Dispatchable units have typically made up almost all capacity and generation in traditional systems. These can be roughly categorized into baseload, load following, and peaking units. Baseload units are the least expensive to operate and run whenever they are available. These are typically highly efficient coal plants such as Monroe and nuclear plants such as Fermi. Load following units may be older steam plants which are less efficient than baseload plants. Peaking units are the least efficient and most expensive units to operate. These are typically gas turbines or diesel units.

Plant dispatch under Baseline Conditions in 2036 is depicted Figure 5.16. These estimates provide the operation predictions for DTE Electric’s generation in 2036. To estimate the Baseline emissions in 2036, the analysis applies the emission factors to each generating unit and their operation prediction. Having this estimate of Baseline dispatch and emissions allows for direct comparison to Counterfactual conditions that add the hypothetical nuclear plant’s generation. Once the hypothetical nuclear plant is added to the model, the model predicts the reordered dispatch and corresponding emissions. Subtracting these emissions from the Baseline predictions provides the estimate of emission changes resulting from the hypothetical nuclear plant’s operation.

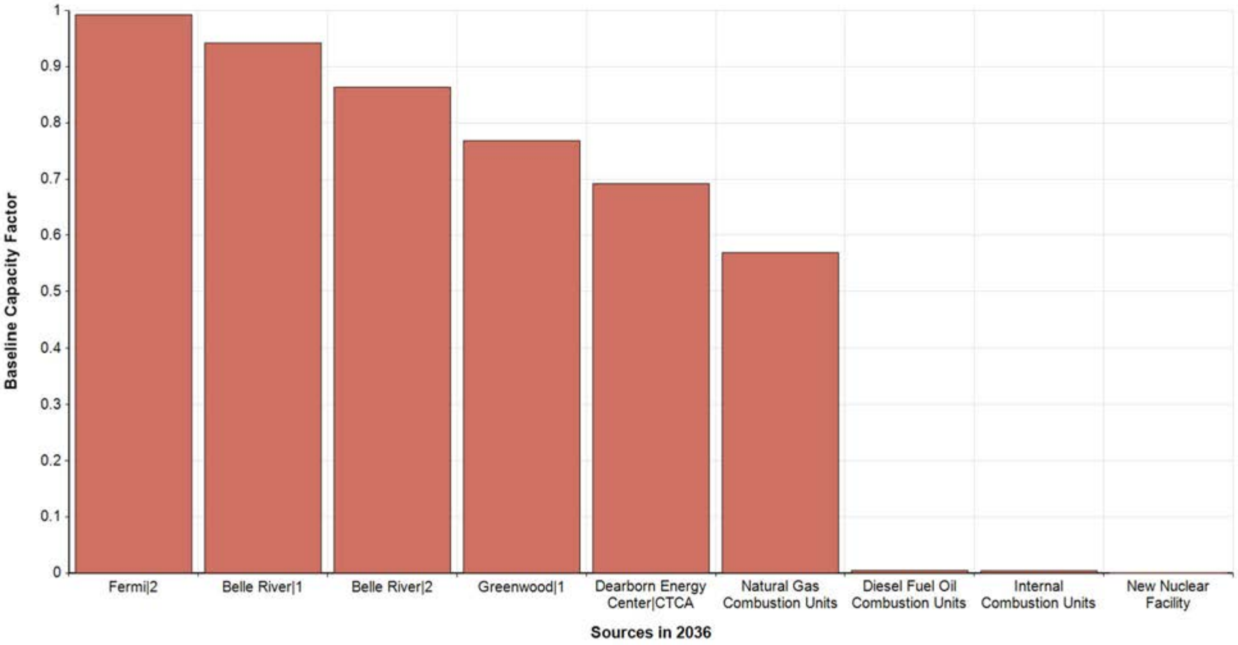
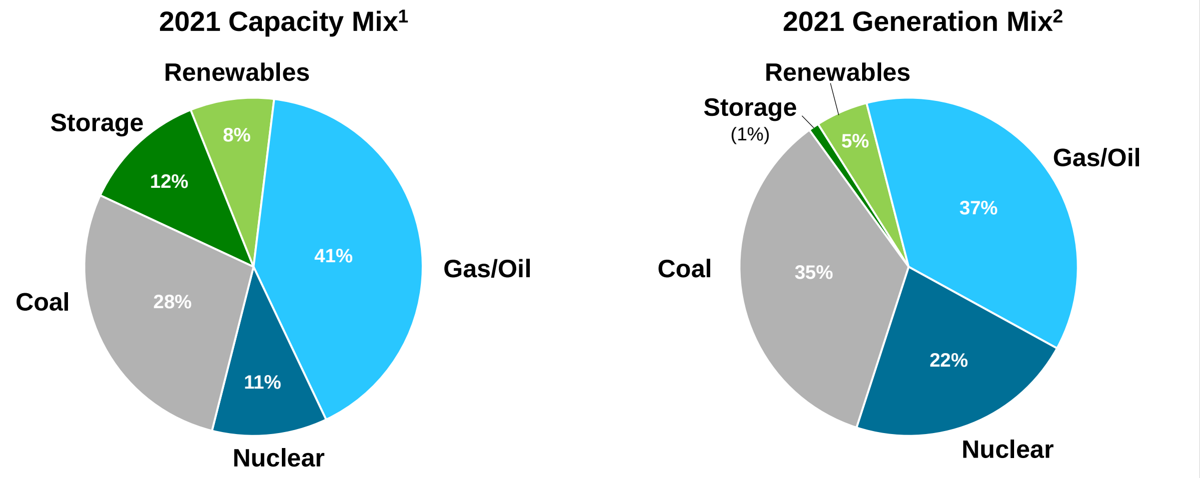


Figure 5.16: DTE Electric's Baseline Plant Dispatch - 2036

5.2 The Consumers Energy Electric System

Consumers Energy serves 1.8 million residential, commercial, and industrial electricity customers (CMS Energy 2023; Consumers Energy 2023a). The company owns and operates an extensive network of distribution infrastructure, encompassing around 87,110 miles of overhead distribution lines and 9,418 miles of underground distribution lines. Consumers Energy provides electric service in 62 counties of Michigan's Lower Peninsula. The analysis modeled Consumers Energy's system using the same approach as the DTE Electric system. This section presents a brief discussion of the power system modeling that was conducted for the Consumers Energy system.

Consumers Energy utilizes a mix of energy sources including coal, solar, wind, hydroelectric pump storage, and natural gas to generate electricity. Figure 5.17 depicts Consumers Energy's capacity and generation by resource type using the U.S. EPA's 2021 eGRID data (eGRID 2023).



Data Source: eGRID (2023)
Notes
1. Percentages represent the total megawatts of nameplate capacity by resource type.
2. Percentages represent total megawatts generated by each resource type.

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Figure 5.17: Consumers Energy's 2021 Capacity and Generation Mix

5.2.1 The Consumers Energy IRP

Consumers Energy's IRP intends to supply cleaner electricity and protect the environment while ensuring that the transition is affordable (Consumers Energy 2021a). The approach for supplying cleaner electricity involves transitioning away from old coal and natural gas plants into newer natural gas plants and renewables while also increasing energy efficiency.

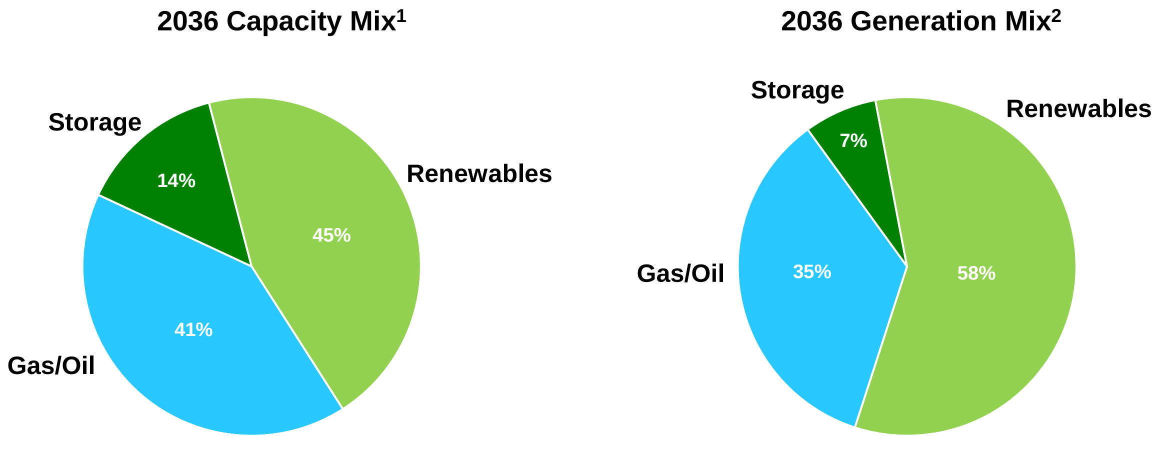
Regarding Consumers Energy's energy efficiency plans, Michigan's peak energy needs are driven by air conditioning. This peak demand has been met by operating fossil fuel power plants on the hottest days of the year. The substantial amount of solar power that Consumers Energy is developing will offset that peak. Energy Waste Reduction (EWR) and Demand Response (DR) will have a further impact. The increased use of demand management tools such as energy waste reduction programs will give customers more control over their monthly energy bills, equipping them to save energy and money over the long term.

Considering storage, mid- to long-duration storage technologies provide grid flexibility to support intermittent energy resources. These technologies utilize thermal, mechanical, chemical, or electrochemical processes and employ storage materials such as salt, sand, iron, zinc, water, and air. Examples of storage systems include flow batteries; pumped hydroelectricity; and batteries utilizing iron, zinc, or sodium. Consumers Energy plans "to achieve operational readiness of batteries by 2030 or sooner to consistently and reliably serve customers peak and off-peak demand," and Ludington will continue to operate during the 20-year planning period (Consumers Energy 2021a, 2021b, 2021c).

5.2.2 Baseline Power System Model

The Consumers Energy IRP describes a vision of the power system through 2040. For this evaluation, the period selected is 2036 which ensures sufficient time for a nuclear plant to be constructed. The Baseline power system model represents demand and supply conditions over this time period. Consumers Energy intends to integrate significant amounts of renewable generation by 2036. Because renewable generation sources cannot create electricity on demand, this introduces the importance of modeling net load—load with renewable generation subtracted away. Net load is modeled using the same approach undertaken for the DTE Electric system.

Figure 5.18 presents the modeled capacity and generation for Consumers Energy in 2036 using the results of the net load evaluation. The pie chart on the left in Figure 5.18 presents the planned capacity mix by generation types in 2036. Consumers Energy will operate its fossil and dispatchable capacity to meet load net of renewables (pumped storage, battery, solar, and wind) at lowest cost. The pie chart on the right of Figure 5.18 presents Consumers Energy's expected 2036 generation mix as predicted by EPSM. Figure 5.19 depicts plant dispatch under Baseline Conditions in 2036. The estimates of plant dispatch provide the operation predictions for Consumer Energy's generation in 2036.



Data Source: eGRID (2023); Consumers Energy (2022); EPSM (Veritas Economics 2011)
Notes
1. Percentages represent the total megawatts of nameplate capacity by resource type.
2. Percentages represent total megawatts generated by each resource type.

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Figure 5.18: Consumers Energy's 2036 Capacity and Generation Mix

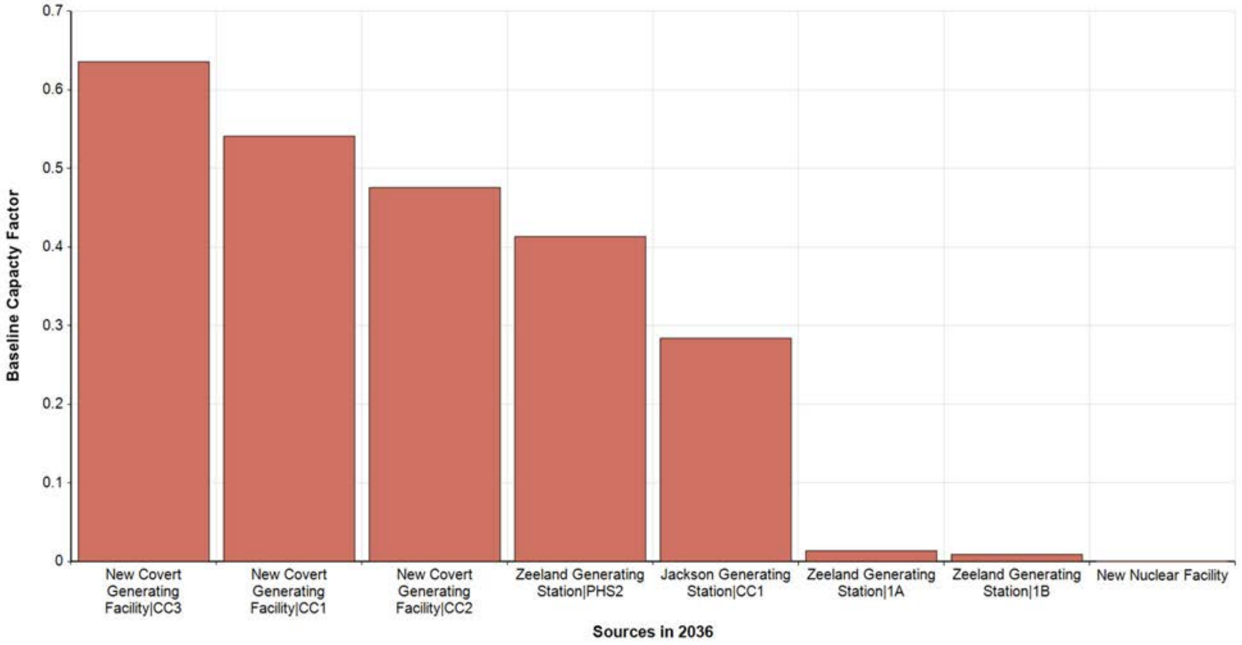

Figure 5.19: Consumers Energy Baseline Plant Dispatch - 2036

5.3 Counterfactual Evaluation–Operating a Hypothetical Nuclear Plant

Counterfactual power system emissions evaluations were conducted for operating a hypothetical nuclear plant in both the Consumers Energy and DTE Electric power systems. In both cases, construction was specified to occur from 2032 to 2035 with operations beginning in 2036. To evaluate the emissions effect, the Counterfactual evaluation incorporates a 720 MW nuclear plant into each power system model in 2036. The model results from the Counterfactual evaluation (with the hypothetical nuclear plant) are compared to those from the Baseline evaluation (without the hypothetical nuclear plant). Differences between the model results produce the estimated impacts from the hypothetical nuclear plant.

For both the Baseline and Counterfactual models, emissions are calculated as the product of per MW emission factors for CO_2, SO_2, and NO_X for each unit and modeled generation for that unit. The emissions effect of the hypothetical nuclear plant is estimated as the difference between total 2036 Baseline and Counterfactual emissions. Table 5.3 presents the resulting change in system-wide emissions for DTE Electric and Consumers Energy in 2036, the year the hypothetical nuclear plant is specified to come online in the power system model.

Table 5.3
Air Emission Reductions with Operating a Hypothetical Nuclear Plant (Tons)

Service Territory	Emission	Annual Reduction in 2036
DTE Electric	Carbon dioxide (CO_2)	365.2K
	Sulfur dioxide (SO_2)	62.4
	Nitrogen oxide (NO_X)	140.5
Consumers Energy	Carbon dioxide (CO_2)	1.2M
	Sulfur dioxide (SO_2)	6.2
	Nitrogen oxide (NO_X)	197.2

As depicted in Table 5.3, CO_2 reductions are nearly three times higher for the Consumers Energy location relative to the DTE Electric location whereas SO_2 emissions are more than ten times higher when the plant is modeled in the DTE Electric system. This difference results from the modeled 2036 power system characteristics for each company. Both companies are pursuing aggressive decarbonization strategies that rely heavily on solar generation. However, DTE Electric has more electricity coming from wind whereas Consumers Energy is intending to rely more on natural gas to serve nighttime load. The Consumers Energy natural gas generation is replaced by nuclear generated electricity resulting in higher CO_2 offset. DTE Electric is also serving more peak load with SO_2 emitting diesel than Consumers Energy. Generation from the hypothetical nuclear plant reduces the operation of the diesel generators, resulting in higher SO_2 reductions when the nuclear plant is modeled within the DTE Electric system.

These emission reduction predictions are the result of a complex power system evaluation, and it is useful to provide context for the estimates. The maximum CO_2 reduction is 1.2 million tons per year, which occurs when the hypothetical nuclear unit is modeled as being in the Consumers Energy system. CO_2 emission factors vary by plant efficiency, and fuel type. However, according to the Energy Information Administration, in 2019 coal-fired generation produced 2,257 pounds of CO_2 per MWh. At this rate, siting the hypothetical nuclear plant in the Consumers Energy system results in a CO_2 reduction that is approximately equal to eliminating the output of a 140 MW coal plant running continuously.

Nuclear power provides additional power system benefits beyond CO_2 reductions. Perhaps most importantly, nuclear power provides a stable and consistent power supply. Unlike solar and wind, nuclear plants can operate continuously, providing a very reliable electricity source to complement renewables. Considered against natural gas plants, power systems with nuclear plants are more diversified and can ameliorate the effects of natural gas shortages and price fluctuations on system reliability and costs. Finally, a new nuclear plant would be very long lived, both due to the nature of the technology and because it would not be subject to environmental pressure due to emissions. As a result, the plant would provide these benefits to the people of Michigan for many decades to come.

6. References

Berkman, Mark, and Dean Murphy. 2015. “Michigan Nuclear Power Plants’ Contribution to the State Economy.” Available at https://d3n8a8pro7vhmx.cloudfront.net/nuclearmatters/pages/518/attachments/original/1623696355/Sep15-Nuclear-Matters-Report_Michigan-Value-of-Nuclear.pdf?1623696355. Retrieved on June 7, 2023.

Black, Geoffrey and Steven Peterson. 2019. “Economic Impact Report: Construction and Operation of a Small Modular Reactor Electric Power Generation Facility at the Idaho National Laboratory Site, Butte County, Idaho.” Prepared for Regional Economic Development for East Idaho (REDI). Boise State University: Idaho Policy Institute; University of Idaho: McClure Center for Public Policy Research. Available at https://line.idaho.gov/wp-content/uploads/2019/02/smr-economic-impact-report.pdf.

Black, Geoffrey A., Faith Aydogan, and Cassandra Koerner. 2019. "Economic Viability of Light Water Small Modular Nuclear Reactors: General Methodology and Vendor Data". Renewable and Sustainable Energy Reviews, 103, 248-258. Available at http://dx.doi.org/10.1016/j.rser.2018.12.041

Carelli, Mario D., and Daniel T. Ingersoll, eds. 2015. *Handbook of Small Modular Nuclear Reactors*. Woodhead Publishing Series in Energy: Number 64. Available at http://www.aben.com.br/Arquivos/350/350.pdf. Retrieved on May 30, 2023.

Clean Energy Ministerial. 2022. “Nuclear Energy—Providing Power, Building Economies.” NREL/TP-6A50-82419. Available at https://www.nrel.gov/docs/fy22osti/82419.pdf. Retrieved on June 6, 2023.

Clifford, Catherine. 2022. “The Energy in Nuclear Waste Could Power the U.S. for 100 Years, But the Technology Was Never Commercialized.” Available at https://www.cnbc.com/2022/06/02/nuclear-waste-us-could-power-the-us-for-100-years.html. Retrieved on June 5, 2023.

CMS Energy. 2023. “Consumers Energy.” Available at https://www.cmsenergy.com/about-cms-energy/consumers-energy/default.aspx#:~:text=Consumers%20Energy's%20Natural%20Gas%20Business&text=It%20serves%20an%20area%20that,includes%20215%20cities%20and%20villages.. Retrieved on October 2, 2023.

Consumers Energy. 2019. “News Release: Consumers Energy Announces Plans to Develop Solar Power Plant in Cadillac.” Available at https://www.consumersenergy.com/news-releases/news-release-details/2019/02/21/consumers-energy-announces-plans-to-develop-solar-power-plant-in-cadillac. Retrieved on October 2, 2023.

Consumers Energy. 2021a. “2021 Clean Energy Plan.” Available at https://www.consumersenergy.com/-/media/CE/Documents/company/IRP-2021.ashx. Retrieved on October 2, 2023.

Consumers Energy. 2021b. “Consumers Energy Celebrates New Solar Power Plant in Cadillac.” Available at https://www.consumersenergy.com/news-releases/news-release-details/2021/07/19/consumers-energy-celebrates-new-solar-power-plant-in-cadillac#:~:text=Cadillac%20Solar%20Gardens%20will%20generate,includes%20a%20battery%20storage%20system.. Retrieved on October 3, 2023.

Consumers Energy. 2021a. *Application: Case No. U-21090*. Available at https://mi-psc.my.site.com/sfc/servlet.shepherd/version/download/068t000000Nib8YAAR. Retrieved on October 2, 2023.

Consumers Energy. 2021b. *Application: Case No. U-21090—Part 2*. Available at https://mi-psc.my.site.com/sfc/servlet.shepherd/version/download/068t000000NibJWAAZ. Retrieved on October 2, 2023.

Consumers Energy. 2021c. Application: Case No. U-21090—Part 3. Available at https://mi-psc.my.site.com/sfc/servlet.shepherd/version/download/068t000000NibWaAAJ. Retrieved on October 2, 2023.

Consumers Energy. 2022. *Application: Case No. U-21090 – Second Rebuttal Testimony of Richrd T. Blumenstock*. Available at https://mi-psc.my.site.com/sfc/servlet.shepherd/version/download/0688y000002ufaHAAQ. Retrieved on October 2, 2023.

Consumers Energy. 2023a. “Electric Operation Statistics.” Available at https://www.consumersenergy.com/company/electric-generation/electric-operations-statistics. Retrieved on October 2, 2023.

DTE Electric. 2023a. 2022 DTE Electric Integrated Resource Plan: Summary. Available at https://dtecleanenergy.com/downloads/IRP_Executive_Summary.pdf. Retrieved on July 27, 2023.

DTE Electric. 2023b. Official Exhibits of the DTE Electric Company. Exhibit A-31 Part 2. Available at https://mi-psc.force.com/sfc/servlet.shepherd/version/download/0688y000007l7m0AAA. Retrieved on August 3, 2023.

DXP Enterprises | Integrated Flow Solutions. 2019. “What Is Balance of Plant in Power Plants?” Available at https://ifsolutions.com/what-is-balance-of-plant-in-power-plants/#:~:text=The%20Balance%20of%20Plant%20(BoP,plant%20running%20stably%20and%20efficiently.. Retrieved on May 26, 2023.

eGRID. 2023. “eGRID with 2021 Data.” Available at https://www.epa.gov/egrid/download-data. Retrieved on July 21, 2023.

Entergy. 2023. “Meet the Nuclear Professionals: “Big C” Takes on His 22nd Refuel Outage at River Bend Station.” Available at https://www.entergynewsroom.com/article/meet-nuclear-professionals-big-c-takes-on-his-22nd-refuel-outage-at-river-bend-station/. Retrieved on June 5, 2023.

EZMT. 2023. “EZMT Energy Zones Mapping Tool.” Available at https://ezmt.anl.gov/. Retrieved on October 4, 2023.

Filler, Graham, and Samantha Steckloff. 2023. “Opinion: Michigan Should Expand Nuclear Energy. It's Clean, Safe and Reliable.” Available at https://www.freep.com/story/opinion/contributors/2023/04/11/opinion-michigan-should-expand-clean-safe-reliable-nuclear-energy/70100336007/. Retrieved on May 30, 2023.

Fuller, Brandon. 2023. Michigan Energy: Industry Cluster Workforce Analysis.” Lansing, MI: Michigan Center for Data and Analytics. Available at https://milmi.org/_docs/publications/Cluster_reports_2023/Michigan-Energy-Industry-Cluster-Workforce-Analysis-Report.pdf. Retrieved on June 6, 2023.

Gardner, Timothy, and Valerie Volcovici. 2021. “Bill Gates' Next Generation Nuclear Reactor to Be Built in Wyoming.” Available at https://www.reuters.com/business/energy/utility-small-nuclear-reactor-firm-select-wyoming-next-us-site-2021-06-02/. Retrieved on May 26, 2023.

International Atomic Energy Agency. 2012. *Project Management in Nuclear Power Plant Construction: Guidelines and Experience*. IAEA Nuclear Energy Series No. NP-T-2.7. Available at https://www-pub.iaea.org/MTCD/publications/PDF/Pub1537_web.pdf. Retrieved on May 18, 2023.

International Atomic Energy Agency. 2015. “Best Practices in the Refurbishment of Pressurized Heavy Water Reactors.” Available at https://www.iaea.org/publications/15237/best-practices-in-the-refurbishment-of-pressurized-heavy-water-reactors. Retrieved on June 5, 2023.

International Atomic Energy Agency. 2016. *Procurement Engineering and Supply Chain Guidelines in Support of Operation and Maintenance of Nuclear Facilities*. No. NP-T-3.21. Vienna, Austria: International Atomic Energy Agency. Available at https://www-pub.iaea.org/MTCD/publications/PDF/Pub1725_web.pdf. Retrieved on June 7, 2023.

International Atomic Energy Agency. 2023. “Operation and Maintenance of Nuclear Power Plants.” Available at https://www.iaea.org/topics/operation-and-maintenance. Retrieved on June 5, 2023.

Kinsey, Stephen, and William Jessup. 2018. *United States Nuclear Manufacturing Infrastructure Assessment*. Doi:10.2172/1494317. Alexandria, VA: MPR Associates, Inc.

Leontief, W. 1986. *Input-Output Economics*. New York: Oxford University Press.

Michigan Department of Technology, Management & Budget. 2023. “Michigan Payroll Jobs by Industry.” Available at https://www.milmi.org/DataSearch/Industry-Employment-by-Sector. Retrieved on June 6, 2023.

Michigan Public Service Commission. 2022. DTE: *2022 Integrated Resource Plan Appendices*.

Michigan State University Extension and Graham Sustainability Institute University of Michigan. 2021. “Planning & Zoning for Solar Energy Systems: A Guide for Michigan Local Governments.” Available at https://www.canr.msu.edu/planning/uploads/files/SES-Sample-Ordinance-final-20211011-single.pdf. Retrieved on October 4, 2023.

Monroe County Community College. 2023. “Nuclear Engineering Technology.” Available at https://www.monroeccc.edu/programs/nuclear-engineering-technology. Retrieved on June 7, 2023.

NREL. 2023. NSRDB: National Solar Radiation Database. Available at https://nsrdb.nrel.gov/.

New Unit Assistance Working Group, Robert Fisher, and Laurent Moutenot. 2020. *Roadmap to Operational Readiness*. Available at https://www.wano.info/getmedia/346d2b79-2c11-4b09-962f-840ef279e6d0/R2OR-Revision-0-Final-for-Publication-September-2020.pdf.aspx. Retrieved on May 26, 2023.

Norfolk Southern. 2023. “FAQs.” Available at http://www.nscorp.com/content/nscorp/en/shipping-options/dimensional-shipments/faqs.html. Retrieved on August 1, 2023.

Nuclear Energy Institute Inc. 2016. “Decommissioning Nuclear Power Plants.” Available at https://www.nei.org/resources/fact-sheets/decommissioning-nuclear-power-plants. Retrieved on May 25, 2023.

Nuclear Energy Institute Inc. 2020. “Nuclear by the Numbers.” Available at https://www.nei.org/resources/fact-sheets/nuclear-by-the-numbers. Retrieved on May 26, 2023.

Nuclear Energy Institute Inc. 2023. “Jobs.” Available at https://www.nei.org/advantages/jobs. Retrieved on June 7, 2023. NuScale. 2023. “Utah Associated Municipal Power Systems (UAMPS) and NuScale Power Agree to Terminate the Carbon Free Power Project (CFPP).” Available at https://www.nuscalepower.com/en/news/press-releases/2023/uamps-and-nuscale-power-agree-to-terminate-the-carbon-free-power-project. Retrieved on November 29, 2023.

Shykinov, Nick, Robert Rulko, Dariusz Mroz. 2016. “Importance of Advanced Planning of Manufacturing for Nuclear Industry.” *Management and Production Engineering Review* 7(2):42–49.

Shirvan, Koroush. 2022. “Overnight Capital Cost of the Next AP1000.” MIT-ANP-TR-193. Cambridge, MA: Massachusetts Institute of Technology. Available at https://web.mit.edu/kshirvan/www/research/ANP193%20TR%20CANES.pdf. Retrieved on June 8, 2023.

Tan, Caitlin. 2023. “The Opening of TerraPower’s Nuclear Plant in Kemmerer Will Be Delayed by Two Years.” Available at https://www.wyomingpublicmedia.org/natural-resources-energy/2022-12-14/the-opening-of-terrapowers-nuclear-plant-in-kemmerer-will-be-delayed-by-two-years. Retrieved on June 5, 2023.

Union Pacific. Undated. “Past and Present Railroad Job Descriptions.” Available at https://www.up.com/heritage/history/past-present-jobs/index.htm. Retrieved on June 7, 2023.

Unit 202 Productions, Alex Shanahan, and Nolan Beilstein. 2022. “Michigan Cement Plant Recognized as ‘World’s Largest’.” Available at https://www.manufacturing.net/video/video/22445473/michigan-cement-plant-recognized-as-worlds-largest. Retrieved on June 2, 2023.

University of Michigan. 2020. “$5.2M for Digital Twins of Nuclear Reactors Could Bring Down Nuclear Energy Costs.” Available at https://news.umich.edu/5-2m-for-digital-twins-of-nuclear-reactors-could-bring-down-nuclear-energy-costs/. Retrieved on June 1, 2023.

University of Michigan. 2023. “Facts and Figures.” Available at https://ners.engin.umich.edu/about/facts/. Retrieved on June 7, 2023.

U.S. Army. Undated. “CONUS.” Available at https://www.sddc.army.mil/sites/TEA/Functions/Deployability/TransportabilityEngineering/MODES/RailTransport/Pages/CONUS.aspx. Retrieved on August 1, 2023.

U.S. Bureau of Labor Statistics. 2022. “Water Transportation Workers.” Available at https://www.bls.gov/ooh/transportation-and-material-moving/water-transportation-occupations.htm. Retrieved on June 7, 2023.

U.S. Bureau of Labor Statistics. 2023. “Industries at a Glance Truck Transportation: NAICS 484.” Available at https://www.bls.gov/iag/tgs/iag484.htm. Retrieved on June 7, 2023.

U.S. Department of Energy. 2022a. “Nuclear Energy: Supply Chain Deep Dive Assessment.” Available at https://www.energy.gov/sites/default/files/2022-02/Nuclear%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf. Retrieved on May 16, 2023.

U.S. Department of Energy. 2022b. “5 Fast Facts about Spent Nuclear Fuel.” Available at https://www.energy.gov/ne/articles/5-fast-facts-about-spent-nuclear-fuel#:~:text=Spent%20nuclear%20fuel%20can%20be,%2C%20such%20as%20France%2C%20do.. Retrieved on June 5, 2023.

U.S. Department of Energy. 2022c. “America’s Strategy to Secure the Supply Chain for a Robust Clean Energy Transition.” Available at https://www.energy.gov/policy/articles/americas-strategy-secure-supply-chain-robust-clean-energy-transition. Retrieved on December 1, 2023.

U.S. Department of Energy. 2023a. “What are Critical Materials and Critical Minerals?” Available at https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals. Retrieved on November 30, 2023.

U.S. Department of Energy. 2023b. “Learn More About Interconnections.” Available at https://www.energy.gov/oe/learn-more-about-interconnections. Retrieved on November 30, 2023.

U.S. Energy Information Administration. 2017. “Decommissioning Nuclear Reactors is a Long-Term and Costly Process.” Available at https://www.eia.gov/todayinenergy/detail.php?id=33792#:~:text=DECON%20can%20take%20at%20least,radiation%20drops%20to%20safe%20levels.. Retrieved on May 26, 2023.

U.S. Energy Information Administration. 2018. “Today in Energy.” Available at https://www.eia.gov/todayinenergy/detail.php?id=37252#:~:text=Nuclear%20power%20plants%20typically%20refuel,while%20the%20reactor%20is%20offline.. Retrieved on June 5, 2023.

U.S. Environmental Protection Agency. 2016. *Guidelines for Preparing Economic Analyses*. Report Number EPA 240-R-10-001. December. Washington, DC: U.S. EPA. Available at https://www.epa.gov/sites/production/files/2017-08/documents/ee-0568-50.pdf. Retrieved on October 22, 2018.

U.S. Federal Highway Administration. 2019. “Compilation of Existing State Truck Size and Weight Limit Laws.” Available at https://ops.fhwa.dot.gov/freight/policy/rpt_congress/truck_sw_laws/app_a.htm. Retrieved on August 1, 2023.

U.S. Nuclear Regulatory Commission. Undated. “Advanced Construction Methods for New Nuclear Power Plants.” Available at https://www.nrc.gov/docs/ML1214/ML12146A152.pdf. Retrieved on June 5, 2023.

Veritas Economics. 2011. “Veritas Economics Environmental Policy Simulation Model (EPSM).” Working Paper 2011-01. Cary, NC: Veritas Economics. Available at https://veritaseconomics.com/electricity-policy-simulation-model-epsm/

Western Michigan University. 2016. “Consumers, WMU show solar energy commitment with 1-megawatt solar garden.” Available at https://wmich.edu/news/2016/09/35079.

Wheaton, Zachariah. 2023. “Plan to Reopen Nuclear Plant in SW Michigan Leads to Questions About Northern Michigan Plant.” Available at https://www.9and10news.com/2023/04/26/plans-announced-to-reopen-nuclear-power-plant-in-southwest-michigan-leads-to-questions-about-northern-michigan-plant/. Retrieved on June 5, 2023.

The White House. 2023. “Fact Sheet: President Biden Announces New Actions to Strengthen America’s Supply Chains, Lower Costs for Families, and Secure Key Sectors.” Available at https://www.whitehouse.gov/briefing-room/statements-releases/2023/11/27/fact-sheet-president-biden-announces-new-actions-to-strengthen-americas-supply-chains-lower-costs-for-families-and-secure-key-sectors/. Retrieved on December 1, 2023.

World Nuclear Association. 2022a. “Economics of Nuclear Power.” Available at https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx. Retrieved on May 17, 2023.

World Nuclear Association. 2022b. “Decommissioning Nuclear Facilities.” Available at https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx. Retrieved on June 5, 2023.

World Nuclear Association. 2023. “Nuclear Power Reactors.” Available at https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx. Retrieved on June 2, 2023.