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Life Cycle Assessment of Small Modular Reactors Using U.S. Nuclear Fuel Cycle

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LIFE CYCLE ASSESSMENT OF SMALL MODULAR REACTORS USING U.S. NUCLEAR FUEL CYCLE

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Environmental Health Physics

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by
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Accepted by:
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ABSTRACT

In an ever-evolving energy market, it is vital that nuclear technology adapts to become more economically and environmentally feasible. The promising economics and flexibility of small modular reactors (SMRs) may make them the technology of the future for the nuclear industry, offering a simple solution to many of the problems that have plagued the industry in the last decade. Though the economics of SMRs is often a topic of discussion, it is also important to understand the environmental aspects of this technology when implemented in a U.S. market. A life cycle assessment (LCA) of small modular reactors using a U.S. nuclear fuel cycle has been performed to this end, taking care to use U.S. technologies and facilities in every stage of the assessment where possible. The resulting impacts per MWh of electricity produced were found to be 7.64 m^3 for water depletion, 0.88 kg oil-eq for fossil depletion, 2.03 kg Fe-eq for metal depletion, 4.55 kg CO_2-eq for climate change, 18.02 1,4-DB-eq for human toxicity, and 441.07 kBq ^{235}U-eq for ionizing radiation. In terms of climate change, the results were found to be comparable to the 8.4 kg CO_2-eq found by Carless et. al[1] for the Westinghouse SMR and like the 3.89 kg CO_2-eq found by adjusting the findings of the National Energy Technology Laboratory.[2] Most of the climate change impact was found to be in the fuel processing stages, due to high electricity and fossil fuel demands, as well as in construction because of concrete production. These assumptions were verified by performing a sensitivity analysis on electricity source, mine types, transportation, and material disposition during decommissioning. By comparison to other energy generators, nuclear energy, in general, performs similarly to renewable resources with respect to climate change, and small modular reactors perform slightly better than their larger counterparts. These results aid in confirming the overall feasibility of small modular reactor technology in an energy market concerned with climate change impacts.

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CHAPTER ONE

INTRODUCTION

Many questions about the future of the nuclear industry have arisen in the wake of the cancellation of two units under construction in Jenkinsville, South Carolina in 2018 after a decade of construction and $4.9 billion invested.[3] Prior to their cancellation, Units 2 and 3 at the Virgil C. Summer Nuclear Operating Station (VC Summer) were among the first nuclear generators in the U.S. to be fully constructed and brought online in the 21st Century, alongside Southern Company's Plant Vogtle Units 3 and 4 near Waynesboro, GA.[4] Initially proposed in 2008, the hurdles of licensing, equipment procurement, engineering design, and actual construction have caused the project to go beyond its initial schedule, as well as the initially projected costs. In 2017, Westinghouse Electric Company, the primary construction contractor for the project, filed for bankruptcy, leading project partner Santee Cooper to withdraw. With construction only 33.7% complete,[5] the future for these units is grim.

While the events at VC Summer were plagued with additional burdens, such as possible financial mismanagement, the fate of the new units at VC Summer are a hallmark of the nuclear industry - behind schedule and over budget. For a future energy market that is competitive, affordable, and largely composed of low-carbon technologies, it is necessary, at least with the current state of renewable energy technologies, that nuclear energy be a part of the picture. To remain competitive in the face of cheaper natural gas and subsidized renewable energy, the nuclear industry must find ways to reduce the cost of construction and overall investment burdens associated with the commissioning of a new facility. A lesson in cost cutting is exemplified in the automobile industry, where mass manufacturing and standardization of products reduced the average price of an automobile from $825 in 1908 to $575 in 1912.[6] This trend has continued for the production of many products into the 21st century, and, notably, the same solution has been proposed for the nuclear industry in the form of small modular reactors.

Small modular nuclear reactors (SMRs), defined by the Nuclear Regulatory Commission as any light-water reactor producing under 300 MWe,[7] while a new actionable concept to the commercial nuclear power industry, are not a new technology. Designs for SMRs have been utilized in many places across the globe. In the United States, the most common use for a small reactor is in nuclear submarines and aircraft carriers for the Navy, but small reactors have also been used for various research applications.[8] Despite the many historical applications of SMR technology, previous designs are not necessarily applicable in a commercial environment, particular due to the fact that naval small reactors operate using highly enriched uranium (HEU) fuel[9]—which is why many companies have taken on the task of developing SMR technology for use in a commercial fleet. In March of 2018, the U.S. Department of Energy (DOE) developed and sponsored the Small Modular Reactor Licensing Technical Support program to support various entities through cost-shared funding for the development and maturation of SMR designs.[10] Thus far, mPower, NuScale, Westinghouse, and Holtec have submitted design applications and site permits to the NRC. [7]

Some of the primary drivers for innovation in SMR technology are the reduced up-front construction costs and attractive technological and safety features offered by the small modular design. As is exemplified by the example of VC Summer, projects undertaking the task of constructing a large nuclear power plant face significant capital investments, long construction, and they are also limited in siting by their large generation capacity. The smaller capacity offered by an SMR is beneficial in places where there are incremental changes in the electricity demand, the demand itself is smaller than the capacity offered by conventional nuclear reactors, or there are siting issues based on the safety risk presented by a large facility. Additionally, one of the major advantages for SMR technology is the ability for many of the major components in the steam cycle to be manufactured in a factory as a single module.[11] Carless et al. found that, while SMRs do not differ greatly in overall costs of *operation* from their traditional counterparts, the flexibility, modularity, and adaptability of SMRs offer both a technological and economical advantage.[1]

If SMRs are to lead to a new generation of growth for the nuclear industry, then environmental implications, as well as the economic implications, of specific SMRs should be quantified. Part of the appeal of nuclear energy, beyond its ability to provide reliable energy, is its ability to deliver this energy with much lower carbon emissions compared to fossil fuel technologies. While there are obvious environmental footprints associated with the nuclear fuel cycle (*i.e.*, mining) and power plant construction, the generation of nuclear energy is relatively free of carbon emissions.[12] While traditional nuclear technology has been the subject of some previous life cycle assessments (LCAs)[13,14], the environmental impacts of the SMR life cycle has rarely been explored using life cycle assessment. This is, in part, due to the lack of available data on SMR fuel cycle processes, despite their frequent use in places, such as the U.S. Navy. However, design information for various

SMRs are available for review, and assumptions could potentially be made by scaling down certain resources from that of a large nuclear reactor. Considering the possibility of mass production would be relevant to include given the modular nature of this technology, though this is difficult to quantify given current information.

While the possibilities and implications of SMR technology may seem obvious to an expert in energy generation, many people do not know about the intricacies of energy generation. In general, the public does not fully grasp the cause of regional differences in how energy is produced or even know the expanse of energy generation technologies. For example, a layperson interested in sustainable energy options may believe that solar energy technology could be used to support the entire country, rather than as part of a much more diverse energy portfolio. However, solar energy is not economical for all regions and has a lower power density than most energy technologies. As such, solar energy is ideal as a component of a portfolio in certain areas of the world, but not as the sole provider of energy.

Energy education is an important aspect of a growing economy, where the energy demand continues to grow and the urgency of reducing the impact to the planet increases. *Energize!* is an interactive, multi-player game funded by the Department of Energy with the goal of educating the technically oriented layperson about the impacts of various energy technologies and the importance of balancing the energy grid in the face of constant and growing demand. As a possible component of a future U.S. energy portfolio, SMRs will be implemented into this game alongside traditional light water reactors (LWRs) and other technologies such as coal, natural gas, hydro, wind, and solar. The work done in this thesis contributes to the *Energize!* content, particularly regarding the environmental impacts of SMRs.

The overall goal of this study is to quantify the environmental impacts of producing electricity using small modular nuclear reactor technology. Life cycle assessment facilitates foresight of potential environmental implications of future technologies, which enables companies and taxpayers to make informed decisions about energy technology investments. In this life cycle assessment, the functional unit is the production of 3.6×10^8 MWh of electricity by small modular technology (*i.e.*, one SMR facility containing twelve 60 MWe modules operating at 95% capacity for 60 years).

CHAPTER TWO

BACKGROUND

Life cycle Assessment

Life cycle assessments (LCAs) are a type of environmental analysis meant to highlight the impacts a product, system, or service has on the environment throughout its lifetime. In general, LCAs begin at resource extraction (the "cradle") and end at disposal or recycling of the final product (the "grave"). A diagram of the components typically included in an LCA is shown in Figure 2.1.[15]

Typically, resource extraction is the initial stage considered in an LCA and accounts for sourcing all the resources needed for the product or process of interest. For most products or processes, the resource extraction stage consists of mining operations. The processing of the extracted materials is considered, which could include refining or purifying a mined material. The manufacturing stage includes the process(es) that bring the product/service to its final form before being delivered to the consumer or user. For example, in the case of a water bottle, this would be the stage in which the bottle itself was constructed from the processed plastic. Distribution is the transportation that occurs between different stages of the life cycle, most notably between the manufacturing and use stage. The use stage is the phase in which the product or service is utilized by the consumer for a specific purpose, such as the use of a washing machine to clean clothes. And, finally, the end of life stage considers the final disposal or storage of a product, including any recycling or reuse.[16]

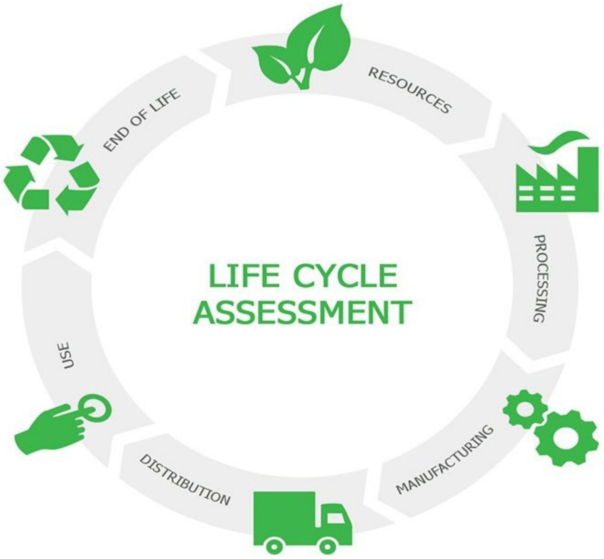


Figure 2.1. Diagram of the stages included in a typical life cycle assessment.[15]

In an LCA, material flows to and from the environment, as well as the economy, are typically tracked. These flows, in the case of life cycle assessment, must be quantifiable in terms of a given product and incudes both “inputs” and “outputs” to a process relative to the environment (or the technosphere). For example, it will take a certain number of kilograms of concrete to produce a building; the concrete is a flow into this process, and the building is the product. Because the effects of producing a single product are vast and difficult to capture in their entirety, it is necessary in an LCA to define the scope (or boundary conditions) of the assessment. For example, in assessing the impacts of producing a spiral notebook, it is probably irrelevant to consider the amount of coffee consumed by the employees of the wood pulping company. A clear goal definition is necessary to determine the appropriate project scope, which includes definition of key impact categories and the life cycle stages. These definitions of a goal and scope comprises the first of four phases in the LCA framework.[16]

The second phase in the LCA framework is the compilation of a life cycle inventory (LCI). An LCI is effectively a list of types and quantities of different inputs and outputs for each process in a life cycle. Results from the LCI are used to inform the life cycle impact assessment (LCIA), the third phase, which quantifies the effects of the resource use and releases associated with producing a certain product/service. An impact assessment can be performed using one of several cultural perspectives dictated in the OpenLCA software. The "cultural perspective' dictates the weighting scheme applied to the various impacts when summarizing into impact categories, and the available options are Hierarchical (H), Individualist (I), and Egalitarian (E). These weighting schemes are based on differing assumptions about time periods and whether technological advancements will be available to deal with the impacts. The Individualist perspective is a short-term optimistic viewpoint; the Hierarchical perspective is one which assumes a medium-length time period and makes no assumption as to the ability of future technology to handle or avoid impacts; and the Egalitarian perspective focuses on a long-term time period with a more pessimistic approach to potential results of impacts.[17] The third and final phase of the LCA framework, an interpretation, can, and should, be performed on these results, speculating on the cause of discrepancies, suggesting improvements to future studies, acknowledging limitations, etc. The first three phases, however, are the only phases required for the LCA to meet the standards outlined by the International Standards Organization for LCA analyses.[16]

The Nuclear Fuel Cycle

The nuclear fuel cycle, shown in Figure 2. 2, is composed of many stages, all of which contribute to the environmental footprint of a given nuclear energy technology. The U.S. currently utilizes the once-through nuclear fuel cycle, which will be modeled in the proposed LCA. A once-through (or open) nuclear fuel cycle does not include reprocessing and recycling of used nuclear fuel. That is, the fuel fabricated for use in the reactor is only used once, after which the used fuel is cooled and stored on site for eventual disposition in a deep geological disposal facility. The proposed LCA is focused on a comparison of a small modular LWR with a traditional LWR; therefore, the comparison of an open vs. closed fuel cycle is beyond the scope of this work. While the amount of fuel used in a SMR differs from that of a traditional nuclear power plant, the front end and back end fuel cycle

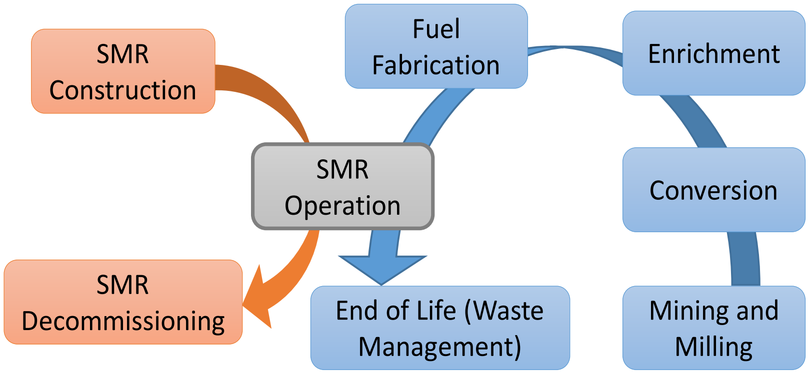


Figure 2. 2. Illustration of SMR life-cycle phases (orange boxes) including fuel cycle steps (blue boxes), where SMR operations connects both the nuclear fuel cycle steps with the life-cycle phases.

processes are the same. Differences are highlighted in construction, operation, and decommissioning, primarily related to reactor design in terms of the fuel needed per energy produced.

Many life cycle assessments on nuclear technology utilize the EcoInvent inventory database, which is based on a European "closed" fuel cycle. In the EcoInvent inventory database, all entries for nuclear technology are derived from a closed fuel cycle and a Swiss reactor design.[18] Though this method may be appropriate for rough estimates of nuclear impacts, it does not truly capture the impacts of an open fuel cycle utilizing domestic, U.S. facilities and U.S.-based technologies. Thus, in order to assess the environmental impacts of the small modular reactor technology, a life-cycle inventory was built for a closed, U.S. fuel cycle utilizing domestic facilities where possible. Transportation between the fuel cycle steps, including the often-vast distances traveled between the mine site and conversion facilities, is captured. These fuel cycle processes are detailed in the following sections.

Mining

One of the most environmentally impactful steps of any industry, mining presents significant ecological and human health risks. In the nuclear power industry, the primary element that is mined for use as fuel is uranium. Uranium ore is found in many locations across the globe and is procured in several fashions. The method by which the uranium is mined largely depends on the geology of the region, a factor which also helps determine the purity and accessibility of the uranium that is mined. The countries that produce the largest amounts of uranium are Kazakhstan, Niger, Namibia, Australia, and Canada.[19] The three primary modes by which uranium is extracted from the earth include underground, open-pit, and *in situ* leach mining. Worldwide, open-pit and underground mining efforts represent 42% of all uranium mined, *in situ* leach mining represents 51%, and the remaining 7% is mined as a by-product of other resources, such as gold or copper.[19]

Open-pit mining can be employed for near-surface uranium deposits and entails removing the layer of earth from above the uranium deposit, resulting in large accumulation of waste rock. For a uranium deposit further below the surface, underground mining is traditionally used.[19] Both open-pit and underground mining lead to environmental concerns due to oxidation of heavy elements and transition metals found in the waste rock and in the remaining exposed rock. Oxidation of the heavy elements and transition metals leads to acid mine drainage, which can greatly impact the pH conditions of local water bodies and devastate associated ecosystems. Further, the oxidation of uranium from a +4 to a +6 oxidation state mobilizes the metal, allowing for transport of uranium in surface or ground water.[20] Enhanced mobility due to oxidation contributes to the environmental impact from other heavy metals found in mines (*e.g.*, As, Hg) and presents a significant human health hazard. In addition to the production of heavy metals and acid mine drainage, uranium mines can also expose workers to radon and its alpha-emitting progeny, which presents a human health hazard.

In situ leach mining involves oxidizing and extracting uranium via the use of either an acid or alkaline solution, depending on what other minerals are present in the uranium deposit. The solution is pumped into a permeable geologic layer (*e.g.*, sand) containing uranium and then extracted from the well after the uranium, along with the other metals in the sand, are oxidized. Because uranium is mobilized underground in the *in situ* leach process, the use of this mining technology is limited to deposits encased by impermeable rock. Further, these types of deposits, which typically contain low-grade ore, become economical to mine using the *in situ* leach process.[21] Despite the economic advantages of *in situ* leaching, as well as the reduced amount of waste rock generated compared to other methods, *in situ* leaching can be of environmental concern due to the fact that it mobilizes uranium and other heavy metals.

Milling

Uranium ore extracted via underground or open pit mining requires a milling process to purify the uranium or remove other metals and materials from the ore. Conventional milling involves crushing the uranium ore, leaching the uranium from the ore using an acidic or alkaline solution, depending on the characteristics of the ore itself, and concentrating the U-bearing solution by stripping solvents with an ammonium sulfate solution and precipitating ammonium diuranate (ADU) with ammonium gas (Figure 2.3)[21]. Finally, the ADU is converted to U_3O_8 by drying/roasting, which yields the final product called "yellowcake".

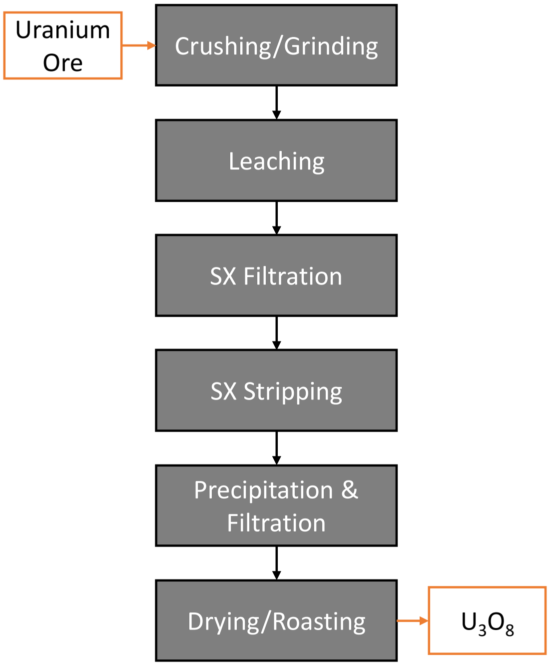


Figure 2.3. Diagram of the traditional uranium milling process, which utilizes solvent extraction (SX) to separate uranium from the dissolved ore.[21]

The hazards associated with milling come primarily from the production and storage of the associated wastes, which are called mill tailings. The exact percentage of uranium ore that contributes to mill tailings depends on the grade of the ore being mined, but can be as much as 99.9% for a 0.1% grade ore.[21] The heavy metals associated with the uranium ore can be mobilized during the milling process and present a risk to the environment. It should also be noted that, because the percentage of the ore contributing to mill tailings is so large and because these tailings include daughters in the ^{238}U decay chain, a large fraction of the total radioactivity of the ore is present in the mill tailings; an estimated 85% of the radioactivity in the uranium ore goes to mill tailings.[21]

In general, mill tailings are stored in reinforced retention ponds on site. These ponds are typically exposed to the atmosphere and subject to erosion over time, which increases the risk of heavy metals and radionuclides spreading into the environment. Of interest is ^{222}Rn, a daughter in the ^{238}U decay chain. Because ^{222}Rn is present as a gas, it presents an inhalation risk to workers or by persons nearby both uranium mining and milling operations. Further, the alpha-emitting radon daughters (particularly ^{218}Po and ^{214}Po) can cause significant damage to lung tissue and other respiratory organs.[21]

Purification and Conversion

Following milling, uranium in the form of yellow cake (*i.e.*, either ammonium diuranate or U_3O_8) remains only 70-90% purified, and so milling is usually followed by the simultaneous purification and conversion of the yellow cake to UF_6, which is the form of uranium used for enrichment.[22] The most common methods for conversion are the dry hydrofluor and wet solvent extraction processes. The hydrofluor process first involves grinding the impure-U_3O_8 into a very fine powder, feeding it into a fluidized bed reactor at high temperatures (between 1000-1200 °F), reducing by hydrogen, interacting with anhydrous fluorine, and then treating with fluorine gas to result in UF_6. The wet solvent extraction process is very similar to the hydrofluor process, with the exception that the U_3O_8 is first treated via solvent extraction to remove impurities.[22] In the U.S., only the hydrofluor, also called dry conversion, process is used.[23] In fact, the U.S. conversion facility is the only facility that uses the hydrofluor process. Thus, a U.S.-specific inventory includes significantly different flows of material and energy associated with the conversion and purification processes.

Enrichment

Although many methods of uranium enrichment have been explored throughout the history of the nuclear industry and still more have been proposed, there is only one method that is currently employed in U.S. production: gas centrifugation.[24] The gas centrifugation utilizes a series of rotating drums that force the heavier $^{238}UF_6$ gas to the outer walls, separating the heavy $^{238}UF_6$ from the light (and fissile) $^{235}UF_6$. The heavy and light molecules are evacuated, separately, as a depleted and enriched uranium hexafluoride gas. In practice, thousands of gas centrifuges operate in sequence for increased throughput. Gas centrifugation is much more energy efficient than its predecessors, such as magnetic separation (via the calutrons) and gaseous diffusion.[22]

The only operating uranium enrichment plant in the United States is owned by Uranium Enrichment Corporation (URENCO) and located in Eunice, New Mexico. The URENCO plant is licensed to enrich uranium up to 5.5% U-235 and operates at 4.8 million SWU per year, providing roughly 1/3 of the total enrichment demand for the United States nuclear reactor fleet, the remainder either being imported or a resulted of weapons-grade uranium down-blended. The down-blending of weapons uranium was not considered in this analysis. The energy requirements of gas centrifuge plants are, on average, 40 kWh per SWU.[25]

Fuel Fabrication

Once the uranium has been purified, converted, and enriched to the desired percentage, it is then shipped to one of three existing fuel fabrication facilities in the U.S.: Global Nuclear Fuel-Americas in Wilmington, North Carolina; Westinghouse Columbia Fuel Fabrication Facility in Columbia, SC; and AREVA, Inc. in Richland, Washington.[26] The enriched UF_6 is received from the enrichment plant as a solid and reheated to a gas. The UF_6 gas is then chemically treated to produce UO_2 powder, pressed into a pellet, and sintered. The sintered pellets are loaded into zircalloy fuel rods (also manufactured at the fuel fabrication facility), which are arranged into fuel-assemblies. The size of the fuel rods and fuel assemblies depends on the reactor design.[26] There is little information about how this process might change with the introduction of SMR technology. One may presume that fuel fabrication facilities could also manufacture the modules, in addition to the fuel assemblies, for SMRs.

Waste Management

The waste management step in the nuclear fuel cycle pertains to the handling and storage of nuclear fuel after it has been irradiated, or “spent,” in the reactor. For traditional light water reactors, every 18 to 24 months, approximately 1/3 of the fuel is removed from the reactor core and replaced with fresh assemblies.[27] Following this removal, the fuel assemblies are still extremely hot, both in terms of thermal heat and the high amounts of radiation being released due to the short-lived fission and activation products in the fuel. Therefore, the assemblies must be cooled for a period after their removal from the reactor core prior to any further storage or reprocessing. Initial cooling occurs in wet pool storage. At a nuclear facility, there are pools filled with borated water and reinforced with several feet of concrete and steel, typically 40 feet deep, where the assemblies are mechanically placed.[28] This cooling period is typically between five and ten years,[28] although lack of options for post-cooling storage has led many nuclear facilities to leave spent fuel in the cooling pools for much longer.

The current commercial fuel cycle in the U.S. is a once-through fuel cycle in which spent nuclear fuel (SNF) is eventually placed into a deep geological repository without any reprocessing or recycling.[29] To date, no deep geological repository for spent nuclear fuel has been completed, requiring most nuclear facilities with SNF to move the spent fuel from wet to dry storage. Dry cask storage enables the storage of several SNF assemblies in a steel container, which is typically surrounded by layers of concrete and steel for shielding (Figure 2.4)[30]. Dry cask containers come in a variety of

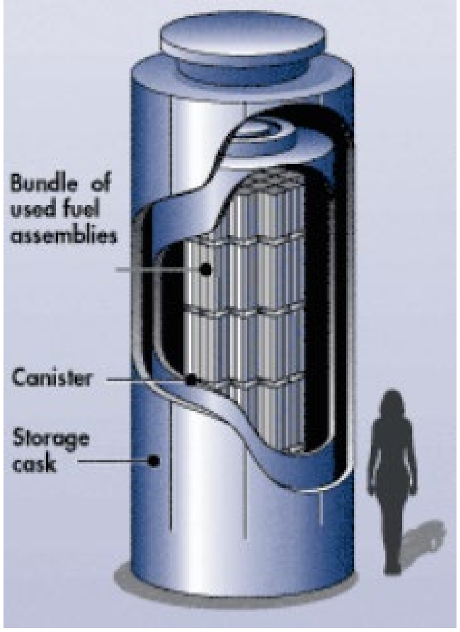


Figure 2.4. Schematic of a dry cask for storage of SNF.[30]

designs and configurations, but they are typically found on concrete pads outside of the reactor building, yet within the facility perimeter.

SMR Technology

Small modular reactors (SMRs) utilize similar technology as a standard nuclear power reactor with the exceptions that the power produced is typically less than 300 MWe for LWR designs, and a large fraction of the equipment is modular by design.[31] The modularity is typically captured in the reactor vessel components, such as with the pressurizer, steam generator, reactor core, etc. The advantage of the modular design is that many of these components could be manufactured, assembled into the reactor module, and fueled at a single facility, then shipped directly to the energy production site. This reduces the capital costs and construction time.[32]

Oregon State University (OSU) began developing an SMR design for a U.S. Department of Energy funded program in 2000 to encourage the development and licensing of commercial SMR technology. The DOE funding for this project officially ended in 2003, but OSU scientists and engineers continued research on the SMR design, with specific aims to implement cooling via natural circulation as a safety feature. In 2007, OSU transferred its SMR designs, as well as use of the test facility it had created for the SMR, to the newly founded NuScale Power.[33] Currently, Fluor Corp. is the primary investor in NuScale and is steadily working toward commercialization, with an NRC Design Certification Application underway.[34] This SMR design is the furthest in the licensing process of all designs currently seeking licensing from the NRC and thus is the design referenced most often in this analysis.[7]

Construction

The construction phase of an SMR is one of the ways that it differs the most from a standard LWR. The process of construction for a full-sized nuclear power plant requires a large capital investment and often requires long construction times. Thus, construction of a nuclear power plant often makes nuclear power production less competitive than other energy types. The United States, possibly due to high security standards, has the longest construction time for nuclear power plants than any other country in the world, with a median construction time of 100 months.[35] SMRs, by contrast, have a much lower projected construction time. This is in part due to their reduced size as well as the fact that many of an SMR's components are projected to be mass-producible and shipped to site for assembly. From the initial pouring of concrete to the final physical construction, the time to completion for an SMR is cited by NuScale as 28.5 months. From mobilization to completion, the time is projected to be 51 months.[36]

Operation

The operation of the NuScale SMR would not differ greatly from that of a LWR in the United States. Light water reactor technology uses water for cooling, moderation, and steam-generation. The NuScale SMR is a pressurized water reactor design, having a primary loop of pressurized water to absorb heat from the reactor core, which exchanges heat to a secondary loop of water in a steam generator.[37] The steam generated in the secondary loop turns a turbine (located in the turbine buildings on site) to produce mechanical energy that will then become electricity. Unlike a large PWR, however, no pumps or additional valves are needed to direct the flow of the water in the primary or secondary loop. Instead, the NuScale SMR design utilizes natural circulation to direct cooled water back into the reactor core after going through the steam generator. In addition to eliminating pumps and valves, the NuScale SMR design also eliminates the need for coolant control via spray systems and implements digital instrumentation and control design. From the digitalized control room, as many as 12 units (modules) can be operated.[38]

Decommissioning

The decommissioning step in the life cycle of a nuclear reactor includes the steps taken to shut down, decontaminate and/or isolate the radioactive materials residual to former energy production. In the U.S., there are two decommissioning methods typically employed: Decontamination (DECON) and Safe Storage (SAFSTOR). The DECON process involves removing all the major radioactive components from the reactor site, either by disposing as low-level radioactive waste or decontaminating before ultimate disposal. The DECON process is estimated to take approximately 7 years. By contrast, SAFSTOR involves *in situ* containment of the facility for later decontamination, allowing for much of the radioactivity to decay away before final disposal. The SAFSTOR process is estimated to take about 60 years, 10 of which are for the decontamination activities themselves.[39] Like the fuel fabrication step of the fuel cycle, it is uncertain how this process may change with the implementation of modularity. Since the primary system, which contains most of the contamination upon shutdown, is contained within a nuclear module, the impact of modularity on the decommissioning process may be profound. Decommissioning can be a resource intensive process due to the cutting, decontamination, and disposal of contaminated equipment. If there were storage methods for the modules, such as enlarged dry cask storage, the reduction in resources for this step could greatly impact the life cycle assessment results.

CHAPTER THREE

METHODS

The methods employed for this life cycle assessment include the development of the life cycle inventory, the life cycle impact assessment, a data quality assessment, and sensitivity analyses.

Life cycle Inventory Assumptions

As previously discussed, the life cycle inventory includes all of the energy requirements and material flows (*i.e.*, inputs and outputs) associated with each life cycle stage. The OpenLCA platform was used to perform the life cycle assessment in this study. OpenLCA is a convenient, free, and therefore, widely utilized software program within the life cycle assessment community. In fact, many of the processes and material flows necessary to model different stages of an energy production life cycle are readily accessible within OpenLCA through the use of variatious databases. In this work, the EcoInvent database (Version 3.1) was used, which includes datasets on the production of concrete, mining of particular resources, and regionally-produced energy, among other things. Database processes were manually constructed for *in-situ* leach mining, conversion, enrichment, fuel fabrication, construction, operation, decommissioning, waste management, as well as transportation between each stage. A built-in EcoInvent database was used for underground and open pit (conventional) mining and milling. Assumptions made for each life cycle stage are detailed in the sections below and summarized in the bill of materials (Table B.1) in Appendix B.

Mining and Milling

The mining and milling of uranium ore extracted via underground or open pit mining were assumed to co-exist at the same site (as is often the case). Therefore, emissions, water and energy use, as well as other parameters for the facility operations are representative of both mining and milling. The distribution of natural uranium used in this study is normalized based on the country of origin, as well as the method of mining. Since the United States uses only 10% of domestically-produced uranium[41], the source of natural uranium in this life cycle study assumes a redistribution based on the country of origin of uranium imports. Over 80% of uranium imported into the U.S. comes from only five different countries - Canada, Australia, Russia, Uzbekistan, and Kazakhstan.[41] As such, the distribution of the uranium imports considered for this LCA were normalized to consider only uranium mined from these countries. Over 80% of uranium imported into the U.S. comes from only five different countries - Canada, Australia, Russia, Uzbekistan, and Kazakhstan.[41] As such, the distribution of the uranium imports considered for this LCA were normalized to consider only uranium mined from these countries (Table 3.1). In 2017, 50% of the world's uranium was mined via *in situ* leach mining.[21] Of the countries that export uranium to the U.S., Uzbekistan and Kazakhstan have 100% *in situ* leach mining,[42,43] while Australia has approximately 20% *in situ* leach mining.[44] The remaining 80% of major Australian mines are distributed between underground and open pit mining technologies. In Canada, mining occurs entirely through underground and open pit mining,[45] while Russian mines are distributed almost evenly between *in situ* leach mining and open-pit and underground mining.[46]

Conveniently, the EcoInvent database includes a process that represents both underground and open-pit uranium mining processes called "uranium, in yellowcake." The process includes some geographical specificity with options including Regional North America (RNA) and Rest of World (RoW). For countries whose primary production method was either open-pit or underground mining, the default uranium mining process available in the EcoInvent database was used. The EcoInvent database does not have a process for *in situ* leach mining, which is responsible for most uranium mined from Kazakhstan and Uzbekistan.[42,43] For the ISL mining process, the relationships between ore

Table 3.1. Distribution of uranium resources assumed in this analysis by country and mine type.

Country	% of U.S. Imports	Underground/ Open-Pit (%)	*In Situ* Leach (%)	% Contribution of Mined Uranium
Canada[45]	29.63	100	0	29.63% uranium, in yellowcake – RNA (EcoInvent)
Australia[44]	22.22%	79.34	20.66	17.63% uranium in yellowcake – RoW (EcoInvent) 4.59% uranium ore from ISL (this study)
Kazakhstan[43]	24.69%	0	100	24.69% uranium ore from ISL (this study)
Russia[46]	16.05	55.93	44.07	8.98 % uranium in yellowcake – RoW (EcoInvent) 7.07 % uranium ore from ISL (this study)
Uzbekistan[42]	7.41	0	100	7.41 % uranium ore from ISL (this study)

grade, mine type, and associated emissions or resource usage were calculated to determine the flows for the ISL mining process (Equations 1-4 in Appendix A).[47]

Conversion

Conversion in the U.S. is accomplished through the dry hydrofluor process, as opposed to the wet solvent extraction method used at conversion facilities in other countries. The Conversion process built for this life cycle assessment used data from an Idaho National Laboratory study on the average environmental emissions and resources used by uranium conversion processes.[47] While this data is not a direct correspondent to the dry hydrofluor process used by the U.S., the average includes information from the Honeywell Metropolis Works facility, where all U.S. uranium is converted to UF_6. The feed to product ratio used in the life cycle inventory is 1:1.25 (Table 3.2) according to the World-Nuclear Association, which states that 249 tons of uranium ore is required to produce 312 tons of uranium hexafluoride.[48]

Table 3.2. Sources of uranium used in the conversion stage

Source of uranium	**Contribution to conversion stage (%)**	
uranium, in yellowcake – RNA	29.63%	0.24
uranium in yellowcake – RoW	26.61%	0.21
uranium ore from ISL	43.76%	0.35

Enrichment

All uranium enrichment in the U.S. is performed using gas centrifugation at the URENCO facility in Eunice, New Mexico. The Environmental Impact Statement (EIS) for the construction and operation of the facility is readily available and contains information about chemicals used throughout the process, environmental emissions, and water usage.[25] The energy use of the facility was calculated based on the energy requirements of a typical gas centrifuge facility (40 kWh/SWU)[25] and the capacity of the URENCO facility (4.7 million SWU/yr).[49] Furthermore, since EIS data is given on a per year basis, the mass of enriched product was converted to a per year basis using URENCO SWU calculator,[50] assuming a product assay of 4.95%[51], a tails assay of 0.23%,[50] and a feed assay of 0.711%.[50] The number of SWUs required per kg of product is approximately 8.1 SWUs.

Fuel Fabrication

The inventory data for the fuel fabrication stage, much like the conversion stage, is based on an average of several facilities across the globe; however, the fabrication of uranium oxide fuel is differentiated from the fabrication of mixed oxide fuel, which is only produced in countries that reprocess used nuclear fuel.[47] In addition to some of the more typical environmental flows considered for a manufacturing-type process, the amount of zirconium used in the production of a NuScale SMR fuel assembly was also included in the assessment. The NuScale SMR fuel assembly resembles that of a typical 17x17 PWR fuel assembly,[52] but half the height. Therefore, the inventory assessment was performed by adjusting the volume of assembly material from approximately 4 meters[52] for a standard assembly and approximately 2 meters for the NuScale assembly.[37] While this is sufficient information for the characterization of a fuel assembly, the materials and processes required for the manufacture of a NuScale module were not quantifiable given current available estimates. For this reason, the fuel fabrication stage of the life cycle may be an underestimate when compared with the potential impacts of fabricating the module as well.

Waste Management

There is little information available on the environmental flows of handling and storing used nuclear fuel at a dry cask facility on site, and essentially no information on how this process may change with the implementation of small modular reactor technology. For this assessment, only the materials required to construct the dry storage cask for the fuel were considered. This means that flows other than steel, concrete, and nuclear waste were disregarded. Because this evaluation is for small modular reactor technology and no specialized cask design has been proposed for the NuScale SMR design, it was assumed that a vertical, canistered used fuel cask that is standard for LWRs would be used for the storage of used nuclear fuel. Even though the NuScale assemblies are approximately half the height of a standard PWR assembly, stacking used assemblies is not expected due to the difference in heat profile after burn-up for stacked *versus* unstacked used fuel assemblies. Therefore, the used fuel casks for the used SMR assemblies are assumed to be about half the height of traditional dry casks. Outside the scope of this LCA are the design, testing, and licensing efforts that would be necessary to utilize a new dry casks storage container for onsite storage of used SMR fuel. This study considers nth-of-a-kind (NOAK) deployment rather than first-of-a-kind (FOAK) deployment, so additional processes necessary to onboard the new technology are not considered.

The Nuclear Regulatory Commission has not, to date, specified any requirements for the storage of used nuclear fuel from a small modular reactor that would be different than that of a standard nuclear power plant.[53] Furthermore, vendors of small modular reactor technology, such as NuScale Power, have also not specified a strategy for handling fuel discharged from the reactor specific to the modular nature of the technology. Therefore, it is assumed that the strategy will be the same as that of a standard nuclear power plant apart from perhaps a size difference in the storage cask.

Construction of SMR

Data for the construction of a small modular reactor facility was provided directly by NuScale Power, a U.S. company with a mature small modular reactor design. The numbers provided by NuScale Power were approximate estimates and are representative of a 720 MWe facility, which contains twelve 60 MWe modules. This information was supplemented with that from an Environmental Impact Statement from Westinghouse for the construction of a small modular reactor facility along the Clinch River in Oak Ridge, TN.[54]

Operation of SMR

Because the operation of a nuclear power plant impacts the environment very little outside of water consumption, this as well as passenger transport (transportation of workers from their homes) to the site were some of the only flows considered for this stage of the life cycle. Other flows considered were nitrogen oxides, carbon monoxide, particulates, and some other emissions. Information for water usage was taken from publicly available literature on the NuScale SMR design,[51] and the information about emissions is from the Westinghouse Environmental Impact Statement for the Clinch River Site.[54] For fuel consumption, The NuScale design is cited to use approximately 1/20th the amount of fuel as that of a standard nuclear generator, where the initial loading of a standard, 1000MWe nuclear generator is 100 tonnes of UO_2[55] making the initial loading of a NuScale SMR about 5 tonnes of UO_2. For a refueling cycle of 24 months, where 1/3 of the reactor core is replenished with fresh fuel, and a lifetime of 60 years, the total amount of fuel used in a NuScale generator is 55 tonnes. For a facility of twelve modules, this totals to 660 total tonnes of UO_2 fuel.

Decommissioning of SMR

As was mentioned in the discussion of waste management, the application of modular technology to nuclear energy production could make a definite difference in the way the fuel is handled at the end of life. Due to the modular nature of small modular reactors, it is possible that dry storage casks would evolve to accommodate this change in technology. The "plug and play" nature of small modular reactors may allow for the "unplugging" and storage of an entire module upon decommissioning, thus reducing much of the energy and material demands of the decommissioning process. Already, there are designs proposed for micro-reactors that include simplified decommissioning of an entire module.[56] Furthermore, were it to be the case that this could be accomplished in a factory setting for individual modules, it is possible that the facility infrastructure could be used beyond the estimated 60-year lifetime of the modules themselves, thus reducing the impact per kWh of energy produced from construction of the facility. However, this strategy is purely speculative. In lieu of reliable information about the decommissioning processes of a small modular reactor facility, it must be assumed that the practices will be the same as that of a standard nuclear power plant.

Over the last few decades, 32 nuclear facilities have undergone decommissioning in the U.S., with only a fraction of these facilities having completed their decommissioning.[57] Of these facilities, fewer still have publicly accessible documentation quantifying the material and energy flows employed during the decommissioning process. The most detailed account of material and energy flows for a U.S. facility is available for the Maine Yankee facility in Wiscasset, Maine; however, this account only provides details for the waste shipped from the site, as well as the economics of the decommissioning.[58] No information regarding the energy, water, or diesel-use at the facility during the decommissioning process is provided.

In the absence of detailed material and energy flows for decommissioning of a U.S. facility, data was used instead from a report on the decommissioning of a VVER facility in Lubmin, Germany.[59] This report documents not only the wastes associated with the decommissioning of the facility but also the energy and material flows for each step in the decommissioning process, such as cutting and decontamination. The VVER design, while different than that of the standard LWR used in the U.S., differs primarily in the details of the reactor-specific equipment. The primary difference between a VVER design and standard LWR is in the orientation of the steam generators, shape of the fuel assemblies, design of the pressure vessel, and design of the pressurizers.[60]

While these differences in design can account for changes to the decommissioning strategy that must be employed, these differences would be minute compared to the entire facility. The difference that must be considered is not in the design of the facility, but in the decommissioning practices of the host country, Germany. Nuclear decommissioning practices in Germany differs from decommissioning in the U.S. in that much of the building materials (e.g., concrete and steel) are decontaminated and recycled for secondary use. Because the process of creating the cement for concrete is extremely energy intensive ,[61] the reuse of this material could have profound impacts on the result of the life cycle assessment depending on the boundary conditions of the assessment. Of note, the process of recycling is also very energy intensive, requiring the use of an LCA approach to gauge any underlying environmental impacts.[62] In the United States, the question of decontamination and recycling of these materials is handled on a state-by-state basis and is largely not practiced. While the data from the German VVER reactor decommissioning was utilized for the decommissioning stage of this LCA, a sensitivity analysis was performed to consider additional impacts associated with recycling the decontaminated concrete and steel.

Transportation

Transportation was considered as a separate stage between all the other stages in this life cycle assessment (Figure 3.1). For example, transportation from mining and milling facilities to the conversion facility was considered as a separate LCA stage than transportation from the conversion facility to the enrichment facility. For simplicity, all the transportation stages are combined in this subsection.

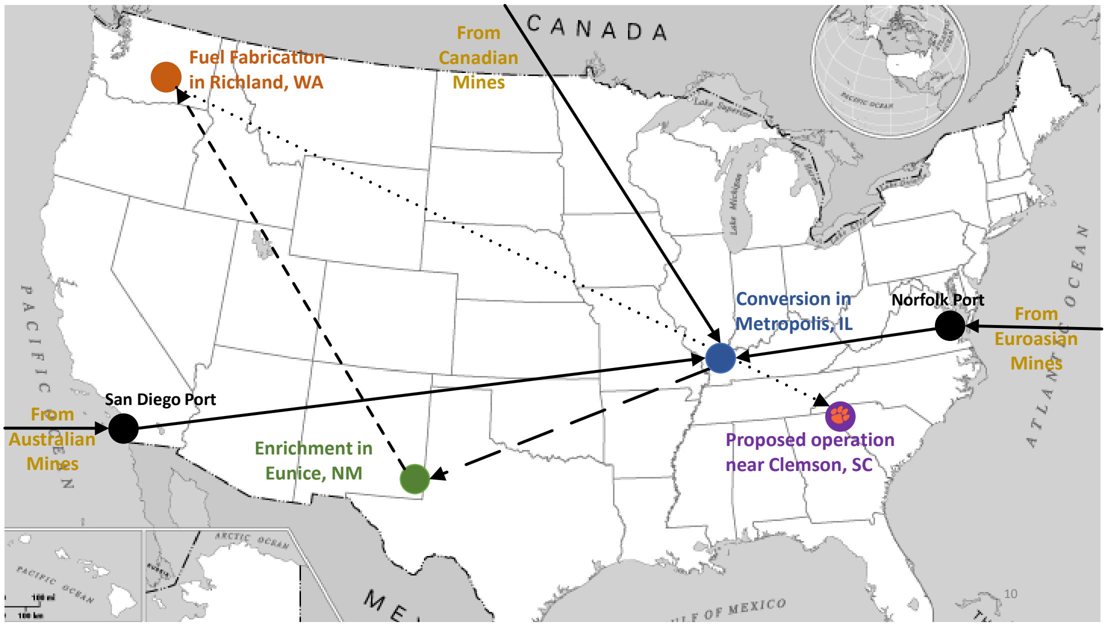


Figure 3.1. Map showing approximate locations for the U.S. fuel cycle facilities as well as the line-of-sight transportation paths between all stages of the LCA.

It was mentioned in the discussion of the mining and milling stage that most uranium used in the U.S. nuclear fuel cycle is imported from other countries. For this reason, consideration of transportation following this stage is important. For countries on a different continent than the U.S., transoceanic transportation from the major ports of each country to major ports in the U.S. were considered. The U.S. ports used in this analysis, Norfolk, VA and San Diego, CA, were chosen based on proximity to the source country as well as likelihood of accepting nuclear material based on U.S. Naval presence. For the calculation of the distance traveled by the freight, an online sea routes calculator was used.[63] For Canadian imports, transportation was assumed to occur by rail from Saskatoon to Metropolis, IL, the location of the conversion facility in the U.S. The remaining travel for the uranium ore from Kazakhstan, Uzbekistan, Russia, and Australia was also assumed to occur by rail. It was assumed that 0.34 tonnes of uranium ore would be shipped in 210-literliter containers for each shipment.[64]

From the conversion facility in Metropolis, IL, the remaining transport was assumed to occur by truck in Type 48Y packaging. Each package was assumed to weigh 2359 kg, and shipments were limited to one package per truck in accordance with Nuclear Regulatory Commission specifications for shipment of uranium hexafluoride.[25] After arriving in Eunice, NM, the packaging for the uranium hexafluoride is re-used for storage and transportation of depleted uranium and so is not considered a waste stream of this transportation.[25]

Because most of the data used in this analysis is for the NuScale Power SMR design, the fuel vendor for this design was chosen as the next transportation point for the now-enriched uranium. NuScale has announced its partnership with AREVA for fabrication of the fuel for their SMR design,[65] and so the fuel fabrication stage was assumed to occur in Richland, WA, the U.S. location for AREVA's fuel fabrication operations. This shipment was assumed to occur via truck and in Type 30B packaging weighing 635kg each. The recommended number of packages per shipment is 3, as specified by the Nuclear Regulatory Commission, though a maximum of 5 can be shipped.[25] In this case, the recommended was used.

According to NuScale Power, following fabrication, the module will then be shipped to the site of operation in 3 components for assembly.[37] The total weight of the module is 700 tons,[37] making each shipment approximately 233 tons each. This transportation, like most shipments in the fuel cycle, would also be done by truck. The distance traveled by this shipment would, of course, depend on the chosen location for the SMR facility. Because of market infrastructure, the likeliest location for the first small modular reactor facility in the U.S. would be in the southeastern region. Already, a site permit is being sought by the Tennessee Valley Authority for a facility in TN.[66] The hypothetical location for a small modular reactor facility was chosen to be Clemson, SC.

No transportation of used nuclear fuel is considered, as it is assumed that all waste will be stored on site. Further, no permanent storage solution has been reached by the U.S. that would dictate any further transportation of the fuel following discharge from the reactor and subsequent cooling. The specific mileage and weight data used for transportation throughout the life cycle is reported in Table B.2 of Appendix B

Impact Assessment

The ReCiPe 2008 database was used to assess the impact associated with the life cycle inventory constructed for this study.[67] A ReCiPe 2016 database has been published. As a newer database, ReCiPe 2016 is less extensively vetted. Future work should include a comparison of the ReCiPe 2008 and 2016 databases for the system detailed in this study. The LCA impacts were calculated in terms of 1 MWh of electricity produced using a Hierarchical viewpoint. The Hierarchical viewpoint is the most commonly used perspective for LCA studies because it is neither optimistic nor pessimistic with respect to the assessment of the impacts. For reference, ReCiPe considers an “optimistic” viewpoint as one in which all possible measures for limiting environmental impacts are taken. Of the eighteen midpoint and three endpoint indicators, or impact categories, included in ReCiPe

2008, this study focused on six of the more commonly evaluated impact categories, including:

1. Water depletion (m^3)
2. Fossil depletion (kg oil-eq)
3. Metal depletion (kg Fe-eq)
4. Climate change (kg CO_2-eq)
5. Human toxicity (kg 1,4-DB eq)
6. Ionizing radiation (kBq ^{235}U-eq)

The impacts of discrete processes and material flows are measured in terms of equivalent characterization factors, which describe the relative impact a chemical or toxin has on the environment in a specific impact category. Characterization factors are calculated based on the fate, exposure, and effects of a particular chemical or toxin.[68] For example, 1 kg methane produces equivalent climate change impacts as 28 kg CO_2.[69] The methodology governing the calculation of each impact category is detailed in the ReCiPe 2008 manual.[70]

Water depletion refers to the amount of water used for the different processes considered throughout the lifecycle, whether or not the water is consumed. Alternatively, metal and fossil depletion consider the metals and fossil resources extracted and consumed for the purpose of processes in the lifecycle. For example, the uranium ore mined for use in the nuclear fuel cycle contributes to metal depletion, as do the metal components (*e.g.*, iron and chromium in steel) used in construction of the facility. An example of fossil depletion is the production and combustion of fuel for transportation.

The climate change impact category considers the adverse effects to the climate resulting from the use of certain chemicals or resources. For example, the production of electricity via a coal-fired generator releases CO_2 into the atmosphere impacting climate change. The human toxicity impact category considers the adverse impacts to human health, which is caused by harmful chemicals or pollutants making their way into the human food chain. While the LCA midpoint does not directly quantify the fate of those toxins, the choice of the Hierarchical approach (as opposed to the Egalitarian or Individual approach) provides the baseline assumptions for the degree of countermeasures against toxin release into the environment and eventual impact on humans.

Similarly, the ionizing radiation impact category considers the potential for human exposure to and health impacts from ionizing radiation from routine releases of radionuclides throughout the fuel cycle. For consistency with the other impact categories assessed, the midpoint ionizing radiation impact (*i.e.*, potential exposure) is assessed in this study. The potential for human exposure to ionizing radiation depends on the amount of ionizing radiation determined in the life cycle inventory (in terms of Bq per functional unit), the environmental fate of the radionuclide(s), as well as the potential human exposure pathway (Figure 3.2). Effectively, the ionizing radiation midpoint impact category is an assessment of the *potential* dose given the amount and type of radiation released throughout the lifecycle.[70] Within the ReCiPe/OpenLCA framework,[71] the data used for calculating radionuclide release, fate, and potential exposure is based on models published in 1985 by the International Atomic Energy Agency (IAEA)[72] and exposure factors defined by Dreicer et al. (1995)[73] and UNSCEAR (1982),[74] which consider atmospheric releases, liquid releases into rivers, and liquid releases into the ocean. The ionizing radiation impact category is reported in equivalents of exposure from an atmospheric release of ^{235}U. As such, the units are reported as Bq ^{235}U-eq, rather than man.Sv. For example, the using a

Heirarchist perspective, the characterization factor for atmospheric exposure from ^{235}U is 1.40 x 10^{-8} man.Sv/kBq or 1.00 ^{235}U-eq, whereas atmospheric exposure from ^{129}I, which is a greater risk factor for atmospheric exposure, is 6.20 x 10^{-6} man.Sv/kBq or 4.43 x 10^{1} ^{235}U-eq.

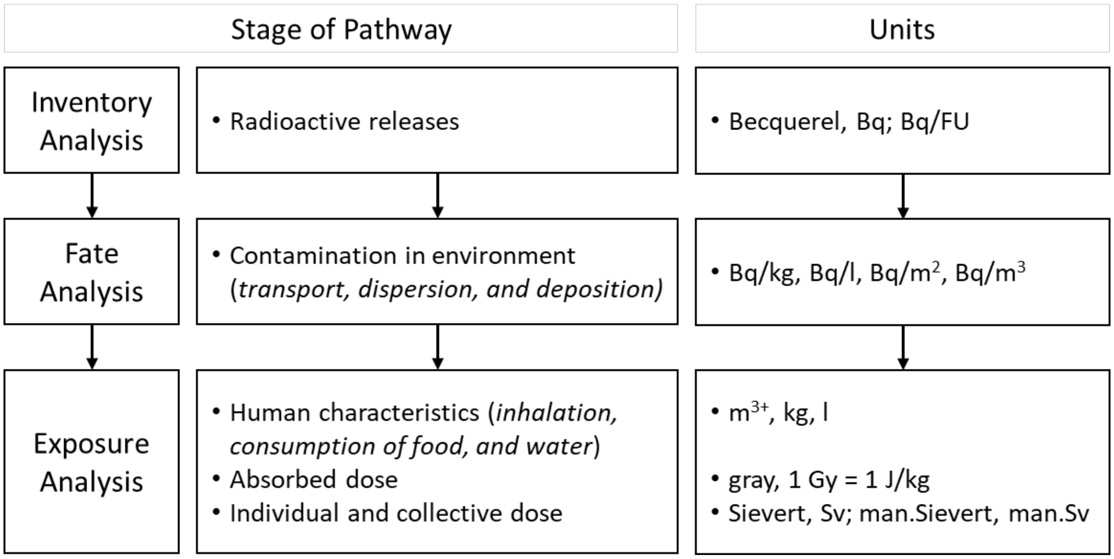
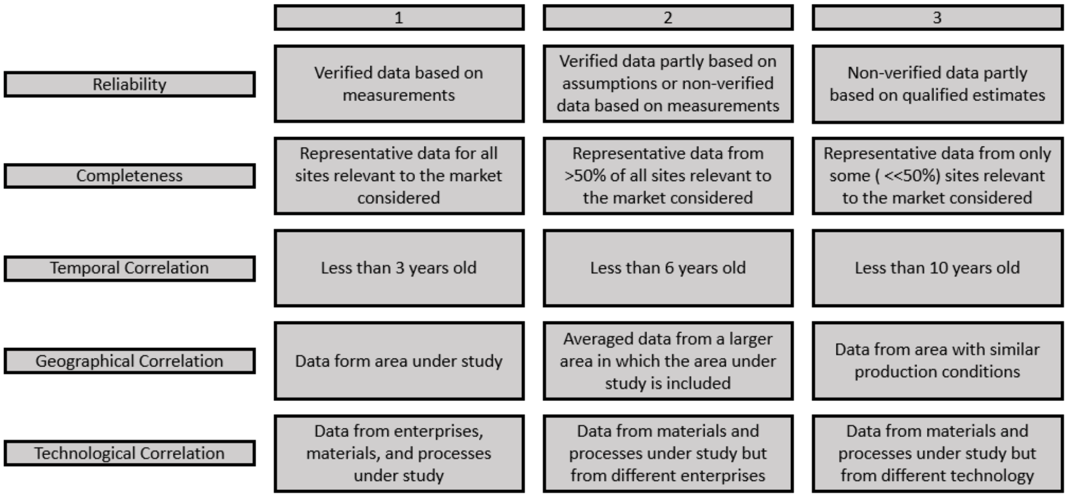


Figure 3.2. Overview of the analyses implemented in the impact assessment as performed using the ReCiPe database. The flowchart is modified from Dreicer et al. 1995[73] *and Frischknecht et al. 2000.*[71]

Data Quality Analysis

Data quality analysis is a means to semi-quantitatively assess the quality of data on which a lifecycle inventory is built. The pedigree of the data for each LCI flow was documented using the pedigree matrix housed within the EcoInvent database (Figure 3.3). A pedigree matrix consists of a series of indicators about which the data quality is ranked. For example, the EcoInvent pedigree matrix includes five indicators for data quality assessment: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation.[75] The portion of the EcoInvent pedigree matrix in Figure 3.3 shows rankings one through three out of a total of five, where one is the best.



	1	2	3
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates
Completeness	Representative data for all sites relevant to the market considered	Representative data from >50% of all sites relevant to the market considered	Representative data from only some (<<50%) sites relevant to the market considered
Temporal Correlation	Less than 3 years old	Less than 6 years old	Less than 10 years old
Geographical Correlation	Data form area under study	Averaged data from a larger area in which the area under study is included	Data from area with similar production conditions
Technological Correlation	Data from enterprises, materials, and processes under study	Data from materials and processes under study but from different enterprises	Data from materials and processes under study but from different technology

Figure 3.3. EcoInvent pedigree matrix with descriptions of the quality ranks 1-3. All data used in this work ranked 3 or below.[61]

Sensitivity Analysis

Due to uncertainty in some of the parameters in various life cycle stages, several sensitivity analyses were performed. One such uncertainty is in the materials used for the construction stage of the life cycle, as all values available from current small modular reactor vendors are merely low-end estimates intended to sell the technology. In addition, a materials sensitivity can highlight why life cycle assessments seem to vary so broadly, even when considering the same technology. Further, the boundary conditions defined by the goal and scope of an assessment can significantly impact the outcome of the life cycle assessment. In order to determine whether an assumption about material or boundary conditions will have much impact on the results, a sensitivity analysis should be performed.

An additional area of interest when considering the sensitivity of the life cycle is the source of the uranium. As described in the background on the nuclear fuel cycle, there are primarily 3 extraction techniques for uranium: open-pit, underground, and *in situ* leach mining. While open-pit and underground mining are expected to have similar impacts to resources and environment, the process of *in situ* leach mining could yield significantly different results. For the processing stages of uranium (conversion, enrichment, etc.), the location of the processing facility could greatly impact the results of the assessment. This is because many stages in the nuclear fuel cycle are relatively energy intensive and thus are subject to the effect of the energy portfolio of that region. The regional energy portfolio for each processing facility was incorporated for the base-case. To demonstrate the effects of energy source on the assessment, several cases were considered in which the electricity source for the entire life cycle was changed to the same source. For example, in one case, all stages of the life cycle were assumed to source their energy from coal electricity. This was repeated for nuclear and hydroelectric sources. Additionally, because the U.S. imports much of its uranium resources from other countries, and processing facilities for uranium fuel are located at vast distances from one another, it is relevant to consider the impact of transportation on the results of the assessment. This was accomplished by considering a case where transportation is included and one where it is removed entirely.

Lastly, because the data for decommissioning was sourced from a report on the decommissioning of a German facility, it is important to note the potential differences in strategy between the U.S. and Germany. In Germany, when the report was published, decommissioning entailed not only decontamination of the general area but also of the concrete, steel, and various other materials for recycling.[59] While there is no nation-wide regulation addressing the possible recycling of decommissioning materials in the U.S., there are few, if any, states that have adopted this strategy. Instead, contaminated concrete and steel are generally treated as low-level nuclear waste and stored as such. Thus, a sensitivity analysis on the decommissioning phase, where in one case the materials are mostly recycled, and in the other they are not. For the former assumption, the resources required to recycle the materials are considered as well as the reduction in low-level waste. For the latter, all materials resulting from the decommissioning stage are treated as low-level nuclear waste.

In summary, the sensitivity analyses considered for this assessment include:

1. Electricity source
2. Mine type
3. Transportation
4. Materials during construction and decommissioning

CHAPTER FOUR

RESULTS AND DISCUSSION

LCIA results

Of the 18 midpoint impact categories available from the ReCiPe analysis,[70] the six impact categories analyzed within the scope of this work include: water depletion, fossil depletion, metal depletion, climate change, human toxicity, and ionizing radiation. The "base-case" analysis (Table 4.1) is based on the fuel cycle inventory described in the methods, and includes the reactor building as well as the support structures. The electricity use for each stage modeled in the "base-case" is representative for the region in which that stage occurs. For example, enrichment in the U.S. occurs in Eunice, New Mexico, so the electricity use for the enrichment process is sourced from the Texas Reliability entity (TRE). The only stage in which the regional electricity grid is not modelled is in the mining and milling stage, because the EcoInvent process, in which all flows are already defined, for underground and open pit mining was used. Thus, the electricity source for open pit and underground mining are predetermined and could not be altered.

Table 4.1. Midpoint impacts based on the "base-case" inventory assessment.

Impact Category	Base-case Analysis
Water depletion	7.64 m^3
Fossil depletion	0.89 kg oil eq
Metal depletion	2.03 kg Fe eq
Climate change	4.55 kg CO_2 eq
Human toxicity	18.02 kg 1,4-DB eq
Ionizing radiation	441.07 kBq ^{235}U-eq

The percent contribution of each fuel cycle stage to an impact category can further detail the underlying influences on the ultimate impacts. Figure 4.1 shows that the majority (>80%) of climate change impact is due to processes in the front-end of the fuel-cycle. The operation of front-end fuel cycle facilities, such as conversion, enrichment, and fuel fabrication facilities, have a high energy demand. For example, the enrichment required for the NuScale design (4.95% ^{235}U), requires 8.15 SWU per kilogram of product, and each SWU is estimated to use 40 kWh, totaling 326 kWh/kg of product.[25] Furthermore, enrichment occurs in Eunice, NM, where fossil fuels make up about 70% of the electricity portfolio[76] and greatly contribute to the climate change impact category. Likewise, for conversion and fuel fabrication, electricity is the primary resource demand. For the mining and milling stage, the use of natural gas and diesel for processing uranium and operating large equipment is the primary contributor to the climate change impact.

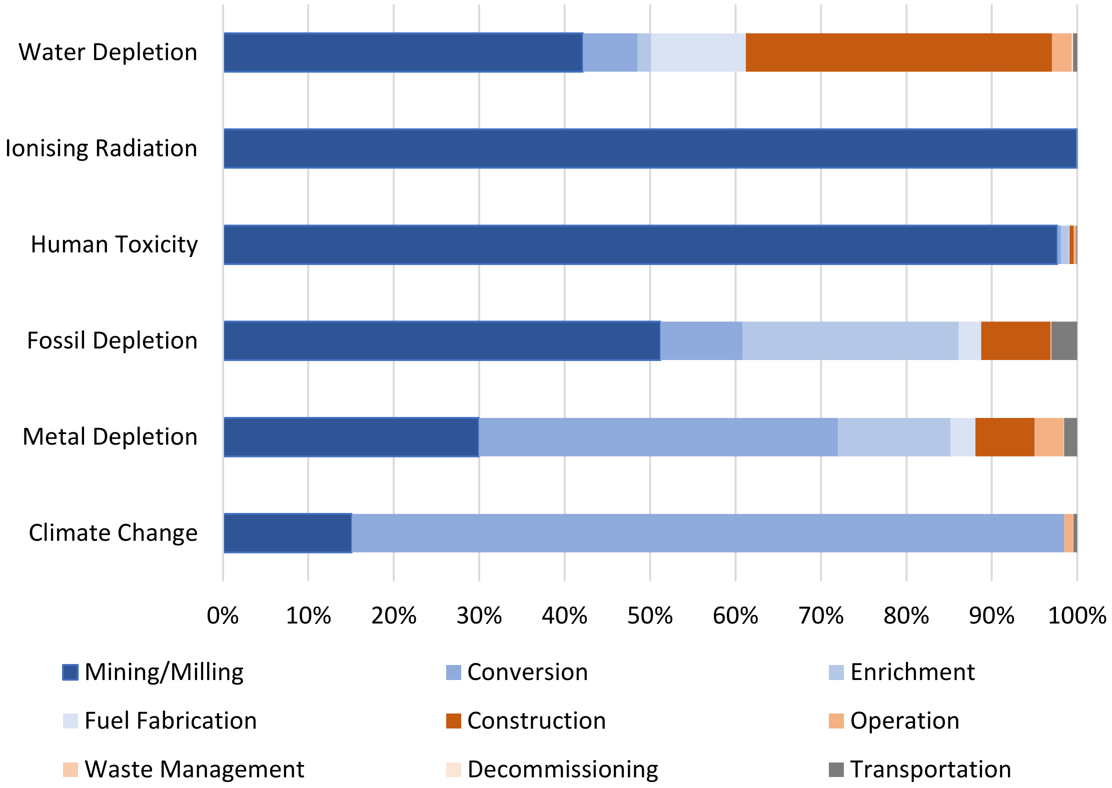


Figure 4.1. Distribution of impacts among the life cycle stages for small-modular reactor technology.

The construction stage contributes ~7% to the total climate change impact due to the large volume of concrete and steel used in the facility. The manufacture of concrete is very energy intensive—more specifically, the manufacture of the cement that is used in concrete. First, rock must be quarried, followed by several iterations of crushing. It is then heated to approximately 2,700 °F, blasted with flame, forcibly cooled, and the mixture is then crushed again.[61] These processes require the use of diesel, natural gas, coal, and other CO_2-emitting resources. Finally, transportation throughout the fuel cycle contributes 1.5% to the total climate change impact. Most uranium resources are imported to the U.S. from overseas suppliers, requiring transoceanic transportation. Furthermore, U.S.-based uranium processing facilities (*e.g.*, conversion, enrichment, fuel fabrication) are located at facilities across the country, requiring shipments either by train or by truck.

Corresponding with the climate change impact distribution, the fossil depletion impacts too are found mostly in the front end of the fuel cycle. This correlation is because the combustion of fossil fuels is what contributes a majority of climate change impacts, alongside such processes as concrete production. The fuel processing stages are large consumers of natural gas, electricity, diesel, or a combination thereof. Mining and milling are responsible for the largest fraction of nearly all the impacts, due to how resource-intensive the processes are, except for water use. Water use is the highest for the construction stage, due to the high quantities of steel and concrete required in this stage.

Data Quality Analysis

After ranking each flow (where information was available) in the inventory using the EcoInvent pedigree matrix, OpenLCA was used to determine the data quality for all possible midpoint impact categories. Based on limitations in inventory data, the only impact category, of the 6 considered in this analysis, that could be evaluated for data quality was climate change. The summative data quality for the climate change impact was 3 for reliability, 2 for completeness, 3 for temporal correlation, 2 for geographical correlation, and 1 for further technological correlation. For reliability, the climate change impact comes from non-verified data based partly on qualified estimates.[77] This was the case for much of the life cycle assessment, because data for stages such as construction and operation were based on speculative information from the small modular reactor vendor, where no physical facility is available for measurements to verify those estimates. The ranking of the data's completeness corresponds to a set that represents greater than 50% of all relevant facilities to the market.[77] Because this was an assessment for U.S. facilities, information directly from U.S. facilities was sought. Where this was not available, averages in which these facilities were included was used instead.

The temporal correlation received a ranking of 3, which corresponds to less than 10 years difference in time from the time period of the data set.[77] The age of the sources used in this assessment varied greatly; while information from the vendor is less than 3 years old, some environmental impact statements used in the assessment are well over 10 years old. The geographical correlation is strongly related to the reliability indicator; it was ideal for information to come directly from the facility of interest, but inclusive averages were used in lieu of this. Great care was taken to source data from the correct geographical locations, although much of the data is averaged from a larger area, which includes the area of interest.[77] The technological correlation, in terms of the flows used to calculate the climate change impact, was found to have a score of 1, because the inventory flows represented the technology being assessed, rather than a similar technology. Vendor-reported data was used for the construction and operation stages, and well-documented reports were used for all other fuel cycle stages, which are not unique to the SMR technology of interest apart from fuel fabrication. The fuel fabrication stage was altered quantitatively to represent the fabrication of SMR fuel assemblies; however, accurate representation of SMR module fabrication could not be included due to lack of manufacturing precedence.

Sensitivity Analyses

Sensitivity analyses were performed to better understand the parameters that most affect the results of the base-case life cycle assessment. The sensitivity of the assessment was evaluated based on the source of electricity, mining technology, transportation, facility infrastructure boundary condition, and recycling upon decommissioning.

To evaluate the sensitivity of the LCA on electricity source, three comparison cases were constructed in which the electricity use for all life cycle stages (except for mining and milling) were sourced entirely from coal, run-of-the-river hydroelectricity, or nuclear (Figure 4.1). It should be noted that the case in which electricity is sourced from nuclear energy, this process was sourced from the available EcoInvent process for nuclear energy. While the nuclear energy process in EcoInvent is not entirely representative of U.S. nuclear electricity production, which is why the nuclear fuel cycle was also considered in this assessment, it does broadly represent the impact differences associated with using nuclear as an energy source throughout the lifecycle processes relative to other sources. The electricity source could not be adjusted for the underground/open-pit mining process since this was sourced directly from the EcoInvent database.

As expected, when much of the fuel cycle electricity is sourced from coal, all the impacts evaluated are increased. In fact, fossil depletion and climate change are significantly increased (by 162% and 673%, respectively). Coal electricity is, by definition, a fossil fuel and requires a high flux of fuel input per electricity output. The increase in human toxicity (171%) is likely related to the increased coal mining activity and production of greenhouse gasses and heavy metals associated with coal electricity. The increase in water depletion (57%) is likely the decrease in use of less water-intense electricity sources (e.g., natural gas). Though the increase in metal depletion (555%) is dramatic as expected, ionizing radiation (~1.7%) is lower than one might anticipate. The operation of a coal electricity plant is known to produce ionizing radiation due to the presence of uranium and thorium in coal. When coal is burned in the generator, the resulting fly ash concentrates thorium and uranium up to 10 times more than the original coal.[78] The contribution of radionuclides released during operation of a coal electricity plant may not be fully included in the effluent flows within the EcoInvent database. Additionally, the magnitude of ionizing radiation due to the mining and milling stages of the life cycle is sufficiently high that even a large increase in the ionizing radiation of an operating coal plant would pale in comparison.

Converting the majority of fuel cycle electricity to run-of-the-river hydroelectricity dramatically increases water depletion (by 21349%) due to the inherent nature of *hydro*electricity. The increase in metal depletion by ~1.8% may be due to the metal demand of the technology used for such a generation facility, an element which would be captured in life cycle assessment. While materials such as concrete and steel contribute greenhouse gasses during their production, most electricity generators use these materials in high quantities. Therefore, while there is a reduction in climate change impacts when using only hydroelectricity associated with the lack of producing and/or combusting a fuel, this reduction is not a dramatic one because these infrastructure materials are still present.

Using only nuclear electricity for most of the life cycle electricity results in a decrease in both fossil depletion (-18%) and climate change (-9%). Nuclear electricity is often cited as a carbon-free (or carbon-neutral) energy source, particularly compared with coal electricity, which is supported by this sensitivity analysis. The reduction in fossil depletion and climate change is less for the nuclear electricity scenario as compared with the hydroelectricity scenario because, while nuclear energy does not require fossil fuels to produce electricity, fossil fuels (i.e. diesel) are used extensively throughout the fuel processing steps of the life cycle. Likewise, while metal depletion (+8%) is less than that from the all coal electricity scenario (+555%), it is still higher than that from the all hydroelectricity scenario (+1.8%), because the nuclear fuel, UO_2, is mined as a metal resource. The ionizing radiation impact category for the mostly nuclear electricity scenario increases by 7% due to the radioactive nature of nuclear fuel, where the greatest contribution comes from the mining/milling process. This is due mostly to the radon released during the mining process in addition to mill tailings.

Based on the distribution analysis for the base-case and some minor discrepancies in the impact assessment for different electricity sources, the technology for uranium mining was also evaluated, where the options for uranium mining technology depend on the ore grade and deposit geology. In recent decades, *in situ* leach mining has become more prevalent for uranium extraction, but underground and open-pit mines are still used widely. Australia and Russia use a combination of traditional mining (*i.e.*, open pit and underground mining) and *in situ* leach mining (of the contributing countries used for this assessment). The other countries considered in this assessment use either traditional mining (*i.e.*, Canada) or *in situ* leach mining (*i.e.*, Kazakhstan and Uzbekistan).

When *in situ* leach mining (ISL) is the only mining method employed, there is an increase in the water depletion (+4%) and fossil depletion (+39%) impacts, but a reduction in metal depletion (-83%), climate change (-17%), human toxicity (-95%), and ionizing radiation (-100%). The slight increase in water depletion is a result of the extraction method employed with ISL mining: an acidic or alkaline solution is pumped into the earth via injection wells, oxidizes the uranium and other metals, and then is pumped back to the surface for processing. This method, naturally, has a higher water consumption than methods such as underground and open-pit mining. However, further milling is not necessary. The increase in fossil depletion is likely a result of the resources necessary to operate the ISL mining process. As shown in Appendix B – Inventory Data, one of the input material flows for the ISL mining process is high pressure natural gas. The large reduction in metal depletion for all ISL mining is likely because the ISL method solubilizes uranium *in situ* so that the solubilized uranium can be extracted via pumping without requiring removal of large masses of rock, thus reducing the consumption (*i.e.*, depletion) of metal. The reduction in ionizing radiation and human toxicity are inextricably linked. Because ISL mining does not require the additional step of milling, there are no resultant mill tailings. Mill tailings are a significant source of ionizing radiation released to the environment, and the heavy metals present in mill tailings are a human health risk. Further, occupational exposure to ionizing radiation is greatly reduced for ISL compared with underground mining. While there are potential environmental and human health risks associated with the use of the ISL leaching solution, potential risks are not included in the

LCA. That is, the scope of this LCA does not include impacts associated *accidental* releases to the environment.

The sensitivity analysis of the LCA based on different boundary conditions enables better comparison between published studies (See Comparison to Other LCAs), which often set vastly different boundaries depending on the objectives of the study. For example, transportation is commonly excluded from LCA analyses if one assumes that the transportation impacts are the same between systems that are being compared. Even though transportation only contributes 1.5% to the climate change impact category of this LCA (Figure 4.1), the sensitivity analysis shows that the exclusion of transportation from this

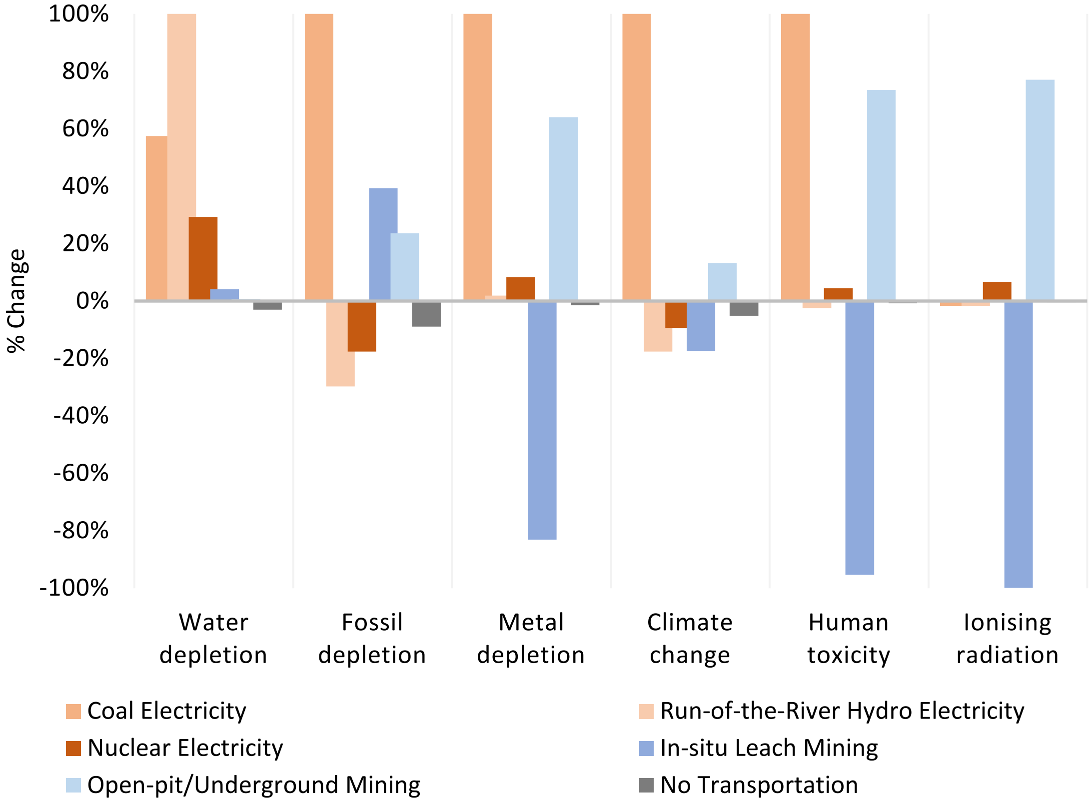


Figure 4.2. Percent change in life cycle impacts (legend) based on different scenarios (x-axis) as compared with the base-case fuel cycle analysis.

LCA leads to measurable changes in water depletion (-3%), fossil depletion (-9%), metal depletion (-1.5%), as well as climate change (-5%). The production, processing, and combustion of fuels in transportation vehicles of various types logically influences these impact categories, especially fossil depletion and climate change.

Many life cycle assessments on energy generation technology look only at the construction of the generator (*i.e.*, reactor building) itself, and not any of the support facilities; however, the additional infrastructure will increase the overall impact. Further, when comparing different types of electricity generation technology, the material and energy flows associated with the support structures are likely different. Inclusion of the support structures essentially probes the sensitivity of the LCA on the amount of construction materials (concrete and steel) on the life cycle in general. Since small-modular reactor vendors are providing low-end estimates for construction materials, it is worthwhile to assess the sensitivity of the overall life cycle impacts on the amount of construction materials. The difference in the effects of transportation on climate change in the impact distribution and the sensitivity analysis is due to the fact that the sensitivity accounts for all transportation in the lifecycle, including the transportation of employees to the facility during operation; for the impact distribution, only the transportation stages were considered.

When the life cycle is considered for the reactor building only (*i.e.*, without including the support structures of the small-modular reactor facility), there is a small reduction in both water depletion (-2%), climate change (-2%), and fossil depletion (-2%), while the other impact categories exhibit changes of < 1% (Figure 4.3). The reduction in water depletion, climate change, and fossil depletion impact categories correlates to the reduced need for production of cement for concrete, which is a major material, along with steel, used in construction.

Upon decommissioning, the concrete and steel used during construction can be decontaminated and recycled, driving down the need to produce new concrete and steel. While decontaminating and recycling these building materials reduces the need for producing new material, the process of recycling concrete and steel is very energy and resource intensive.[62] When the boundary conditions of the LCA are modified to include impacts associated with recycling concrete and steel upon decommissioning, water depletion, fossil depletion, metal depletion, and climate change are increased by <1%. Naturally, combining the recycling of concrete and steel with elimination of support structures from the assessment further reduces the impact compared to the recycling case alone, but it is still more than the reactor building scenario by itself. Because these values are all so low, it is difficult to extricate much meaning from the numbers. The statistical uncertainty (which was not considered in this analysis) in the values could be sufficient to render the change in impacts insignificant. For a more thorough examination of the sensitivity of impacts to materials use and disposition, a detailed uncertainty analysis should be carried out.

The incentive to decontaminate and recycle concrete, however, is based on more than just the noted impacts. Recycling these materials would result in a decreased flux of material to landfills or to LLW facilities, which would potentially reduce costs for the company performing the decommissioning. Additionally, whether to recycle concrete and steel for environmental reasons depends on the priorities of the assessing entity; for example, if reduction in solid waste or LLW is the priority in decommissioning, recycling these materials would be an excellent option to accomplish this task.

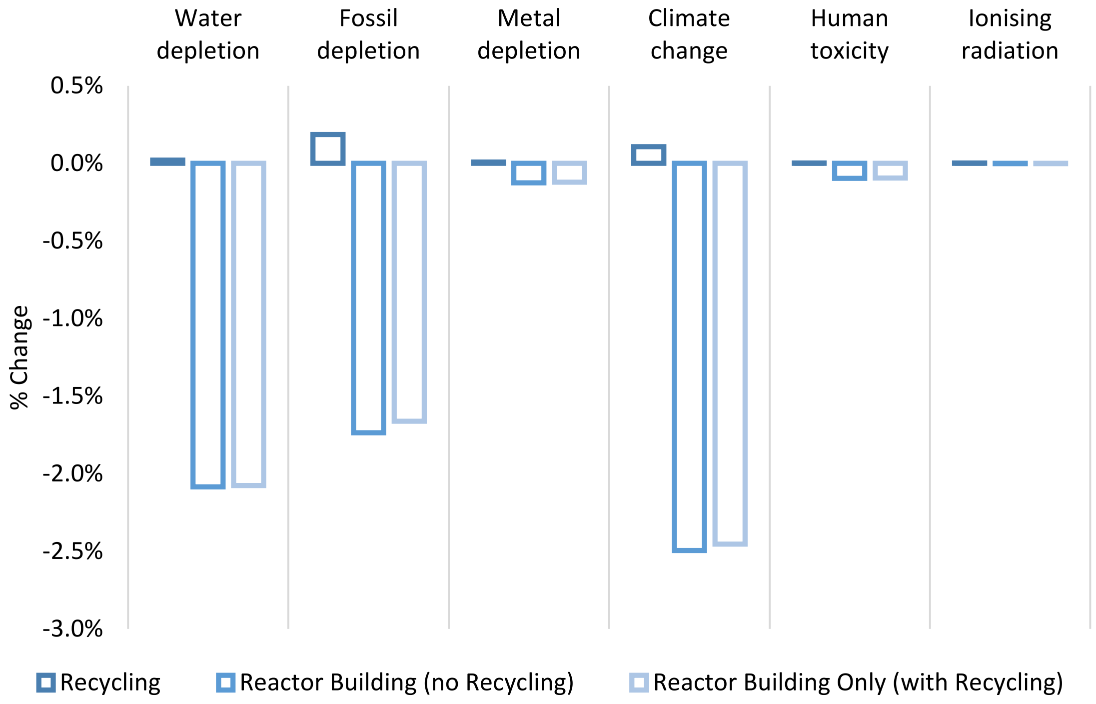


Figure 4.3. Percent change in impacts based on materials usage during construction and disposition during decommissioning.

Comparison with Other LCAs

Comparison of this LCA with previously published studies further highlights the effect of different LCA boundary conditions and emphasizes the need to consider appropriate fuel cycle facilities and processes for the system of study. Several LCA analyses have been published on nuclear fuel cycles, many of which are summarized in the review by Manfred Lenzen.[79] The climate change impact calculated by Carless et al.[1] and the National Energy Technology Laboratory(NETL)[2] are compared with this LCA. Carless et al. considered the environmental competitiveness of a Westinghouse integral pressurized water reactor (iPWR; a small-modular reactor) and the Generation III+ Westinghouse AP1000 reactor.[1,2] The NETL report is a detailed life cycle assessment highlighting the environmental impacts of existing nuclear energy technology as well as that of Generation III+ technology.

The climate change impact computed in this study appears much lower than that reported by Carless et al. and NETL (Table 4.2). Closer inspection of the NETL assessment reveals some details that could account for this disparity: in the fuel cycle being considered in the NETL assessment, 52% of the uranium hexafluoride is assumed to be enriched by using gaseous diffusion technology (and 48% by centrifugation).[2] Because this assessment was published in 2012, and the Paducah Gaseous Diffusion Plant did not cease operation until 2013,[80] enrichment for U.S. commercial reactors was accomplished using both gaseous diffusion and centrifugation. Since 2013, the National Enrichment Facility in Eunice, New Mexico has become the only operating enrichment facility in the U.S. The gaseous diffusion enrichment process is much more energy intensive than centrifugation, resulting in a greater climate change impact. In the NETL assessment, the contribution of diffusion enrichment to the climate change impact of the Gen III LWR was 27.7 kg CO_2-eq/MWh, while the impact of centrifuge enrichment was only 0.2 kg CO_2-eq/MWh—despite that each method is used in approximately equal amounts.[2] Thus, the impact of the enrichment process using 100% centrifugation would be about 0.4 kg CO_2/MWh. Based on the contribution graph shown in Figure 4.1, the enrichment process contributes 1.1 kg CO_2-eq/MWh to climate change impact, which is far more comparable.

The NETL assessment also considered the contribution of the transmission and distribution of electricity. A post-process adjustment of the NETL LCA to remove gaseous diffusion enrichment and transmission and distribution of electricity results in a climate change impact of 8.50 kg CO_2-eq/MWh and 6.30 kg CO_2-eq/MWh for the Gen III and Gen III+ LWR, respectively. Of note, the NETL impact assessment for the Gen III+ LWR goes from nearly double that of the Carless assessment of the AP1000 to less than half that of the Carless assessment (6.30 for Gen III+ LWR) when adjusted, which emphasizes the sensitivity of the LCA on the LCA boundary conditions, as well as the methodology employed for the LCA. There are generally two methods employed for life cycle assessment: process chain analysis (PCA) and economic input-output (EIO) method. Process chain analysis requires quantified knowledge about the material and energy flows required for all the life cycle processes considered. When information about these flows is not readily available, researchers often employ the EIO method. The EIO method attributes environmental impacts based on the cost associated with the life cycle processes considered. However, the environmental impacts are not always driven by the economics of the life cycle processes, resulting in an over- or under-estimation of the impacts compared with those quantified using the PCA method.[81] The higher fuel cycle impacts determined by Carless et al. may be due to the use of the EIO methodology.

In fact, the NETL assessment for the Gen III+ LWR can be further adjusted for comparison with the NuScale SMR reactor LCA presented here considering the reduction of impacts associated with the AP1000 and the Westinghouse iPWR SMR as determine by Carless et al. With the 38% reduction in impacts between the full-scale reactor and the

SMR, the NETL adjusted assessment for an SMR is 3.89 kg CO_2/MWh – similar in magnitude to the 4.55 kg CO_2/MWh calculated in this study.

Comparison to Other Energy Generators

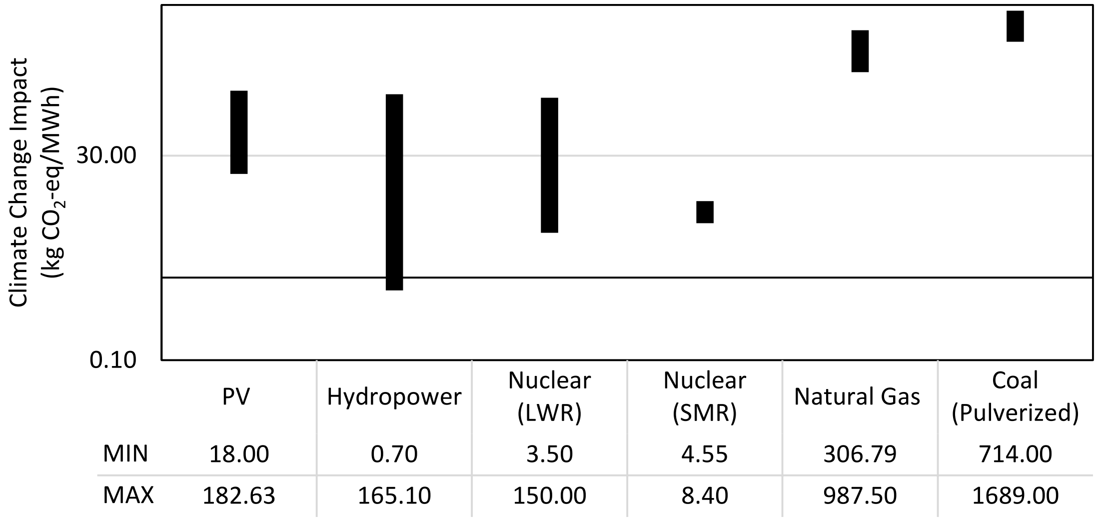
Table 4.2. Comparison of climate change impacts between Carless et. al,[2] the National Energy Technology Laboratory,[3] and this assessment for nuclear energy technology.

Reference	***Reactor Type***	***Climate Change (kg CO_2-eq/MWh)***
This study	NuScale (SMR)	4.55
Carless et al.[2]	iPWR SMR	8.40
Carless et al.[2]	AP1000	13.60
NETL[3]	Gen III LWR	39.50 (8.50)[a]
NETL[3]	Gen III+ LWR	25.80 (6.30)[a]

[a] Adjusted LCA impact considering gaseous centrifugation as the only enrichment process and discounting impacts from distribution and transmission of electricity.

The climate change impact of nuclear energy generation technologies is further compared with other energy generators (Figure 4.4). OpenEI provides a comprehensive comparison of several LCAs on different energy generators, showing a wide spread between the minimum and maximum value for the calculated climate change impact.[82] The importance of the LCA boundaries and assumptions is emphasized by the large range of climate change impacts for the technologies considered in Figure 4.4. Because the range represents several different LCAs, the boundaries and assumptions for each assessment will vary at least slightly—possibly dramatically in some cases. For this reason, it is vastly important to be transparent about boundaries and assumptions in life cycle assessment and to understand these limitations in other assessments when making a comparison.

The spread in the data for the SMR nuclear technology is representative of the difference between the nuclear LCAs previously discussed. As expected, nuclear technology outperforms energy technologies based on fossil fuel resources, such as coal and natural gas. Further, nuclear technologies, both traditional full scale and SMR, have a similar climate change impact as PV solar and reservoir hydropower generators, supporting the argument made by the nuclear industry that nuclear technology is a "clean" energy like that of renewables. However, it should be noted that certain characteristics of nuclear energy, specifically the generation of nuclear waste, impacts the definition of nuclear technology as "clean."



	PV	Hydropower	Nuclear (LWR)	Nuclear (SMR)	Natural Gas	Coal (Pulverized)
MIN	18.00	0.70	3.50	4.55	306.79	714.00
MAX	182.63	165.10	150.00	8.40	987.50	1689.00

Figure 4.4. Bar graph marking the maximum and minimum LCA climate change impacts of various electricity generators (kg CO_2-eq/MWh). The nuclear SMR minimum is from this study and the maximum is from Carless et al.[2] All other maximum and minimum values are from OpenEI.[82]

Considerations for New **Technology**

In the discussion of a new technology, it is important to acknowledge the difference between the first deployment, or first-of-a-kind (FOAK), *versus* the nth deployment, or nth-of-a-kind (NOAK). New technologies often require unique component manufacturing, which in turn may require non-existent facilities. At the very least, retrofitting of existing manufacturing facilities requires investment in engineering design and development beyond that required to develop the ultimate new technology. In the example of small modular reactor technology, a major advantage often cited is the ability to factory-build the entire reactor module (*e.g.*, the *NuScale Power Module* or *NPM*), requiring assembly, but far less construction, on-site.[83] Fabrication of initial SMR modules will likely occur using existing infrastructure. However, a specially-designed facility would enable more efficient and cost-effective manufacture of SMR modules. While the cost saving advantage of a factory-built reactor is often expressed in support of SMR technology, no plans for said factory could be found at this time. The lack of appropriate production methods can lead to an increase both in expense and in environmental impacts of a technology. The assessment presented in this work considered a mature SMR technology (*i.e.*, NOAK approach) in that efficient production methods were assumed to exist for the fabrication of necessary components, including the modules, fuel assemblies, and dry storage casks. A FOAK assessment of small modular reactor technology would likely yield significantly different results, specifically with respect to the fuel fabrication, construction, waste management, and decommissioning stages.

CHAPTER FIVE

CONCLUSIONS AND FUTURE WORK

The U.S. electricity grid is facing much change in light of concerns over flexibility, economics, and climate change impacts. For the nuclear industry to stay competitive in a changing market, it is important to adopt new and innovative technologies to meet the demands of a future generation. However, technological advances should occur with consideration of both the economic and environmental impacts of deployment. Life cycle assessment allows for a technology to be described in terms of its environmental impacts across the entire life cycle, from the extraction of materials for use to the disposal of the technology at the end of its life. The available inventory data for life cycle assessments on nuclear technology is based on European fuel cycle, and many assessments use outdated technology for some processes (i.e. the NETL assessment using gaseous diffusion for enrichment). To evaluate the impact of a SMR in the U.S., there is a need to evaluate the nuclear fuel cycle processes specific to the U.S.

The LCA presented in this work evaluated the environmental feasibility of small modular reactor technology using the U.S. nuclear fuel cycle and found that most of the impacts evaluated are associated with front end fuel cycle processes (*e.g.*, > 80% for climate change impacts). The SMR technology evaluated (NuScale design) was shown to have lower environmental impact than traditional nuclear reactors, as well as other energy technologies (*i.e.*, coal and natural gas), based on comparison with other LCA studies.

Sensitivity analyses and comparison with existing LCA showed that the LCA outcome can strongly depend on the boundary conditions of the system, as well as the availability and accuracy of the data used in the life cycle inventory. Throughout this work, approximations for inventory data were supported with literature, however, many of those "gaps" in data warrant further investigation. Impacts related to FOAK *versus* NOAK with consideration of impacts associated with construction of necessary fuel cycle facilities (*e.g.*, module fabrication facility). Extend into risk assessment and influence of even newer tech (extended refueling such that entire modules last similar to Navy reactors).

Also emphasized in this work is the lack of on the back-end of the fuel cycle for SMR technologies, specifically strategies outlined for waste management and decommissioning. With increasing public interest in the collide of climate and environmental issues, detailed evaluation of waste management and decommissioning of SMR technology should be completed prior to commercial deployment and could even serve as an additional selling point for SMR technology. Combined with the economic favorability,[84] the lower environmental impact of small modular reactors can help to incentivize the deployment of this new technology and to predict its success in an evolving energy market.

APPENDICES

APPENDIX A

Equations Used for *In Situ* Mining Process

For the calculation of resource use and emissions for the *in situ* leach mining process (within the mining and milling stage), relationships from an Idaho National Laboratory study[47] were used. These relationships are summarized Equations 1-3, which quantify uranium yield (*Y*) as a function of ore grade (*G*), water consumption (*w*), and energy intensity in GJ (*e*), respectively.

$$Y_{ISL} = 0.686 - 0.0506(\log(G))^2$$

Equation 1[47]

$$w = \frac{100}{G * Y_{ISL}} w_{ISL} + w_U$$

Equation 2[47]

Where w_{ISL} is 9.88×10^{-3} ML/t (mega-liters per tonne) ore is the amount of water consumed prior to refining and w_U is the amount of water required for the refining step.[47]

$$e = \frac{100}{Y_{ISL}} e_{ISL} + e_U$$

Equation 2[47]

Where e_{ISL} is the energy required to pump the solution to the ore body, and e_u is the energy required to convert the ore to material desired.[47]

APPENDIX B

Life Cycle Inventory Data

Table B.1. Bill of Materials for the base case LCA, including the name, EcoInvent category (if applicable), designation of process (P) or flow (F), and the quantity for all inputs and outputs in the LCA stages. Output materials are denoted with light grey shading versus *input materials without shading. Where applicable, the data quality assessment is also included for reliability (Rel.), completeness (Com.), temporal correlation (Tem.), geographical correlation (Geo.), and technological correlation (Tec.).*

<table>
<tr><th colspan="10">Stage: Mining (Open Pit and Underground)</th></tr>
<tr><th>Name</th><th>EcoInvent Category</th><th>P/F</th><th>Value</th><th>Unit</th><th>Rel</th><th>Com</th><th>Tem</th><th>Geo</th><th>Tec</th></tr>
<tr><td>uranium, in yellowcake - RNA</td><td>B.0721:Mining of uranium and thorium ores</td><td>P</td><td colspan="2">Input for Conversion Stage</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td></tr>
<tr><td>uranium, in yellowcake - RoW</td><td>B.0721:Mining of uranium and thorium ores</td><td>P</td><td colspan="2">Input for Conversion Stage</td><td>1</td><td>2</td><td>1</td><td>2</td><td>1</td></tr>
<tr><th colspan="10">Stage: Mining (ISL)</th></tr>
<tr><th>Name</th><th>EcoInvent Category</th><th>P/F</th><th>Value</th><th>Unit</th><th>Rel</th><th>Com</th><th>Tem</th><th>Geo</th><th>Tec</th></tr>
<tr><td>electricity, high voltage - RU</td><td>D:Electricity, gas, steam and air conditioning supply</td><td>P</td><td>7.42×10^4</td><td>MJ</td><td>5</td><td>2</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>electricity, high voltage - AU</td><td>D:Electricity, gas, steam and air conditioning supply</td><td>P</td><td>5.30×10^4</td><td>MJ</td><td>5</td><td>2</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>natural gas, high pressure - RoW</td><td>B.0610:Extraction of crude petroleum</td><td>P</td><td>14.48</td><td>m^3</td><td>5</td><td>2</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Water</td><td>Elementary flows/Resource/in water</td><td>F</td><td>5.21×10^6</td><td>l</td><td>5</td><td>2</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Uranium ore</td><td></td><td>F</td><td>1</td><td>t</td><td>5</td><td>2</td><td>1</td><td>1</td><td>1</td></tr>
<tr><th colspan="10">Stage: Conversion</th></tr>
<tr><th>Name</th><th>EcoInvent Category</th><th>P/F</th><th>Value</th><th>Unit</th><th>Rel</th><th>Com</th><th>Tem</th><th>Geo</th><th>Tec</th></tr>
<tr><td>electricity, high voltage - SERC</td><td>D:Electricity, gas, steam and air conditioning supply</td><td>P</td><td>54</td><td>GJ</td><td>3</td><td>2</td><td>3</td><td>2</td><td>1</td></tr>
</table>

Land use III-IV	Elementary flows/Resource/land	F	0.57	m^2*a	3	2	3	2	1
natural gas, high pressure - US	B.0610:Extraction of crude petroleum	P	582.29	m^3	3	2	3	2	1
transport, freight train - US	H.4912:Freight rail transport	P	722.51	t*km	5	4	1	1	1
transport, freight, sea, transoceanic ship - GLO	H.5012:Sea and coastal freight water transport	P	3.13×10^3	t*km	5	4	1	1	1
Uranium ore		F	0.35	t	1	2	1	2	1
uranium, in yellowcake - RNA	B.0721:Mining of uranium and thorium ores	P	0.24	t	1	2	1	2	1
uranium, in yellowcake - RoW	B.0721:Mining of uranium and thorium ores	P	0.21	t	1	2	1	2	1
Water	Elementary flows/Resource/in water	F	1.00×10^5	kg	3	2	3	2	1
Carbon dioxide	Elementary flows/Emission to air/low population density	F	7.00×10^4	kg	3	2	3	2	1
UF_6		F	1	t	3	2	3	2	1
Stage: Transportation from Conversion to Enrichment									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
transport, freight, lorry 7.5-16 metric ton, EURO5 - GLO	H.4923:Freight transport by road	P	2.10×10^4	t*km	2	1	1	2	3
UF_6		F	12.5	t	2	1	1	2	3
UF_6		F	12.5	t	2	1	1	2	3
Stage: Enrichment									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
aluminium oxide - GLO	C.2420:Manufacture of basic precious and other non-ferrous metals	P	2.28×10^{-3}	kg	2	1	4	1	1
diesel - Europe without Switzerland	C.1920:Manufacture of refined petroleum products	P	0.34	kg	2	1	4	1	1
electricity, high voltage - TRE	D:Electricity, gas, steam and air conditioning supply	P	326.20	kWh	3	1	1	1	1
natural gas, high pressure - US	B.0610:Extraction of crude petroleum	P	5.38	m^3	2	1	4	1	1

nitrogen, liquid - CA-QC	C.2011:Manufacture of basic chemicals	P	7.07×10^{-5}	kg	2	1	4	1	1
UF_6		F	9.81	kg	3	1	1	1	1
Water	Elementary flows/Resource/in water	F	152.00	kg	2	1	4	1	1
4.95% Enriched UF6		F	1	kg	3	1	1	1	1
1	Elementary flows/Emission to air/low population density	F	8.68×10^{-4}	kg	2	1	4	1	1
hazardous waste, for incineration - GLO	E.3822:Treatment and disposal of hazardous waste	P	0.30	kg	2	1	4	1	1
low level radioactive waste - GLO	E.3822:Treatment and disposal of hazardous waste	P	0.15	kg	2	1	4	1	1
Nitrogen dioxide	Elementary flows/Emission to air/low population density	F	8.68×10^{-3}	kg	2	1	4	1	1
VOC, volatile organic compounds	Elementary flows/Emission to air/low population density	F	1.39×10^{-3}	kg	2	1	4	1	1
Stage: Transportation from Enrichment to Fuel Fabrication									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
4.95% Enriched uranium		F	2.28×10^{3}	kg	2	1	1	2	3
transport, freight, lorry 16-32 metric ton, EURO5 - GLO	H.4923:Freight transport by road	P	7.25×10^{3}	t*km	2	1	1	2	3
4.95% Enriched uranium		F	2.28×10^{3}	kg	2	1	1	2	3
Stage: Fuel Fabrication									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem.**	**Geo**	**Tec.**
4.95% Enriched Uranium		F	1.78	t	2	1	1	1	4
electricity, high voltage - WECC, US only	D:Electricity, gas, steam and air conditioning supply	P	286.20	GJ	3	2	3	2	4
Land use III-IV	Elementary flows/Resource/land	F	7.16	m2*a	3	2	3	2	4
natural gas, high pressure - US	B.0610:Extraction of crude petroleum	P	47.82	m^3	3	2	3	2	4
Water	Elementary flows/Resource/in water	F	1.90×10^{5}	kg	3	2	3	2	4
Zirconium	Elementary flows/Resource/in ground	F	6.71	kg	4	2	1	2	4

Carbon dioxide	Elementary flows/Emission to air/low population density	F	4.89×10^4	kg	3	2	3	2	4
Fuel		F	1.35	t	4	2	1	2	4
Stage: Transportation from Fuel Fabrication to Operation									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
Fuel		F	0.45	t	2	1	1	2	3
transport, freight, lorry 16-32 metric ton, EURO5 - GLO	H.4923:Freight transport by road	P	8.76×10^4	t*km	2	1	1	2	3
Fuel		F	0.45	t	2	1	1	2	3
Stage: Construction									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
concrete, normal - GLO	C.2395:Manufacture of articles of concrete, cement and plaster	P	1.45×10^4	m^3	3	1	1	1	1
diesel - Europe without Switzerland	C.1920:Manufacture of refined petroleum products	P	6.61×10^6	kg	3	1	1	1	1
steel, chromium steel 18/8 - GLO	C.2410:Manufacture of basic iron and steel	P	8.00×10^3	t	3	1	1	1	1
Water	Elementary flows/Resource/in water	F	9.81×10^8	kg	3	1	1	1	1
Carbon dioxide	Elementary flows/Emission to air/low population density	F	1.65×10^4	t	3	1	1	1	1
Nuclear facility		F	1	item	3	1	1	1	1
Stage: Operation									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
Fuel		F	660	t	4	1	1	1	1
Nuclear facility		F	1	item	4	1	1	1	1
transport, passenger car, EURO 5 - RER	H.4922:Other passenger land transport	P	1.08×10^8	mi	4	3	1	1	2
Water	Elementary flows/Resource/in water	F	1.979×10^{12}	kg	4	1	1	1	1

Carbon monoxide	Elementary flows/Emission to air/low population density	F	259.20	t	3	3	1	3	2
Electricity		F	3.60×10^{8}	MWh					
Nitrogen oxides	Elementary flows/Emission to air/low population density	F	2.03×10^{3}	t	3	3	1	3	2
Nuclear facility		F	1	item	4	1	1	1	1
Particulates, < 10 um	Elementary flows/Emission to air/low population density	F	399.60	t	3	3	1	3	2
Sulfur oxides	Elementary flows/Emission to air/low population density	F	1.12×10^{3}	t	3	3	1	3	2
UNF		F	13.50	t	3	3	1	3	2
VOC, volatile organic compounds	Elementary flows/Emission to air/low population density	F	32.40	t	3	3	1	3	2
Stage: Waste Management									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
concrete, normal - GLO	C.2395:Manufacture of articles of concrete, cement and plaster	P	8.55	m^3	4	3	1	2	4
steel, chromium steel 18/8 - GLO	C.2410:Manufacture of basic iron and steel	P	6.75	t	4	3	1	2	4
UNF		F	12.50	t	4	3	1	2	4
Dry Cask		F	1	item	4	3	1	2	4
Stage: Decommissioning									
Name	**EcoInvent Category**	**P/F**	**Value**	**Unit**	**Rel**	**Com**	**Tem**	**Geo**	**Tec**
acetylene - GLO	C.2011:Manufacture of basic chemicals	P	5.90	kg	1	4	2	4	5
argon, liquid - GLO	C.2011:Manufacture of basic chemicals	P	23.92	kg	1	4	2	4	5
concrete, normal - GLO	C.2395:Manufacture of articles of concrete, cement and plaster	P	184.20	m^3	1	4	2	4	5
diesel - Europe without Switzerland	C.1920:Manufacture of refined petroleum products	P	3.27×10^{3}	kg	1	4	2	4	5

electricity, high voltage - US	D:Electricity, gas, steam and air conditioning supply	P	552.27	MWh	1	4	2	4	5
heat, district or industrial, natural gas - Europe without Switzerland	D.3530:Steam and air conditioning supply	P	8.72×10^3	MJ	1	4	2	4	5
heat, district or industrial, natural gas - Europe without Switzerland	D.3530:Steam and air conditioning supply	P	1.03×10^3	MWh	1	4	2	4	5
hydrogen, liquid - RER	C.1920:Manufacture of refined petroleum products	P	949.43	kg	1	4	2	4	5
lead - GLO	C.2420:Manufacture of basic precious and other non-ferrous metals	P	0.96	t	1	4	2	4	5
Nuclear facility		F	1	item	1	4	2	4	5
oxygen, liquid - RER	C.2011:Manufacture of basic chemicals	P	2.18×10^5	kg	1	4	2	4	5
phosphoric acid, industrial grade, without water, in 85% solution state - GLO	C.2011:Manufacture of basic chemicals	P	0.88	t	1	4	2	4	5
steel, chromium steel 18/8 - GLO	C.2410:Manufacture of basic iron and steel	P	4.97	t	1	4	2	4	5
Water	Elementary flows/Resource/in water	F	8.52	m^3	1	4	2	4	5
Waste, nuclear, low and medium active/m^3	Waste/ecopoints 97, CH	P	819.50	t	2	4	2	4	5

Table B.2. Data used to determine impacts associated with transportation throughout the fuel cycle based on total distance traveled, mode of transporation, and weight per shipment.

Source	Destination	Travel Type	Packaging	Distance (km)	Weight per shipment (t)
Adelaide, Australia	San Diego, CA	Sea Freight	210 liter containers	13738.14	0.35
Novorossiysk, RUNVS	Port Charleston, SC	Sea Freight	210 liter containers	10878.65	0.35
Port Charleston	Metropolis, IL	Train	210 liter containers	938.25	0.35
San Diego, CA	Metropolis, IL	Train	211 liter containers	3069.01	0.35
Saskatoon, Canada	Metropolis, IL	Train	210 liter containers	2638.00	0.35
Metropolis, IL	Eunice, NM	Truck	Type 48Y	1657.30	12.50
Eunice, NM	Richland, WA	Truck	Type 30 B	2490.94	2.28
Richland, WA	Clemson, SC	Truck	Type A	375.51	233.33

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