Analyzing the Feasibility of Reintroducing Nuclear Power to Worcester Polytechnic Institute

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Abstract

The increased risks of climate change are forcing communities to rethink how they meet their energy needs. In this project, we investigated the feasibility of integrating a small modular nuclear reactor (SMNR) at WPI for both research and power generation. During this investigation, we conducted interviews, directed a survey, and viewed carbon emissions data. By analyzing this information, we found that implementing an SMNR would benefit the institution by providing additional research opportunities and reducing overall emissions. These benefits would be achieved through the cogeneration of heat and electricity in a safe manner, by utilizing SMNR technology as soon as 2026, when it is predicted to be commercially available.

Executive Summary

Global warming is a reality, and as such, the world needs to rethink the sustainability of its energy usage to avoid making the Earth inhospitable. Many energy sources that mitigate this problem have been studied and implemented in various parts of the world, including the United States. Worcester Polytechnic Institute (WPI) has taken steps to reduce energy usage on campus, but has not gone far enough in improving campus sustainability to mitigate climate change, as WPI is still far from carbon neutral. WPI should implement more sustainable energy sources on campus to further reduce its carbon emissions. WPI prides itself in innovation, so implementing new sustainable technology on campus would establish WPI as a leader in the green energy field. This project was created to establish the feasibility of having a nuclear microreactor at WPI.

Since the technology is very new and relatively unknown, the group started the project by looking at information already available and conducting research into SMNRs and microreactors. Small Modular Nuclear Reactors (SMNRs) are a new type of reactor that produces smaller amounts of energy compared to Nuclear Power Plants and are made of separately manufactured parts instead of as a whole unit. Microreactors are a subset of these reactors, and they only produce enough energy to power a college campus, rather than an entire city or multiple cities. These reactors make up an entirely new generation of nuclear reactors, called generation IV reactors, because they innovate on many aspects of traditional reactor designs. The group also did research on WPI's sustainability goals to learn what progress WPI wants to make in sustainability and what steps they have already taken.

Once our research on existing material was complete, the team shifted focus on exploring our research question and how we were going to answer it. To determine if a microreactor would be feasible at WPI, the reactor would have to be able to perform research and generate energy at a rate that matches WPI's needs on campus. Furthermore, the reactor would ideally be able to easily integrate into WPI's energy infrastructure and face little community resistance. The ideas were refined and finalized as the first five objectives of the project. The first objective aimed to understand all the capabilities of microreactors in generating energy, while objective two aimed to do the same but for research capabilities. While nuclear reactors, strictly speaking, don't generate greenhouse gasses, the process of creating, fueling, and decommissioning them does, and quantifying that and comparing these emissions to WPI's plans to have a natural gas cogeneration plant was objective three of the project. Furthermore, understanding WPI's energy infrastructure is crucial to understanding if a microreactor would easily integrate with the system, if it would supply enough energy to meet WPI's needs, and if it would significantly reduce WPI's carbon emissions. This comprised objective four. The fifth objective aimed to gauge the WPI community's opinions on a potential nuclear reactor at WPI to ensure there would be little community resistance. Lastly, the sixth objective was to use our findings to determine if implementing a microreactor at WPI is feasible based on several criteria.

In fulfilling our objectives, we conducted several interviews. We interviewed a leading member of MIT's nuclear research program, an engineer working at WPI's power plant, and a member of Westinghouse, the company that is developing a microreactor called eVinci, which is WPI's primary interest, and physics professor and nuclear

researcher David Medich of WPI who is partly working with Westinghouse. Additionally, we conducted an online survey to gather opinions on implementing a microreactor on campus from the WPI community.

The group had many findings in the areas of sustainability, nuclear research, safety, and community receptivity. In the area of sustainability, we found that eVinci could produce enough energy for WPI's needs with the exception of peak usage at certain times of the year, so backup systems to provide additional energy would be needed in conjunction. The group also found that the eVinci has very low carbon emissions, and that implementing it would eliminate most of WPI's carbon emissions. The group also found that the eVinci reactor should be able to integrate with WPI's current heating systems, but more research is needed about electricity infrastructure. In the area of nuclear research, the group found that the eVinci reactor can simultaneously be used for power generation and nuclear research, and could generate revenue through funded research to offset the cost of the reactor. In the area of safety, the group discovered that eVinci is a remarkably safe design, with very low risk of harm on a college campus, and has simpler operating procedures but still produces nuclear waste. The group also analyzed the survey results and concluded that the overall WPI community is very receptive to the proposal of having a microreactor on campus. Overall, the group concluded that the findings so far suggest the eVinci is a viable solution to WPI's sustainability problems and the idea should be developed further.

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Introduction

As global warming becomes more prominent with each passing year, scientists are trying to find a way of producing energy that is less harmful to the environment. To help combat global warming, greenhouse gas producing fossil fuels should be replaced with cleaner alternative energy sources that are low-carbon or carbon-neutral. Trying to find an energy source that creates less pollutants than fossil fuels, whilst also producing a stable amount of energy, has led to controversy among scientists, as there is no scientific consensus on which method of energy production is the best option. It is part of WPI's responsibility as an institution of higher education to contribute to the fight against global warming by minimizing their own carbon footprint. While WPI is on pace to meet its sustainability goals, the most recent sustainability plan is not sufficient for meeting the pathways recommended by the Intergovernmental Panel on Climate Change (IPCC). WPI is still far from carbon neutrality, and WPI can only lower its electricity usage so much before it needs to rely on other methods to reduce its carbon emissions, such as implementing carbon-neutral energy sources.

Nuclear energy is a potential candidate to reduce the necessity of fossil fuels, yet it is met with public controversy over its feasibility and its safety. To make nuclear energy more economically viable, there has been an effort to make nuclear reactors that are smaller and safer (World Nuclear Association, December, 2021). This has resulted in a surge in interest from scientists and the nuclear industry for the development of generation IV small modular nuclear reactors (SMNRs), which function like nuclear power plants, but are scaled down in size and energy production and have improved safety features. Unlike larger nuclear power plants, SMNRs are capable of operating in unconventional locations where other forms of energy are not viable (Office of Nuclear Energy, 2010). These reactors are modular, meaning they can be more easily manufactured and assembled (Mignacca, B. & Locatelli, G., 2020). It is still up for debate whether generation IV SMNRs are a viable option for a sustainable energy source to help reduce the world's reliance on fossil fuels, and with the technology still in development for commercial use, the feasibility of the technology is not well understood.

In addition to power generation, nuclear reactors are an important tool for nuclear research in a wide array of fields, including medicine, materials, and food safety (IAEA, 2016). Given the enhanced safety of Generation IV reactors and their capability to be used for nuclear research, the technology could give rise to the first ever use of a research reactor as a power source. Typically, the energy produced by a research reactor is an unwanted byproduct and is disposed of. This practice is wasteful, but could be more sustainable if that energy could be used to displace the use of fossil fuels. If WPI were to use a generation IV research reactor to power its campus, it would be at the forefront of innovation in sustainability.

The goal of this project was to analyze the potential of SMNRs to safely and efficiently produce energy and facilitate research at WPI. We analyzed the Westinghouse eVinci reactor's energy output, safety features, and waste production, and compared them to the current energy systems at WPI in order to determine if they would be a viable energy source and improve WPI's overall sustainability.

Chapter 2: Background

2.1 Sustainability

2.1.1 Dimensions of Sustainability

The concept of sustainability originated from forestry, where it was used to describe the practice of not harvesting more than the new growth can yield (Kuhlman & Farrington, 2020). Sustainability has since been expanded to include initiatives in several areas, all under one overarching goal: to ensure the prosperity of future generations (Kuhlman & Farrington, 2020). Sustainability is often viewed as having three dimensions: social, economic, and environmental. Social sustainability involves generating happiness and well-being for society, which is not strictly defined but is commonly associated with social justice, self-determination, and cultural diversity (Purvis et al., 2018). Economic sustainability involves growing economies and generating revenue in a manner that will not result in a collapse in the future. Lastly, environmental sustainability involves managing human impacts from the use of non-renewable resources and pollution so that the Earth can continue to be a liveable place. While all three dimensions are critical to the prosperity of future generations, this project is most relevant to environmental sustainability because of the discussion of the environmental impacts of energy production.

2.1.2 The Issue of Climate Change

The main issue facing sustainability is climate change. Climate change is the process of the environment changing over time due to either natural processes or human activities (Thompson, 2010). The main factor contributing to climate change is the release of greenhouse gasses into Earth's atmosphere. Greenhouse gasses (GHG) are carbon-based compounds that trap heat in Earth's atmosphere, preventing it from leaving into outer space; this process of trapping heat is called the greenhouse effect. GHGs that have been released into the atmosphere are called GHG emissions or carbon emissions. The two most common GHGs are methane (CH_4) and carbon dioxide (CO_2) (Thomspon, 2010). The greenhouse effect is important for allowing life on Earth when occurring at natural levels, but if GHGs reach too high of a concentration in the atmosphere, heat will build up to an undesirable level, and the average temperature of Earth's surface will increase; this process is called global warming (Muradov, & Veziroglu, 2011). Global warming results in a multitude of catastrophic consequences, including rising sea levels submerging coastal cities and extreme temperatures and storms leading to uninhabitable climates and possible drought and famine (Muradov & Veziroglu, 2011, Morales, 2021).

While there are some factors that affect climate change that occur independently of human influence, scientists agree that human impacts are the primary driver of modern climate change; humanity is accelerating climate change through the release of GHGs into the atmosphere from the combustion of fossil fuels for energy production and from processes in other industries (Muradov, & Veziroglu, 2011). To make matters worse, the effects of these human activities on global warming are amplified by the environment because of positive feedback loops.

One major feedback loop is caused by melting permafrost: global warming causes the arctic to melt, and as the arctic melts, methane contained in the permafrost is released into the atmosphere, intensifying the greenhouse effect (Jacobo, 2021). With these feedback loops, there are tipping points; once a threshold of human input is reached, climate change becomes irreversible. One major tipping point is the blue ocean event (BOE), which is defined as the moment when Earth's ice caps have completely melted (Cairns, 2022). Because ice caps act as thermal regulators for the Earth, if they melt, the oceans will begin to heat up significantly. Air currents will then carry the heat over land, causing the climate to heat up exponentially quicker in a process called super-warming (Cairns, 2022).

The Intergovernmental Panel on Climate Change (IPCC) has concluded that the most favorable global warming scenario, which avoids most of the negative impacts of climate change, requires limiting global warming to 1.5°C (IPCC, 2022). The IPCC details that the pathway to achieve this scenario involves reducing global emissions by 50% in the 2030s and then reaching global carbon neutrality in the 2050s. Carbon neutrality is the state of having no net increase in concentration of GHGs in the atmosphere (Muradov & Veziroglu, 2011). This pathway is very difficult to achieve as it would require unprecedented levels of global cooperation, so the IPCC also details various other global warming scenarios, indicating that the second most favorable scenario requires limiting global warming to 2.0°C. This scenario only avoids some of the negative consequences, and the pathway to achieve it involves reducing global emissions by 50% in the 2040s and then reaching global carbon neutrality in the 2070s. To achieve the emissions reductions in these pathways, practices that emit high levels of GHGs must be replaced with more sustainable practices that emit fewer GHGs (IPPC, 2022).

2.1.3 Forms of Sustainable Energy

Power generation, including all its applications, accounts for 86% of global CO_2 emissions (Muradov & Veziroglu, 2011). In the U.S., 25% of GHG emissions come from electricity generation that goes on electrical grids, and 13% come from burning fossil fuels for heating (US EPA [1], 2018). Given that so much emissions come from energy production, reducing emissions from energy production is a necessity for meeting the needs of the emissions reduction pathways laid out by the IPCC. One way to reduce these emissions is by replacing fossil fuels with energy sources that produce lower GHG emissions.

There are many options for sustainable energy sources that produce lower GHG emissions than fossil fuels. The amount of carbon emissions that an energy source produces is commonly referred to as its carbon intensity. There are two main classifications of sustainable energy sources based on carbon intensity: low-carbon sources and carbon-neutral sources. Low-carbon sources produce GHGs during operation, but produce a low amount compared to traditional fossil fuels. One example of a low-carbon source is a decarbonized fossil fuel power plant, which acts the same as a traditional fossil fuel power plant, but some of the GHGs produced from the combustion reaction get captured and stored instead of being released into the atmosphere (Muradov & Veziroglu, 2011). In contrast, carbon-neutral sources produce no GHGs during operation. Some examples of carbon-neutral sources include nuclear, solar, wind, geothermal, hydropower, ocean thermal, and tidal (Muradov & Veziroglu, 2011).

Regardless of how much emissions are produced during operation, all energy sources still have embodied emissions; all energy sources require energy from other sources at some point throughout their lifecycle, called embodied energy, and the embodied energy may produce carbon emissions, called embodied emissions (McGregor, 2021). The energy sources used to provide the embodied energy are called the primary source mix. The best measure of an energy source's sustainability is the mass of GHGs released per unit of energy that the source produces over the course of its lifecycle. Studies looking to estimate an energy source's carbon emissions over its lifecycle perform a Life Cycle Analysis (LCA), where they consider the emissions generated during every individual stage of the source's life cycle. Measurements of an energy source's carbon emissions over its entire lifecycle are referred to as lifecycle emissions. LCAs often have many assumptions that can vary between studies, and different studies look into different areas with more depth than others, leading to a wide range of estimates (Warner & Heath, 2012). Given this heavy variation between studies, the most comprehensive and reliable estimates for life cycle carbon emissions come from studies that compile and analyze the results of many prior LCA studies.

Another important aspect for an energy source to be considered sustainable is its renewability. While it is important for energy sources to not cause harm to future generations through climate change, it is also important for future generations to be able to continue to produce energy without exhausting resources. For an energy source to be renewable, it must not rely on any finite resources as fuel. Wind turbines and solar panels operate using the wind and sun as fuel, respectively, which will theoretically never run out, making them renewable, whereas gas and oil are finite, making them exhaustible (Kuhlman, T., & Farrington, J., 2010).

2.1.4 WPI's Ongoing Sustainability Plans and Progress

WPI has made plans to mitigate climate change by altering its own practices. WPI has identified four areas to increase sustainability: academic programs, operations and facilities, research and scholarship, and community engagement (Office of Sustainability, 2020). Its goals make heavy emphasis of the importance of engaging students with sustainability, as its main philosophy is to train a workforce to be capable of tackling sustainability issues globally. The goal that most directly relates to combating climate change is the goal for operations and facilities. WPI's Sustainability Plan details a set of desired five-year outcomes as criteria for meeting this goal, which are summarized in Table 1.

Table 1: WPI sustainability goals for operations and facilities from 2020 to 2025

Waste Production	Energy
25% reduction in landfill waste 15% reduction in water waste	10% reduction in electricity consumption (kWh/FTe) 25% increase in renewable energy production 30% reduction in use of fossil fuel (gallons)

Additionally, WPI's Greenhouse Gas Reduction Plan defines a goal of a 20% reduction in scope 1 and scope 2 emissions relative to WPI's emissions in 2014 by the year 2025 (WPI [1], 2017). Scope 1 emissions are the emissions produced through the direct burning of fossil fuels by an organization, while scope 2 emissions are the emissions produced through the generation of electricity, heat, or steam (U.S. EPA [1], 2021). There are also scope 3 emissions, which are indirect emissions, and include all other sources of emissions, such as commuter travel, processes surrounding solid products, and biowaste production (U.S. EPA [2], 2021). WPI does not yet have a goal to reduce scope 3 emissions, but it has made the commitment that it will eventually undertake measuring and reducing scope 3 emissions (WPI [1], 2017).

WPI's Greenhouse Gas Reduction Plan details that the main strategy for reducing emissions has been to decrease energy usage by increasing the energy efficiency on campus, which was planned to be done by auditing buildings on campus to see where energy upgrades are feasible. The plan lists some short-term objectives to reduce emissions, including upgrading the energy systems for at least one major building per year and replacing various outdoor light fixtures with more efficient LED lights (WPI [1], 2017). Additionally, WPI made the commitment to pursue the implementation of more advanced energy conservation techniques, more clean electricity sources, and more advanced heating/cooling technology (WPI [1], 2017). WPI's sustainability plan makes many references to promoting creative solutions and innovation, suggesting that it also wants to use student creativity to help advance the sustainability of campus operations (Office of Sustainability, 2020).

Every year, WPI releases a sustainability report that details WPI's progress on all of its sustainability goals, detailing everything WPI has done to increase its sustainability throughout the previous year. In accordance with WPI's plans for increasing sustainability through academics, the report highlights many areas where sustainable solutions were taught and explored, including classes, projects, and competitions. For its goal for operations and facilities, the report keeps track of WPI's electricity consumption, natural gas consumption, and carbon emissions, illustrating WPI has been making steady reductions, as shown in Table 2.[1]

Table 2: Resource usage and carbon emissions during fiscal years 2014-2020 (Caton, 2020)

	2014	2015	2016	2017	2018	2019	2020
Natural Gas (millions of therms)	1.638	1.839	1.602	1.547	1.524	1.516	1.295
Electricity (GWh)	31.85	30.00	29.31	29.09	28.72	24.99	24.46
Emissions (metric tons)	20,000	19,000	19,500	18,500	17,500	17,000	15,500

[1] The decreases from 2019 to 2020 may have been because of fewer students being on campus due to the COVID-19 pandemic instead of because of clean energy initiatives, so the decreases from 2019 to 2020 may not accurately reflect the impacts of changes in WPI's sustainability practices.

The sustainability report also gives insight on the steps WPI has taken to contribute to reaching their energy usage and carbon emissions reduction goals over the previous year. It details that the most noteworthy steps they took to decrease energy usage on campus were to install more LED lights and to install motion sensors on room lights to make them turn off automatically (Caton, 2020). The report also details how WPI has been lowering its heating emissions by replacing its oil usage with natural gas (Caton, 2020). These actions are in line with the steps in the Greenhouse Gas Reduction plan.

2.1.5 WPI's Future Sustainability Plans

WPI seems to have recognized that their ongoing plans are not sufficient for combating climate change, because very recently, WPI has signed two pledges with leading climate action organizations, which will likely lead WPI to implement more aggressive goals for reducing carbon emissions on campus (WPI, 2022). WPI has signed the Carbon Commitment with the organization Second Nature, which requires WPI to develop a plan to achieve carbon neutrality as soon as possible, primarily by reducing energy usage, implementing carbon neutral energy sources, and offsetting or sequestering emissions (Second Nature, 2022). WPI has also signed a pledge with the organization Principles for Responsible Investment (PRI), meaning WPI will incorporate environmental, social, and governance (ESG) considerations into its investment analysis, decision making, and ownership policies and practices (WPI, 2022). As such, WPI is expected to make drastic changes to its sustainability plans over the next few months, hopefully in line with the IPCC's recommendations.

2.2 Nuclear Energy

2.2.1 Nuclear in the Energy Transition

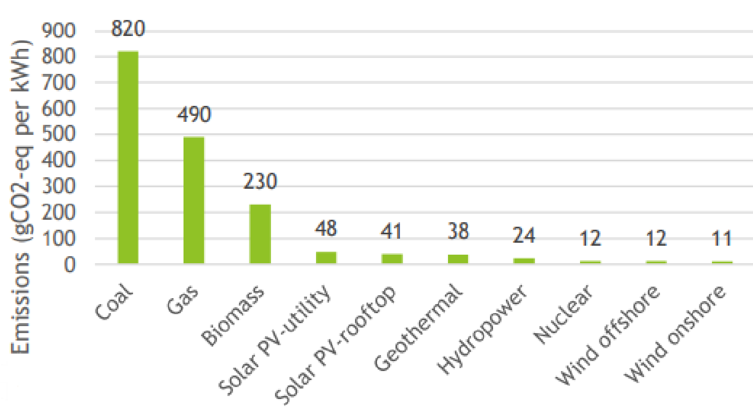
The solution to reducing WPI's emissions may lie in nuclear energy. As the global energy market shifts from carbon-intensive fossil fuels to low-carbon and carbon-neutral energy sources, nuclear energy is a major competitor among the other sustainable energy sources. A major edge that nuclear power has over other sustainable energy sources is that it produces energy very consistently. Nuclear power can produce energy at a higher uptime than any other source, with a capacity factor of 92.5%, as shown in Table 3 (Office of Nuclear Energy, 2021). The capacity factor is a measure of what percentage of the time an energy source can run at full power over a long period of time (Office of Nuclear Energy, 2021). Nuclear reactors can achieve a high-capacity factor because they are designed to run unhindered for months at a time, only occasionally stopping for refueling and maintenance (Office of Nuclear Energy, 2019). Other sustainable energy sources are much less reliable; wind turbines can only generate energy when there is a strong air current, and solar can only generate energy when the sun is within a certain range of angles in the sky, inherently limiting the capacity factor that they can achieve.

Table 3: Capacity factors for energy sources (Office of Nuclear Energy, 2021)

	Nuclear	Geothermal	Natural Gas	Hydropower	Coal	Wind	Solar
Capacity Factor	92.5%	74.3%	56.6%	41.5%	40.2%	35.4%	24.9%

Another major benefit of nuclear energy is that it has very low carbon emissions. It is carbon neutral and it has very low embodied emissions compared to other energy sources. Warner and Heath screened 274 LCA studies and narrowed them down to 27 articles that fit their criteria for being reliable sources, and found the median of the emissions estimates to be 12 gCO_2-eq per kWh (Warner & Heath, 2012). This value has also been supported by the 2014 IPCC report (Schlömer, 2014). A comparison of the lifecycle emissions between various energy sources based on data from the IPCC is shown in Figure 1.

Figure 1. Life-cycle carbon emissions for various energy sources based on data from the 2014 IPCC report



Nuclear energy has a slight disadvantage in that it is not renewable. Unlike most other sustainable energy sources, nuclear energy uses tangible fuel made from mined resources. The fuel that powers most nuclear reactors in the world is uranium. Uranium is abundant in the Earth's crust, but it is technically finite, meaning it can be exhausted (Shwageraus, 2020). Uranium is found in varying levels of ore grade, but nuclear fuel requires uranium at a high purity, which could lead to problems over time, as nuclear fuel could become more difficult to obtain as the available ore grades become less pure (Sovacool, 2008). Nuclear fuel has the possibility of being recycled, which could get it closer to being renewable, but this does not lead to infinite reusability, and this practice is not currently used at all in the U.S. (Office of Nuclear Energy, 2019).

Nuclear energy is also disadvantaged because of its poor economic viability. Nuclear power is more expensive than other renewables on a per-unit-energy basis (Shwageraus et al., 2020). Wolfson argues that nuclear energy is not capable of being the primary energy source to take on climate change because of its relatively poor economic viability, especially because the nuclear industry is characteristically slow to change (Wolfson, 2018). He argues that solar and wind energy are more economically viable and that they will be much more effective options for replacing fossil fuels as quickly as possible (Wolfson, 2018). He does concede that future nuclear technologies could prove to be more economically viable; thorium reactors, generation IV microreactors, fusion reactors, and other technologies have the potential to revolutionize the industry, but they may not be developed fast enough to meet the timeline for the pathway that the IPCC recommends (Wolfson, 2018). Nuclear energy could also improve in its economic viability by using it for the cogeneration of electric and thermal power, which could allow it to save money that would have been spent on additional heating (Shwageraus et al., 2020). While nuclear may or may not be the best option for replacing fossil fuels on an economic scale, it is still a viable option on a small scale given its high reliability.

2.2.2 How Nuclear Reactors Produce Energy

In understanding the capabilities of nuclear reactors for energy production and other applications, it is important to establish what the mechanism is that allows them to produce energy. Nuclear reactors are able to generate electricity by harnessing the energy released from nuclear reactions. There are two types of nuclear reactions: fusion reactions and fission reactions. All current reactors operate with nuclear fission, as no fusion reactor capable of producing net-positive energy has been developed yet. In a fission reaction, an atom with a high nuclear mass is split into multiple smaller atoms. This process can release energy depending on the characteristics of the atom's nucleus. In the atomic world, the mass of the nucleus is not equal to the sum of its constituent parts, those being the protons and neutrons; some of the mass is contained in the energy that keeps the nucleus from breaking apart, known as the binding energy (Young and Freedman, 2019). To be a viable source of energy, a nuclear reaction must release energy rather than consuming it, so it is important to consider how much energy a reaction releases when designing nuclear reactors. A useful quantity to help determine how much energy a nuclear reaction releases is the binding energy per nucleon, which is the total binding energy divided by the sum of protons and neutrons in the atom's nucleus. The higher the binding energy per nucleon, the more stable the nucleus is, so if the reactants have a lower binding energy per nucleon than the products, then the reaction releases energy (Young and Freedman, 2019).

In a nuclear reactor, these nuclear reactions occur in the nuclear fuel within the reactor's core, and the energy released is in the form of heat. As such, for the reactor to provide electrical power, the heat must still be converted into electricity. The main way that this is accomplished is by using a steam turbine; the heat from the fuel is used to boil water into steam, and the steam flows through a turbine connected to an alternating current (AC) generator, converting mechanical energy into usable electricity. Normally, the steam is then condensed back into water and returned to the beginning of the cycle (Energy Information Administration, 2021). Given that the steam is still hot after going through the turbine, this could allow the system to be modified to output steam to be used for heating buildings, allowing nuclear to be used for the cogeneration of electricity and heat.

2.2.3 Nuclear Research

In addition to generating carbon-neutral energy, a nuclear reactor would be especially useful to WPI because it could be used to conduct research and provide academic opportunities to students. Nuclear reactors are useful for research because the products of fission reactions can be used to form a neutron beam, which opens up possibilities for various research applications (World Nuclear Association, June, 2021). WPI previously had a research reactor on campus, but it was decommissioned in 2011 because its neutron beam was not powerful enough for most applications, but bringing a more powerful reactor to campus would allow WPI to perform every common research application (WPI, 2015). It is worth noting that no research reactors currently in operation around the world are used simultaneously for energy production due to limitations in the technology, but reactor designs currently in development can do so (World Nuclear Association, June, 2021)

One of the most common nuclear research applications is neutron scattering, which is the process of passing a beam of neutrons through a sample and analyzing where the neutrons collide with the sample and where they get redirected. It allows researchers to examine samples under a variety of conditions, such as in a pressure vacuum, at high and low temperatures, and under a magnetic field, usually to analyze how the material's properties are affected by those conditions (World Nuclear Association, June, 2021). Other scattering methods are available that do not use neutrons, instead using other particles or using light, but neutron scattering has unique properties that make it valuable in its own right; neutron scattering interacts with the nucleus of an atom, allowing researchers to analyze materials in ways that would otherwise not be possible (Oak Ridge National Laboratories, 2020). Other scattering methods are only able to interact with an atom's atomic shell, making them good when analyzing heavy elements, but ineffective when imaging lighter elements.

Another common nuclear research application is neutron activation, which is the process of bombarding a sample with neutrons, forcing the target nucleus to gain a neutron and become unstable, and thus radioactive, causing it to emit radiation in the form of gamma emissions. Neutron activation can be used to identify the elemental composition of a sample, as each element in the periodic table has a unique set of gamma emissions that can be individually detected (Al Nabhani, 2021). Neutron activation is also common in the medical field, as can be used to produce radioisotopes. There are two primary classifications of radioisotopes used in medicine: tracers and radiant energy emitters. Tracers are tiny amounts of radioactive material that can be as small as a billionth of a gram, and due to their radioactive properties, they are easily detectable, making them useful in diagnostic image testing. Radiant energy emitters are substances that give off high energy radiation, making them useful for treating cancer and other diseases through radiotherapy (Phelan, 1967).

Another noteworthy nuclear research application is neutron transmutation doping, which involves using neutrons to change the properties of silicon to be more conductive of electricity. In neutron transmutation doping, the reactor reflector vessel turns a small amount of the silicon into phosphorus, resulting in n-doping, which is essential for building advanced computer circuitry. Materials testing is another noteworthy application, which involves bombarding a material sample with a very high flux neutron beam to test how well the material can withstand nuclear irradiation. The knowledge gained from materials testing can be used for the development of alloys that are suitable for building nuclear reactors (World Nuclear Association, June, 2021).

2.2.4 Lifecycle of a Nuclear Reactor

To understand the sustainability and safety of nuclear energy, it is important to first understand the processes involved in the lifecycle of a nuclear reactor and its facility. Knowing the parts of a reactor's lifecycle is also important for estimating embodied emissions through an LCA. Hundreds of studies have attempted to estimate the carbon emissions of nuclear power plants, each with differing results due to differences in assumptions about a reactor's lifecycle processes (Hondo, 2005; Lenzen et. al.,2006; Dones et. al., 2007a). Warner and Heath group the many processes of a nuclear reactor's lifecycle into three distinct phases: the upstream processes, the downstream processes, and the operational processes (Warner & Heath, 2012).

The upstream processes only occur once, taking place at the beginning of the lifecycle. The upstream processes include the constructing of the reactor facility and the manufacturing of the materials needed. The downstream processes also only occur once, taking place at the end of the lifecycle once the reactor has run its course. The downstream processes include the decommissioning of the facility, the disposal of non-radioactive waste, and the storage of the radioactive waste (Warner, & Heath, 2012). The decommissioning process involves cleaning up the structures contaminated by radiation, as the radioactivity must be reduced below a certain level before the reactor site can be used for other purposes (U.S. Energy Information Administration, 2020).

The operational processes occur between the upstream and downstream processes, and are continuous throughout the bulk of the reactor's lifecycle. The operational processes consist of the operating and maintaining of the reactor facility and the creation of the nuclear fuel (Warner & Heath, 2012). The process of creating fuel involves many steps.[2] First, uranium ore is mined for, which can be done in an opencast pit or underground, and the

[2] Nuclear reactors can be designed to use other types of fuel than uranium, but we are only considering reactors that use uranium.

ore is typically at a purity of 0.2% uranium or less, with anything above 0.0004% considered worth mining (Sovacool, 2008). To increase its purity, the uranium is milled, which involves leaching it out of the ore using an acid or alkali bath (Sovacool, 2008). Depending on how low the purity of the ore is, this can result in a lot of radioactive waste that needs to be treated. By instead using another technique, called in-situ leaching, a lot of this waste can be avoided. In-situ leaching involves leaching the uranium before extracting it from the ground by injecting leaching chemicals into the ground, and it is currently used in the making of 50% of nuclear fuel in the U.S. (IAEA [1], 2018). After leaching, the uranium is enriched to increase the concentration of uranium-235. Natural uranium has three isotopes: uranium-235, which is useful for nuclear reactions, and uranium-234 and uranium-238, which are less useful. Natural uranium contains around 0.7% uranium-235, while typical fuel uses 4-5% enrichment (Sovacool, 2008). The uranium can be enriched either through diffusion or centrifusion, the latter of which is considered more sustainable (Warner & Heath, 2012). Finally, the enriched uranium is then formed into pellets and made into fuel rods (Sovacool, 2008).

2.2.5 Safety of Nuclear Energy

The primary factor limiting the growth of nuclear energy worldwide is the stigma around its safety. The nuclear industry has built up a stigma of being scary and unsafe due to a few major catastrophes that have tainted its history. In the U.S., the Three Mile Island accident in 1979 was one of these defining moments. In the U.S.S.R., they had the Chernobyl accident in 1986. More recently, in Japan, the Fukushima disaster in 2011 brought a resurgence in this stigma (Ingersoll, 2016), leading some European countries to make plans to decrease their consumption of nuclear energy, with Germany planning to entirely phase out its operating nuclear plants (Appunn, 2021). However, the safety concerns regarding nuclear energy are often misplaced, and, as technology has progressed, nuclear reactors have become remarkably safe.

Radiation exposure is the primary safety concern that nuclear reactors must be designed to protect against. Radiation exposure is measured in units of rems or millirems, with 1 rem equal to 1,000 millirems. The U.S. governmental organization responsible for regulating nuclear reactors to ensure safety is the Nuclear Regulatory Commission (NRC). The NRC classifies high-dose radiation exposure as any dose above 50,000 millirem. High-dose radiation is highly dangerous; exposure to doses this large can cause cells to die, damaging body tissues and organs instantly, and is linked to various types of cancer. When the human body experiences a high dose of radiation in a short period of time, a rapid body response known as Acute Radiation Syndrome (ARS) takes place. The symptoms of this syndrome, as well as the fatality rate, increase with higher levels of exposure. During the 1986 Chernobyl disaster, many of the workers and firefighters experienced symptoms of ARS, as they were exposed to radiation doses ranging from 80,000 to 1,600,000 millirem. Out of the people who received these high radiation doses, roughly 20% died from radiation injuries within three months of first exposure (U.S. NRC [2], 2017). However, high-dose radiation exposure is only possible in the event of a nuclear meltdown.

Nuclear meltdowns are the worst case scenario for safety, and are the main source of controversy about the safety of nuclear energy. A meltdown occurs when the reactor's fuel is not properly cooled (Fairewinds Energy

Education, 2022). To keep the reactor at a stable temperature, a liquid coolant, usually water, is circulated through the core. If the reactor core becomes too hot, it will continuously boil off the coolant around the fuel, exposing the fuel rods to the air. If hot enough, the fuel rods will begin to melt, causing radioactive fuel to build up at the bottom of the reactor's containment vessel. If the meltdown is poorly managed, the hot fuel will eventually burn through the containment chamber floor, releasing radioactivity to the outside world, but this is only the worst case scenario for a nuclear meltdown (Fairewinds Energy Education, 2022). The circulation of coolant is typically sufficient for keeping the reactor at a stable temperature, but in the event that the core produces too much heat for the cooling mechanisms to handle, the reactor operator can insert control rods into the core. The control rods can prevent overheating by cutting off the fission reactions by absorbing the neutrons in the fuel before they can collide with other atoms (Matson, 2011). Although, the core can still produce heat even after the fission reaction is stopped, because the uranium atoms that have already split will continue to produce radioactive byproducts that release heat. Hence, the pumps continue to circulate coolant to prevent overheating after inserting the control rods (Matson, 2011). If the fission reaction can be terminated and the core can be kept cool with flowing water, then a nuclear meltdown, and thus high-dose radiation exposure, is well protected against under normal circumstances.

Catastrophic nuclear meltdowns do not occur under normal circumstances, as they have historically only occurred because of extreme circumstances. As such, they are incredibly rare, and they have become increasingly unlikely as technology has evolved (World Nuclear Association, 2022). The catastrophic events of Chernobyl and Fukushima are prime examples of meltdowns that occurred because of extreme circumstances. The Chernobyl accident was mostly caused by the use of a faulty reactor design that was approved by the Soviet Union, but was disapproved everywhere else in the world (Nuclear Energy Institute, 2019). The reactor had a fatal flaw: unbeknownst to the reactor operators, the control rods that were meant to reduce the fission reaction were built incorrectly, and instead ended up accelerating the reaction, leading to the accident (PBS Frontline, 1993). Meanwhile, the accident in Fukushima was the result of a strong earthquake and a tsunami simultaneously causing damage to the reactor facility (World Nuclear Association, April, 2021). To protect against natural disasters, reactors have containment vessels that are designed to withstand extreme weather events and earthquakes (U.S. Energy Information Administration, 2020), but the combination of these two natural disasters resulted in more damage than the plant was designed to handle. The coincidence of these two natural disasters was most likely because the reactor was built on a fault line. Since these disasters, there have been major improvements to nuclear technology and safety protocols, meaning that both accidents are unlikely to happen again (World Nuclear Association, March, 2021; 2022).

Even with the decreased likelihood of nuclear meltdowns, the NRC still has safety protocols in the event of a disaster. In order to maximize public safety, there are two emergency planning zones (EPZs) around the reactor. Each of these EPZs have a specific safety purpose, with their own protective action plans. The first EPZ is called the plume exposure pathway, and it covers the area within a 10 mile radius around the reactor site. This zone is designed to reduce exposure to radioactive materials from the plant, with protective action plans that include evacuation, sheltering, and even the administering of potassium iodine pills, which help block the absorption of radioactive material. The second EPZ is called the ingestion exposure pathway, with a radius of 50 miles. This zone's purpose is to reduce the dose from the potential ingestion of radioactive materials, with protective action plans that focus on banning contaminated food and water. The size of these zones could vary from the typical settings due to specific site conditions, unique geological features, or the population near the plant (U.S. NRC [1], 2020). These EPZs further reduce the dangers of a nuclear meltdown.

While nuclear meltdowns present the greatest risk of radiation exposure, nuclear reactors still release radiation during normal operation, which must be protected against. The NRC has strict regulations for the amount of radiation a nuclear facility can emit, making any public exposure negligible. The NRC requires that its licensees prevent the yearly public exposure from exceeding 100 millirem, excluding background radiation. Background radiation is radiation that humans are exposed to at all times because of natural processes, and amounts to 310 millirem. The NRC uses the same model to regulate radiation limits as what is used internationally: the linear no-threshold (LNT) model. This model assumes that any amount of radiation exposure increases the risk of cancer, even though there is no data to suggest a link between cancer and radiation for doses below 10,000 millirem, meaning the model likely overestimates the risks of low-level radiation. In 1991, the National Cancer Institute conducted a study that found that counties adjacent to nuclear facilities had no increased risk of death from cancer (U.S. NRC [2], 2017). The NRC still uses the LNT model to be safe, and thus heavily regulates radiation exposure from nuclear reactors, ensuring that operational radiation poses no threat to the public.

Even though the risks of nuclear meltdown and radiation exposure are low, there is still a concern that bad actors could interfere with the reactor and force a disaster, so reactors have additional security regulations in place to avoid a catastrophe. To protect against proliferation and sabotage, a large area surrounding a nuclear power plant is restricted and guarded by armed security teams (U.S. Energy Information Administration, 2020). The NRC has included additional protections against terrorism in its emergency preparedness plans since the September 11th terrorist attacks (U.S. NRC [2], 2020). The NRC's regulations, combined with the high security protocols, make the event of successful sabotage unlikely.

To truly put the safety of nuclear power into perspective, it is important to consider how its safety compares to fossil fuels. Nuclear energy has resulted in far fewer deaths than fossil fuels because of its low impact on air pollution. Using data from studies conducted in 2007 and 2016, researchers have found the rate of deaths from accidents and air pollution due to nuclear energy has been 0.07 deaths per terawatt-hour of energy. This value includes the deaths from the incidents at Chernobyl and Fukushima. In comparison, they found that this value is 2.82 for natural gas, 18.43 for oil, and 24.62 for coal, primarily due to air pollution (Burrows, 2021). A more recent study found that the deaths caused by air pollution were even higher than had been previously estimated, going so far as to claim that 18% of global deaths in 2018 were directly caused by exposure to particulate matter from fossil fuels (Ritchie, 2020). And as large as those death rates already are, they will grow even larger if fossil fuels continue to accelerate climate change, which could lead to unprecedented death rates (Cairns, 2022).

2.2.6 Nuclear Fuel and Waste

Another major concern related to nuclear safety is waste and fuel storage. There are two types of radioactive waste: low-level, and high-level. Low-level waste is defined as anything that was contaminated by high-level waste, though it is not the high-level waste itself. These usually are everyday use items like mops used for cleaning the reactor site or protective clothing. They can also be contaminated tools used for research, like swabs, tissues or syringes (U.S. NRC [1], 2019). Low-level waste is typically stored on the plant temporarily, eventually being transported to a low-level waste disposal site. In the event the waste becomes no longer radioactive, it can be disposed of with ordinary trash (U.S. EPA, 2022). High-level waste is the most dangerous kind of waste because it can stay radioactive for very long periods of time, up to thousands of years. Furthermore, the radioactivity of this waste is usually extremely lethal to humans and other forms of life, even with short exposure (U.S. NRC [1], 2019).

High-level waste includes the fuel in a reactor that can no longer produce energy. This is typically referred to as “spent fuel,” “used fuel,” or “nuclear waste” (U.S. EPA, 2022; NuScale, 2021). In addition to regulating the general safety of a nuclear power plant, the Nuclear Regulatory Commission (NRC) is also in charge of regulating the management, storage, and disposal of used fuel. By the NRC’s policy, used fuel is initially stored in pools of water or in dry cask storage, which involves robust containers on a concrete pad, to cool the fuel and to shield workers from radiation (NuScale, 2021; U.S. Energy Information Administration, 2020; U.S. NRC [1], 2017; U.S. NRC, 2021). These containers are usually stored on site in a secure facility. The NRC asserts that this is a safe way to store used fuel for up to 100 years, but they are only considered a form of temporary storage (Alley, 2012). The U.S. Department of Energy is responsible for the permanent disposal of used fuel in deep geologic repositories, but due to various complications, this practice is not currently used (personal communication, April 5, 2022). While used fuel is hazardous and could run into trouble with storage in the long term, it still has the upper hand over fossil fuels, as fossil fuel pollution cannot be contained (Ramana, 2017).

Spent fuel contains 96% of the original needed material and can be recovered to produce new fuel (NuScale, 2021). Reusing spent fuel reduces the waste’s toxicity by 90%, saves 25% of natural uranium resources, and minimizes the volume of high-level waste slated for disposal in a repository by 75% (NuScale, 2021). Hence, reusing nuclear waste has a major efficiency and safety incentive. As of now, many countries in Europe reuse their waste, however, this is not a common practice in the U.S. (Office of Nuclear Energy, 2019). For example, France currently gets 70% of their energy from nuclear power, with 17% of their electricity derived from recycled nuclear fuel (World Nuclear Association, January 2021). Since the U.S. does not allow this practice, it will continue to rely on excess storage until new regulation arises.

2.3 Microreactors

2.3.1 Introduction to Microreactors

Small reactors are about as old as the nuclear industry itself (Ingersoll, 2016). There has always been interest in the possibility of using nuclear power on a smaller scale. An example of this is that nuclear powered submarines were successfully designed and built. They were not considered for commercial use because the technology was not economically viable at a small scale at the time, but this is expected to change with the production of generation IV reactors (personal communication, March 2022).

Different size reactors are differentiated by their power output. Generally, SMNRs are defined as nuclear reactors that produce a power output up to 300 MW electric, while microreactors produce a power output up to 20 MW electric (Testoni et al., 2021). The power output of these reactors is typically given in terms of electrical energy, as this indicates the amount of energy that can be used for electricity, but power can also be given in terms of thermal energy, which indicates the amount of heat the reactor can produce before the energy is converted to electricity. The microreactor designs currently being developed are predicted to be capable of producing 1 to 5 MW electric, with only a few designs capable of 10 MW electric or higher (Testoni et al., 2021). In knowing the amount of energy produced for certain designs, we will be able to decide which would be best for providing the amount of energy that fits WPI's needs.

2.3.2 Benefits and Challenges of SMNRs

The main benefits that generation IV SMNRs have over nuclear power plants (NPP) are their small size and modularity. These benefits are then furthered by microreactors, as they are even smaller than general SMNRs. The small size of SMNRs and microreactors is predicted to allow for them to have smaller exclusion areas and emergency planning zones and to be more portable (Testoni et al., 2021). These reactors are modular, which means they are made up of multiple separately manufactured parts, which should allow them to be manufactured more easily and to have shorter construction times (Testoni et al., 2021). These benefits are not yet confirmed, as there are no SMNRs currently constructed and in operation to evaluate if they meet these expectations (Testoni et al., 2021). There are other more technical benefits that SMNRs provide: they have inherent load following capabilities and simpler electric grid requirements, allowing for easier operation and installation, they do not require external energy sources to perform safety functions, which removes the risk of having a meltdown due to power outages, and they generally rely less on liquid coolants, which lowers the need for water sources, and lowers the risks associated with improper cooling (El-Emam et al., 2021).

There are still some issues facing the implementation of commercial SMNRs. There are some licensing issues surrounding transporting and building microreactors in facilities, as well as evaluating sites for certain criteria (Testoni et al., 2021). Along with this, there is a need for regulations that address cross-sectoral issues due to complex processes in the manufacturing of SMNRs spanning multiple industries (El-Emam et al., 2021). There are also issues over the security of nuclear facilities, as smaller reactors may allow for increased chances of proliferation and sabotage (Testoni et al., 2021). There must be further consideration into the effects of releasing hazardous wastes and an analysis of possible socio-economic impacts (El-Emam et al., 2021). These issues must be worked out before SMNRs can be put into use commercially, including possible implementation as a research reactor for universities.

Chapter 3: Methods

Our goal for this project was to evaluate the possibilities for improving WPI's sustainability and research capacity by assessing the feasibility of implementing a microreactor at WPI for energy generation and research. This was accomplished through the following objectives:

1. Understand the potential energy-producing capabilities, impacts of waste, and safety of microreactors and how they would contribute to campus sustainability.
2. Investigate the research types, fields, and avenues that would benefit from microreactors, and determine if these research applications are useful to WPI.
3. Estimate the level of carbon emissions associated with generation IV microreactors.
4. Understand WPI's current electrical/heating infrastructure and energy consumption, to assess the potential for a microreactor to lower WPI's carbon emissions.
5. Determine the initial opinions of the WPI community regarding nuclear energy and microreactors.
6. Assess the feasibility of a microreactor at WPI based on findings from objectives 1-5.

In the following subsections we explain our processes for collecting and analyzing data on microreactors and research reactors. We conducted interviews with experts in their field, estimated carbon emissions, surveyed the WPI community, and evaluated the feasibility of having a microreactor on campus. We also obtained and inventoried data from WPI's energy usage, which we used to calculate if the eVinci reactor could produce enough energy to power the campus. We then calculated WPI's carbon emissions to see how much they would be reduced by implementing the eVinci reactor. By accomplishing these six objectives, we were able to present the WPI community with an informed assessment on whether and why we could or should bring a generation IV microreactor to campus.

Objective 1: Evaluating Microreactors and Sustainability

With this objective, we sought to determine if microreactors produce energy safely and sustainably. We researched peer reviewed articles that discussed the capabilities of microreactors that are relevant to sustainability, such as the amount of energy they can produce, the amount of usable heat they can produce, the amount of waste they produce and how it is stored, the amount of fuel they use, and their general safety concerns. We interviewed a Westinghouse representative, as Westinghouse has been in contact with WPI about their eVinci microreactor design. The interview followed the protocol described in Appendix A. The questions asked are listed in Appendices C and D. The data we collected and analyzed helped us assess the advantages and disadvantages of WPI investing in a microreactor as a more sustainable source of heat and electricity.

Objective 2: Evaluating Microreactors for Nuclear Research

Our team investigated the research opportunities that could be provided by a generation IV microreactor and the integration of a nuclear research program at WPI. A primary motivator of introducing a reactor on campus is to enable students and faculty to perform research while producing energy for the campus. We interviewed MIT about their research reactor, as it possesses similar qualities to what the eVinci would have if it were implemented on campus: comparable energy output, size, location, and environment. The interview explored different types of research performed, applications in the medical and materials research fields, views of the MIT community, safety protocols, and the feasibility of concurrent research and power generation. We also interviewed a professor at WPI, who is in contact with Westinghouse, about their perspective on performing nuclear research, and what research they would use a reactor for. The interviews followed the interview protocol in Appendix A. The questions asked are listed in Appendices E and F. After collecting this information, we assessed whether the eVinci would be useful for nuclear research and whether its nuclear research opportunities would provide value to WPI. We did this using the direct interview data and cross analysis with information from the team's various objectives (Yin, 2003).

Objective 3: Estimating Microreactor Carbon Emissions

To aid in our evaluation of the sustainability of microreactors, we researched estimates for the carbon emissions produced during the life cycles of nuclear reactors, made assumptions to apply this data to microreactors, and compared their emissions to those of the other energy plans proposed to WPI. Given that there are little to no measurements for the emissions attributed to generation IV microreactors, and given the eVinci model is not entirely similar to other generation IV microreactor models, we collected data from previous studies for the carbon emissions of earlier generation nuclear power plants and asked some questions in our interview with Westinghouse to help determine what assumptions could be made to apply them to the eVinci model. We researched reported values for carbon emissions in the form of grams of CO_2 equivalents per kilowatt-hour of energy produced throughout the lifecycle of a nuclear reactor, such as the emissions attributed to creating nuclear fuel and building the reactor, and the methodologies used to obtain those values to understand which aspects of the nuclear life cycle were considered. We then evaluated the relevant differences between the nuclear reactors examined and the eVinci model, such as the materials used and the enrichment of the fuel, and we made assumptions to apply the data to form an estimation for the range of values for the carbon emissions of the eVinci model. To serve as comparison for the eVinci's carbon emissions, we estimated the emissions for a renewable natural gas cogeneration plant by researching reported values for the lifecycle carbon emissions of natural gas power plants and the process of creating renewable natural gas.

Objective 4: Understanding WPI's Heating and Electric Infrastructure

For this objective, we evaluated WPI's current heating and electrical infrastructure to aid in an analysis of how the eVinci would affect WPI's carbon emissions. This is important for understanding how the eVinci reactor could help WPI reduce GHG emissions and improve its sustainability. This evaluation was done by analyzing the current systems and the energy consumption across campus. This analysis was split into three parts: to determine if the eVinci would provide enough energy for campus or if backup systems would be needed, to determine by how much the eVinci would lower WPI's total emissions, and to determine whether the eVinci could actually be integrated on campus.

We collected data for WPI's electric and thermal energy consumption from WPI's Sustainability report and by obtaining data from WPI's office of sustainability. We used this data to calculate WPI's average power needs, as shown in Appendix J, and compared them to the information about the eVinci's power production obtained in Objective 1. In addition to WPI's average needs, we also considered WPI's real-time needs. For WPI's heating, the info from the office of sustainability contained data for WPI's usage for each month of the year for the last few years. For WPI's electricity usage, we obtained a rough number for the peak demand from WPI's facilities. We then compared the peak data to the information about the eVinci's power production obtained in Objective 1. From these comparisons, we analyzed whether backup systems would be needed in order to meet WPI's needs. We then determined several potential options for backup systems that could be implemented based on the gaps in the eVinci's energy production.

We also used the data obtained from the sustainability report to calculate WPI's emissions from electricity and natural gas usage by using conversion factors obtained from WPI's Office of Sustainability. These values were compared to data for WPI's total emissions, obtained from the sustainability report, to see how much WPI's emissions from energy usage contribute to their total emissions. Then, using the estimated emissions of the eVinci from Objective 3, we calculated how much emissions the eVinci would produce. We then used this data to calculate how much the implementation of the eVinci on campus would lower WPI's total emissions. Given there were uncertainties in the emissions for the eVinci, we looked at three separate scenarios: a high estimate for its emissions, a middle estimate, and a low estimate. We generated these numbers in Objective 3. Additionally, there were uncertainties in the amount of energy that would be contributed by backup systems to help the eVinci power campus. We considered two scenarios for this: assuming no backup system is needed, and assuming natural gas is used for backup heating. The first scenario assumes zero emissions are attributed to backup systems. To get the emissions for the second scenario, we calculated the amount of additional thermal energy needed for each month of the year based on data for WPI's natural gas usage obtained from the Office of Sustainability, and multiplied by the previously mentioned natural gas conversion factor. Sample calculations for all these calculations are shown in Appendix J.

To better understand how easily the eVinci could integrate with campus, we interviewed WPI Facilities about the current energy infrastructure, such as the heating systems and backup generators. The interview followed the protocol described in Appendix A. The questions asked are listed in Appendix G After learning about WPI's systems, we gathered information about connecting the eVinci to heating systems from interviewing Westinghouse, and found information for the use of microgrids to connect to supply the eVinci's electricity to campus by researching relevant articles.

Objective 5: Determining Community Support and Resistance of Microreactors at WPI

We conducted a survey of the WPI community to determine their opinions regarding the possibility of a microreactor being implemented on campus for research and energy production. The goal of this survey was to assess how receptive the WPI community would be to microreactors, as implementing the microreactor will be less challenging if the project has the support of the WPI community. We also sought to determine which groups at WPI are most or least receptive, and what their major concerns are with the proposal of implementing a microreactor on campus. The findings of the survey will serve to help the WPI Administration and facilities to make an informed decision about the WPI community's views on microreactors.

We spoke with a statistics professor at WPI to learn how best to write the survey questions (personal communication, January 19, 2022). The survey was short and concise to encourage participation, as it was a preliminary analysis of opinions on campus, with the plan that a future group will conduct a more thorough survey. The survey asked the participants their position at WPI, whether they are in a STEM field, and whether they support or oppose various aspects of the proposal for the reactor, and ended with an open-ended space so respondents can share any concerns. This amounted to three predictor variables and three response variables, in addition to the open-ended question. The survey did not ask any of the subjects' names or other personally identifiable information, and responses were depersonalized to keep the survey responses anonymous. The survey was reviewed and approved by the Institutional Review Board (IRB) of WPI to ensure safety and quality standards were met. The survey was then distributed to the WPI Subreddit, the WPI Student Discord server, Potpourri, and by word of mouth to various other groups and organizations at WPI. A gift card raffle was used to encourage responses. Due to the survey being entirely voluntary with the incentive of a gift card there may be some bias in the survey results. Once sufficient responses were recorded, we closed the survey.

We split the survey data into two categories: the multiple-choice and the free response. We analyzed the free responses using a coding method to identify common trends and topics amongst responses (Strauss, 1987). We coded the open responses by hand mapping responses for question four on the survey to underlying themes from open response questions (See Figure 13). To learn how to interpret the multiple-choice data, we spoke with a WPI professor with expertise in statistics research and a data analyst (personal communication, March 30, April 4, April 14, 2022). We used two methods to analyze the multiple-choice data. We first made graphics for the distribution of responses to question 4 stratified by responses to questions 1, 2, and 3, and visually analyzed the shapes of the graphics to understand the trends. We then used the statistical software R to analyze the data. To do so, we removed incomplete responses from the set of multiple-choice responses, and then, to fit a good model, we ran various commands. First, we used the command "cor" to make a correlation matrix of all the questions against one another. This showed the correlation coefficients of every variable against one another, which we used to determine the relationship between the level of support for implementing a microreactor and the demographic variables. We then calculated the log odds and significance factors for each variable against a base question. The log odds were important to determine how well an individual's demographics would impact the likelihood of them supporting or opposing microreactor implementation on campus. The significance factors were used to determine which characteristics were the most important in predicting support or opposition.

Objective 6: Criteria for a Feasible Microreactor at WPI

We compiled the findings of the previous objectives and analyzed them to initially assess whether implementing a microreactor at WPI is feasible. We established criteria for feasibility by following the International Atomic Energy Agency's (IAEA) methods for making a feasibility report for a research reactor (IAEA [2], 2018). The IAEA's methods are directed primarily towards establishing a nuclear research program on a governmental level, so some of the criteria were not applicable to the context of a private university, so we adapted the criteria to fit WPI's situation. Their methods also do not consider use of the reactor for power, so we adapted the criteria to include that as well. The IAEA has three main parts for criteria: stakeholder needs, infrastructure needs, and finances. For the stakeholder needs, we considered who we thought would use the reactor, who might be affected by it, and what the needs of those groups of people would be, and then evaluated if a microreactor could meet all of their needs. For the infrastructure needs, the IAEA lists 19 infrastructure needs that criteria should be developed for, and we adapted these and categorized them into four groups: integration with campus infrastructure, management, safety, and legality. Our criteria for these groups are shown in Table 4. For the finances, we considered the ways that a microreactor could generate revenue, but did not consider estimating dollar amounts. In evaluating the feasibility, we considered whether we found sufficient information to claim whether the criteria were met, and then we determined whether the microreactor met the criteria based on our findings.

Table 4. Criteria for the infrastructure needs for implementing a microreactor at WPI

Integration	Management	Safety	Legality
The reactor must: ● connect to WPI's heat distribution systems ● connect to WPI's electricity distribution systems ● have options for siting on campus	There must be plans for: ● operating the reactor ● refueling the reactor ● storing used fuel	The reactor must: ● present low risk of harm to campus residents ● have safeguards to protect against meltdowns ● have radiation protection ● present low harm to the environment There must be plans for: ● reactor security ● emergency planning	The reactor must: ● be legal for production and commercial use ● be legal for simultaneous power generation and research Additionally: ● there must be plans for licensing the reactor to WPI

Limitations

Knowing the cost of the eVinci reactor is important for determining whether they will be feasible for WPI, as the benefits gained from additional energy, greater sustainability, and more research opportunities must outweigh the investment WPI will need to implement a microreactor. It may be that the eVinci reactor will lower the cost of energy at WPI if they replace more expensive energy sources. With a high capacity factor, cogeneration of heat and electricity, low operational costs, and research revenue, a microreactor could become a financial benefit for the institution. Microreactors are anticipated to provide energy at a lower cost than traditional nuclear plants. One reason for this is that the modularity of microreactors should lead to lower construction costs, as they do not need to be specially designed for each site as do traditional nuclear plants, and instead can be easily built in a factory (Mignacca, B. & Locatelli, G., 2020). A major issue is that the cost of nuclear reactors is very difficult to determine. Early on during this project we investigated the cost estimations methods of traditional nuclear reactors. Nuclear reactors have had a history of poor cost estimation, as companies often end up spending more than they estimated, and their projects often take longer than expected due to delays (Timmer, 2020). Generation IV microreactors are a new technology with no data in regards to costs, there is little expertise on producing them as none are currently commercially manufactured, any estimation would have to be an extrapolation from data on previous generations of reactors. There are many unknowns, including the manufacturing process, installation, maintenance, regulations and certifications. As a result there is much ambiguity in estimating the cost of a microreactor, it is currently more impactful to consider the benefits for the environment and for nuclear research rather than whether they will be economically viable (Mignacca, B & Locatelli, G, 2020).

Another section outside the scope of this analysis is regulation and politics. The Nuclear Regulatory Commission (NRC) classifies nuclear reactors in two categories: power reactors and research reactors. They define each category of reactor as having a primary objective; power reactors are designed to produce mass amounts of energy for extended periods to maximize financial viability, while research reactors are designed to be started and stopped often and to allow for as much access to the core and neutrons as possible while keeping humans safe from radiation. They are each governed under different regulations, as their objectives conflict with each other for traditional research reactors (U.S. NRC, 2022; U.S. NRC [2], 2019). The NRC does not currently allow power reactors to conduct research and research reactors to generate power. Since WPI's microreactor would ideally do both, a new nuclear reactor category and license would need to be created by the NRC. The team early on decided to not look into potential future regulatory changes to nuclear reactors, but this needs to be investigated eventually. It is worth noting that our partners at Westinghouse have invested substantial resources into the development of the eVinvi reactor, capable of simultaneous power generation and research and believe it would pass NRC regulations.

The last major sector that was not analyzed was the location of the reactor. Since both the energy and heat of the reactor is produced at the reactor site, a good likely centralized location must be found for the reactor to be housed in, so as little energy is lost during transportation. Our team did not look into this due to a lack of time and information, but recognize it as important to consider.

Chapter 4: Results and Analysis

4.1 Sustainability

Finding 1: The eVinci microreactor could integrate with WPI's heating infrastructure, and it has load-following capabilities suitable for electrical infrastructure

The eVinci could connect to WPI's existing heating infrastructure. WPI's current systems only produce heat by burning natural gas. The main source of heat on campus is a power plant that produces steam which is fed to two different distribution loops on campus. These loops are known as the east and west loops; the east loop uses steam for hot water exchanges and the west loop uses steam-fed radiators (personal communication, February 10, 2022). Some buildings are not connected to the two loops, and instead they have their own generators and water boilers, and many buildings have emergency heat generators. Gateway Park is also not connected to the two loops, and instead has its own natural gas cogeneration system (personal communication, February 10, 2022). To distribute the eVinci's heat to all of campus, steam pipes will need to be built to connect the buildings outside of the east and west loops (personal communication, February 10, 2022). The WPI facilities representative noted that steam pipes could be built between the main campus and Gateway Park, so the eVinci would be able to provide heat to both (personal communication, February 10, 2022). To integrate the eVinci with the steam pipes, a connection could be built between the steam pipes and the eVinci's open Brayton system to allow the transfer of heat to the steam through air circulation (personal communication, February 2, 2022 and April 5, 2022). The open Brayton system is the reactor's power conversion system, which takes heat from the reactor and uses it to generate electricity, generating waste heat in the process, allowing the reactor to be used for the cogeneration of electricity and heat. This waste heat is available at 200°C, which is a convenient temperature for heating steam, which would simplify the integration (personal communication, April 5, 2022).[3]

The eVinci's load-following capabilities keep it from producing too much or too little energy for the grid. Three systems contribute to this load-following; the open Brayton system, a small battery set, and the reactor itself (personal communication, April 5, 2022). The open Brayton system takes 10-12 seconds to stabilize at a new load. After the energy leaves the open Brayton system, it goes through the battery set, which allows for the following of large demands that change in less than a second. While these two systems control the amount of electricity entering the grid, the reactor itself passively controls the amount of energy it generates to match the level of energy being put out by the open Brayton system. This occurs because of the TRISO fuel's doppler effect, which causes the fuel to

[3] The temperature of the waste heat is dependent on how much thermal energy the eVinci produces. If the reactor produces more than 9 MW thermal, as it would in Option 2 for the backup systems, then this temperature would be higher than 200°C—up to 750°C when used for the full 15 MW thermal.

slow down its reactions as the temperature in the reactor increases. When the Brayton system uses less of the reactor's heat to produce energy, the heat builds up and slows down the fuel's reactions, thus conserving fuel when less energy is needed (personal communication, April 5, 2022).

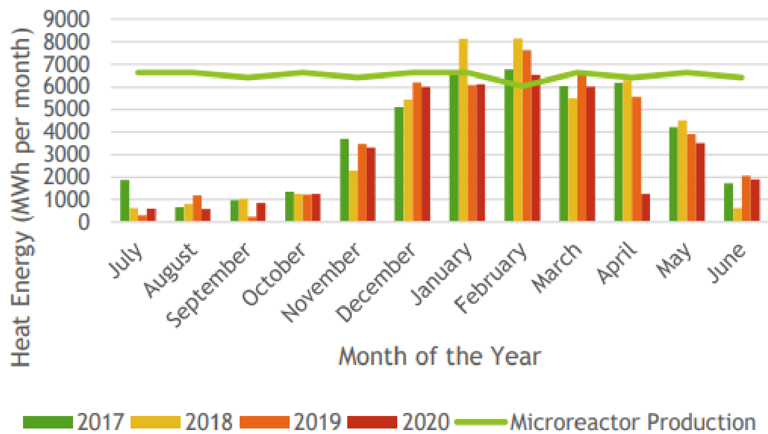
Finding 2: The eVinci microreactor would produce enough electricity and heat to meet WPI's needs with the exception of peak heating demand

The eVinci reactor can handle the yearly energy needs of WPI except at peak usage times. The Westinghouse eVinci reactor is designed to produce 5 MW of electricity and 9 MW of thermal energy (personal communication, March 2, 2022). The reactor core is designed to produce up to 15 MW of thermal energy, but 6 MW thermal energy is lost when producing electricity with the Brayton system (personal communication, March 2, 2022). The reactor would be able to consistently produce this level of heat and electricity, as it has a capacity factor of 99%, which means it is designed to run at full power for 99% of a year, as it would only need to shut down for maintenance for 1% of the year (personal communication, March 2, 2022). For the eVinci to meet WPI's energy needs, it must produce enough for WPI's demand at all times. Based on 2019 data[4], WPI needed an average of 2.85 MW electric and 5.07 MW thermal throughout the year (Caton, 2020). We assume that the 2019 data accounts for all of the electricity and heat usage on campus, including Gateway Park, because WPI uses this data to calculate their emissions in the sustainability reports (Caton, 2020), but we do not know this for certain. This suggests that most of the time, the eVinci should meet WPI's needs on its own. To get a better idea of how often the eVinci would produce enough for campus energy demand, we considered how energy needs change with time; there are rapid, unpredictable changes in needs from moment to moment, as well as more gradual, predictable trends in needs over the course of a day or throughout a year. Generally, electricity demand is higher during the day than at night, and heating needs are higher during the winter months than in the warmer seasons. We were unable to obtain data for the peak hour needs for electricity, although we did obtain an estimate that WPI's peak electric needs are roughly 4.1 MW (personal communication, April 2022). Since WPI has been steadily decreasing its electric and heating usage each year, this number is expected to only decrease with time. We assume that WPI's measurements of electricity consumption on campus are directly indicative of the amount of electricity that the eVinci would need to produce. If this is a reasonable assumption, then the eVinci should be able to produce enough electricity for campus on its own, but if not, a backup system to provide extra electricity may be needed. We also were unable to obtain data for WPI's peak hour heating needs, but we were able to obtain data for WPI's heating needs for each month of the year. The data indicated that the eVinci does not produce enough heat to meet WPI's needs during the coldest months of the year, as seen on Figure 2. In February of 2019, WPI needed 11.4 MW thermal for heating, which is 26% more than the amount the eVinci can produce when simultaneously producing electricity. It is unknown at what efficiency the 9 MW thermal from the eVinci can be used to heat steam or water, so it may produce less than 9 MW in practice. As

[4] We excluded data from 2020, which is the most recent data, because WPI's energy usage was lower than usual due to the COVID-19 lockdown.

such, a backup system to provide extra heat may be needed for the colder months of the year. Hence, the eVinci reactor could potentially meet WPI's peak electric needs, but it is unable to meet WPI's peak heating needs.

Figure 2. WPI's heat usage on campus for each month from 2017 to 2020 compared to the eVinci's heat production at 9 MW thermal



There are several options that WPI could use for backup systems for the eVinci to provide additional energy.[5] Option 1 would be to use separate backup systems for electricity and heating as needed. Option 2 would be to rely on the eVinci for heating, and use a backup system only for producing electricity. The eVinci can sacrifice some of its electricity output to produce extra heat whenever more than 9 MW of thermal energy is needed, and can produce up to 15 MW thermal, so using the eVinci primarily for heating and then having a backup system for electricity would meet WPI's peak heating needs (personal communication, March 2, 2022). Option 3 would be to implement a cogeneration plant as a backup system for both electricity and heat. Option 4 would be to use a cogeneration plant as the main source of energy for campus, and the eVinci's energy would either be backup energy or would be sold to some other entity.

Implementing the eVinci on campus would greatly surpass WPI's goal of reducing gallons of fossil fuel usage by 30%, as most of WPI's natural gas usage would be replaced by the eVinci's energy production. While implementing the eVinci reactor does not technically fit with WPI's goal of increasing renewable energy production by 25% because nuclear power is not renewable, it is much more important for WPI to have carbon neutral energy; implementing the eVinci at WPI would almost completely replace campus electricity usage with carbon neutral energy.

[5] Backup systems may also be needed to provide energy when the reactor shuts down, may that be from regular maintenance or from unexpected safety precautions. The backup systems discussed here do not directly account for this, as they would have to produce enough energy to power the campus entirely on their own. We are uncertain how frequently and for what duration shutdowns would occur, so we do not know how much the backup systems would be needed. The options discussed here could be modified to include mitigations for shutdowns if needed.

Finding 3: The eVinci microreactor would produce significantly lower carbon emissions than a renewable natural gas cogeneration plant

WPI considered a number of options for producing sustainable energy on campus. Multiple companies were contacted to work with WPI to implement their energy systems on campus. One of the primary options they considered was using a renewable natural gas cogeneration plant (personal communication, March 2022). Cogeneration is the principle of producing both heat and electricity simultaneously, which increases energy efficiency over typical electricity generation, and can be used in various types of power generation, including nuclear energy (IAEA, 2017). Renewable natural gas (RNG) is chemically identical to fossil natural gas, but it differs in that it is derived from capturing methane produced during processes in other industries, such as the waste management and agricultural industries (U.S. EPA [2], 2018). The organic waste from these industries is converted into fuel through anaerobic digestion, which is a decomposition technique that uses bacteria (Lee et al, 2021). We compared the proposed cogeneration plant's emissions to the eVinci reactor's emissions to determine which would improve WPI's sustainability more.

In estimating the eVinci reactor's emissions, we used estimates for the emissions of traditional nuclear power plants for the basis of our estimates. To determine the embodied emissions of nuclear energy, Warner and Heath screened 274 LCA studies for nuclear power plants and narrowed them down to 27 articles that fit their criteria for being reliable sources (Warner & Heath, 2012). They also reviewed other studies that compiled and analyzed previous LCAs, and attempted to improve upon their methods. Warner and Heath found the median of the embodied emissions estimates to be 12 gCO_2-eq per kWh (Warner & Heath, 2012). This value has also been supported by the 2014 IPCC report, which is a highly trusted source for information relevant to climate change (Schlömer, 2014). Along with obtaining a median, Warner and Heath found a few key differences between the methods of the LCAs that correlated to differences in emissions estimates. One difference was in assumptions made about how clean the primary source energy mix is. Studies that assumed that carbon-heavy sources like coal were used in the primary source energy mix had significantly higher embodied emissions estimates for nuclear energy than those that assumed more sustainable energy mixes (Warner & Heath, 2012). In a later study, Pehl et al. estimated that by the year 2050, nuclear energy's embodied emissions could decrease three fold, as shown in Table 5, because of a cleaner primary source energy mix (Pehl et al., 2017). Another major difference was in the assessment method used. There are two methods that are considered reliable for making embodied emissions estimates: process chain analysis (PCA) and economic input-output (EIO). Every study looked at PCA, but some studies looked at both PCA and EIO, and are thus considered hybrid (Warner & Heath, 2012). Warner and Heath found that hybrid studies had a much higher median than studies that only looked at PCA, as shown in Table 5. As a result, they suggest that the median of the hybrid studies may be a better estimate than the total median, as the hybrid studies were more comprehensive in their considerations (Warner & Heath, 2012).

Table 5. Embodied emissions estimates for nuclear power plants for different LCA methods and for either present estimates or future estimates. Estimates that include PCA and Hybrid studies are labeled "All"

LCA Method(s) and time	All, by 2050	All, present	PCA, present	Hybrid, present
Carbon emissions (gCO_2-eq/kWh)	4	12	7.2	22

Estimating the embodied emissions of generation IV reactors is difficult for many reasons. The most straightforward way to estimate the emissions is by performing an LCA, but doing so would be outside of the scope of this project due to their complexity. Since generation IV microreactors are not yet commercially available, there is little information to work off of, and as such, no LCAs have been published for generation IV reactors. Additionally, the eVinci is unique in its design among other generation IV microreactors, so a general study on generation IV microreactors may not be entirely applicable. The next best method to estimate the eVinci reactor's carbon emissions is to use data from previous LCAs for nuclear power plants. This method is difficult because previous LCAs do not investigate to what degree the emissions would be affected by changes in the amount of construction materials, the energy output of the reactor, or the enrichment level of the fuel, all of which are relationships that would be needed to accurately estimate the eVinci's emissions from the LWR estimates. As such, the most reliable way to estimate the eVinci's embodied emissions is by making assumptions based on the known differences between LWRs and the eVinci.

The representative at Westinghouse claimed that the eVinci is built from materials that have a lower carbon footprint compared to LWRs, but it also has a lifespan of only 8 years, whereas LWRs have a lifespan upwards of 30 years, so the emissions from construction would likely be similar (personal communication, April 5, 2022). The representative also claimed that the eVinci would produce more emissions during the fuel's enrichment, as the TRISO fuel that it uses needs a higher level of enrichment than a LWR's fuel, but the eVinci also needs less fuel relative to LWRs, so the emissions from creating fuel would likely be similar (personal communication, April 5, 2022). In conclusion, it is safe to say that the estimate for the eVinci's life cycle carbon emissions is not far from the estimate for LWRs. Thus, using 12 gCO2-eq/kWh as a low estimate and 22 as a high estimate should give a good representation of the eVinci's carbon emissions.

Compared to the eVinci, WPI's proposed renewable natural gas cogeneration plant would have much higher life cycle carbon emissions. Renewable natural gas (RNG) releases the same amount of carbon emissions as fossil-derived natural gas (FNG) during combustion, but RNG has slightly lower life cycle carbon emissions than FNG because the creation process for RNG avoids emissions that would otherwise be released during waste treatment processes (Lee, 2021). To estimate the proposed cogeneration plant's emissions, we considered the emissions from FNG and then considered RNG's reductions compared to FNG. O'Donoughue et al. performed a comprehensive analysis of previous LCA studies for FNG and found that the median of the emissions estimates was 470 gCO_2-eq per kWh (O'Donoughue, 2014). The studies they looked at varied in results due to differing assumptions between studies. We did not look into the methods used for LCAs of FNG with much depth because we do not need exact numbers for the purpose of our analysis. Lee et al. performed a life cycle analysis for creating RNG, and found that the amount of emissions avoided by producing RNG are dependent on what kind of waste is used to generate the fuel. They did this by looking at the reduction in emissions from creating RNG from each type of waste compared to the "business as usual" scenarios (BAU). The BAUs are the typical waste treatment procedures done for each type of waste. The reductions in emissions from creating RNG compared to the BAU are shown in Table 6. Lee et al. claim that FNG produces an additional 19.4 gCO_2-eq per kWh over BAU because of how FNG is conventionally produced (Lee, 2021). The reductions in emissions from creating RNG compared to creating FNG are shown in Table 6.

The results of applying the reductions of RNG to the median emissions of FNG are shown in Table 6. As is clear, the emissions of RNG are far higher than the emissions of the eVinci microreactor. Even in the best case, which involves using swine manure, RNG would produce nearly 400 gCO_2-eq per kWh more than the eVinci would. It is likely that WPI's proposed cogeneration plant would produce a different amount of life cycle emissions than the technology that O'Donoughue et al. investigated, but there is not yet enough information available to assess the differences.[6] The gap in emissions between the two is far larger than the margin of error, so slight changes in these numbers would not significantly change this conclusion.

Table 6. Carbon emission reductions of RNG over FG, and the total carbon emissions of RNG. Data for RNG taken from Lee et al, and data for FNG taken from O'Donoughue et al.

Waste Type	Reduction from BAU (gCO_2-eq/kWh)	Reduction from FNG (gCO_2-eq/kWh)	Total Emissions of RNG (gCO_2-eq/kWh)
Swine Manure	-40.6	-60.0	410
Food Waste	-24.2	-43.6	426
Fats, Oils, and Grease	-18.9	-38.3	431
Sludge	+7.5	-11.9	458

Finding 4: The eVinci microreactor would lower WPI's scope 1 and 2 carbon emissions by at least 84%

To determine the amount WPI could reduce its carbon emissions by implementing the eVinci, we needed to know the emissions WPI produces from electricity and heat. WPI gets its electricity from National Grid, and in 2019, WPI used around 25 GWh of electricity. WPI's heating system uses natural gas, and in 2019, WPI consumed around 1.5 million therms of natural gas. WPI's Office of Sustainability uses the following conversion factors to

[6] An additional point of consideration is that the cogeneration of heat and electricity leads to lower emissions per unit of total energy because the application of the waste heat avoids emissions from burning additional fuel for heating. This would lower the emissions estimates for both the proposed cogeneration plant and the eVinci, so this does not affect their comparison.

calculate emissions: 0.0003 MT CO_2-eq/kWh for electricity, and 0.0053 MT CO_2-eq/therm for natural gas (personal communication, March 4, 2022).[7] Thus, in 2019, WPI's electricity usage accounted for 7,500 metric tons of CO_2 emissions, and WPI's natural gas usage emitted around 8,030 metric tons of CO_2, for a total of 15,530 metric tons of CO_2. Electricity and heating do not account for all of WPI's carbon emissions; the EPA indicates that electricity and heating account for 25% and 13% of the US's total carbon emissions, respectively (U.S. EPA [1], 2018), with the rest being due to transportation, agriculture, and industrial emissions. From the 2020 sustainability report, WPI considers emissions for electricity, natural gas, refrigerants, and vehicle gas (Caton, 2020).[8] As such, implementing the eVinci would only impact the first two. The sustainability report indicates that WPI emitted approximately 17,000 metric tons of CO_2 or equivalents (Caton, 2020). This means that electricity and natural gas accounted for 91% of WPI's scope 1 and scope 2 carbon emissions in 2019.

In determining how much the eVinci would decrease WPI's emissions, we looked at a few scenarios. This is because of varying assumptions made around two factors: the emissions produced by the eVinci, and the backup systems. In considering the eVinci's emissions, there are three possibilities: using the high estimate of 22 gCO2-eq/kWh, using the middle estimate of 12 gCO2-eq/kWh, or ignoring scope 2 emissions and using the low estimate of 0 gCO2-eq/kWh. As discussed in Finding 1, there are four options for backup systems. We considered two scenarios: assuming no backup systems are used, or assuming natural gas is used for backup heating. The second scenario reflects option 1 for the backup systems, assuming that no backup electricity is needed.[9] As shown in Table 7, implementing the eVinci at WPI would lower WPI's total scope 1 and scope 2 emissions by 84-91%. These reductions would greatly surpass WPI's goal of reducing emissions by 20% from the emissions in 2014.

Table 7: Percent reduction in WPI's total scope 1 and scope 2 emissions
if the eVinci is implemented on campus for different scenarios

	Scenario without Heating Backup Systems	Scenario with Heating Backup Systems
Scenario with 0 gCO_2-eq/kWh	-91.4%	-89.7%
Scenario with 12 gCO_2-eq/kWh	-88.3%	-86.6%
Scenario with 22 gCO_2-eq/kWh	-85.7%	-84.0%

[7]The value for electricity is based on the standard energy mix in New England rather than National Grid specifically. The value for natural gas amounts to 180 gCO2-eq/kWh, which is much lower than the value O'Donoughue et al. reported, but they considered emissions per unit of electric energy, whereas this value considers emissions per unit of thermal energy, so the values do not conflict.

[8] WPI could be attributable to agriculture emissions due to dining on campus, as well as industrial emissions from WPI merchandise, but these are considered scope 3 emissions, which are excluded from consideration.

[9] We did not consider calculating the emissions for options 2, 3, and 4 for the backup systems because there are uncertainties about the relevant capabilities of the eVinci and the cogeneration plant.

4.2 Nuclear Research

Finding 5: Microreactors can simultaneously be used for energy generation and nuclear research

Within the nuclear research field, the capabilities of a reactor are determined by the flux of its neutron beam, which is a measure of the flow rate of neutrons it can produce in a tight beam. The higher this metric is, the more capable the research reactor is (personal communication, December 2021). This is dependent on the density of neutrons in and around the reactor. Neutrons can be obtained from either the periphery of the reactor, at a low density, or inside the core, at a high density. For traditional research reactors, the density in the periphery is not high enough for some neutron-intensive research applications, so samples need to be placed in the core to irradiate them (personal communication, February 24, 2022). In order to safely put a sample inside the core, the reactor must be shut down briefly (personal communication, February 24, 2022). The core of the reactor also needs to be configured for different experiments, which leads to extended periods where the reactor is not running (personal communication, February 24, 2022). Traditional research reactors also frequently need to be shut down for safety, maintenance, and refueling purposes in a process called a "SCRAM." The research reactor at MIT typically needs to SCRAM a few times each year (personal communication, February 24, 2022). These shutdowns present a problem for using a research reactor for power generation: if the reactor is the main source of energy for campus, when the reactor shuts down, the campus would lose power briefly. This also could lead to a conflict of interest: campus facilities may want the reactor to keep running to power the campus at a time when the reactor needs to shut down for safety reasons (personal communication, February 24, 2022).

The eVinci reactor would be able to circumvent the issue of frequent shutdowns, allowing it to simultaneously be used for energy production and research. One reason for this is because the eVinci can produce a higher neutron flux because of its condensed size (personal communication, March 2, 2022). LWRs operate using a pool of water to dissipate heat from the reactor core, which requires the core to be more distributed. Because of this distributed core, the neutrons are more spread out, lowering the neutron density (personal communication, March 2, 2022). In comparison, the eVinci is much more compact while having a similar power output, which leads to a higher neutron density, both in the core and on the periphery (personal communication, March 2, 2022). The density on the periphery of the eVinci is expected to be just as high as the density in the core of a LWR. This removes the need to use in-core experiments, lowering the frequency of shutdowns (personal communication, March 2, 2022). The eVinci also does not need to SCRAM as frequently as LWRs; the extensive safety features of the eVinci greatly lower the likelihood of needing to shut down for safety, and the refueling and maintenance of the reactor are handled only once every 8 years (personal communication, March 2, 2022). The eVinci is designed to run for extended periods with little downtime, as is clear by its capacity factor of 99%.

Finding 6: Nuclear research is in high demand and could generate revenue from funded research to offset the cost of the reactor

Nuclear research receives a lot of funding from private companies performing experiments and from the U.S. government. The MIT representative made it clear that their research reactor is costly to run, so they offload some of that expense onto third parties through funded research, where customers can pay to use the reactor for their own research (personal communication, February 24, 2022). The MIT representative described how their reactor is consistently busy with research funded by third parties, such as the U.S. government, Westinghouse, and National Grid. A drawback of this model is that the majority of nuclear research at MIT is not student-led, but they still have a few student projects each year through a small, funded program (personal communication, February 24, 2022). Despite this funding, the MIT representative explained that many reactors have stopped being financially viable, and as a result, have been decommissioned (personal communication, February 24, 2022). Even the MIT reactor loses more money from maintaining the reactor than it earns from funded research (personal communication, February 24, 2022). The eVinci would gain additional value from producing electricity and heat, so we expect that the eVinci would not lose more money than it gains (personal communication, March 2, 2022). The representative noted that MIT and the DOE do not mind spending money on the reactor, as they value nuclear research itself very highly (personal communication, February 24, 2022). The representative also noted that the DOE would not help fund their reactor or provide it fuel if it was used for producing energy (personal communication, February 24, 2022), so WPI would not receive funding from the DOE for the eVinci, but WPI could use funded research as a way to help pay for the reactor, and possibly generate revenue, but since we have not considered the expenses of the reactor, it is unclear whether it could profit or save money overall.

It is also clear that if WPI implemented a research reactor on campus, it would get a lot of use. While the supply of nuclear research has decreased from reactors being decommissioned, the demand has remained the same, making reactor space hard to come by. Professor David Medich described being confronted with a minimum three-month waiting period to get reactor space for experiments in the U.S., mentioning it was faster and cheaper for him to ship samples to be irradiated by a reactor overseas rather than to a reactor in a neighboring state (personal communication, March 2, 2022). This high demand extends to the students and faculty at WPI. Question 5 of our survey of the WPI community asked participants to rate their level of interest in participating in nuclear research on campus from 1 to 5, with higher numbers indicating higher interest, and the mean was 2.92 with n=213. Not everyone on campus is expected to be interested in performing research because not everybody works or studies in a field that uses nuclear research, and the reactor would have a limited capacity for how many people could use it for nuclear research, so a mean around 3 is indicative of high interest in the reactor.[10]

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[10] The mean for this question was also artificially lowered due to a mistake with the question: WPI staff, many of whom are ineligible to perform research with the reactor, were not given an option for being "not applicable," so they mostly chose 1, lowering the mean.

4.3 Safety on Campus

Finding 7: Microreactor safety systems make the risk of nuclear meltdowns and exposure to radiation negligible, making them safe to have on campus

The eVinci reactor has extensive safety features that allow for safe operation on a college campus. The reactor has extensive protections against overheating, which is cited as the primary cause of nuclear accidents (Fairewinds Energy Education, 2022). Unlike previous generations of reactors, such as LWRs, the eVinci does not use a liquid coolant to keep the reactor from overheating, removing the concerns of coolant leaks or a need to monitor coolant levels (personal communication, March 2, 2022). The eVinci has passive heat-pipe technology that allows it to cool itself without electricity (personal communication, March 2, 2022). Additionally, the eVinci design takes advantage of TRISO fuel, or tri-structural isotropic particle fuel, which has self-regulating capabilities through the "doppler effect": as the temperature in the core increases, the fission reaction in the fuel inherently slows down and stops (personal communication, March 2, 2022). This is because of the graphite core block in the TRISO fuel, which acts as a moderator for the heat (personal communication, March 2, 2022). TRISO fuel is designed to contain the fission gas products at up to 1,800 °C, but because of the doppler effect, the fuel will stop reacting far before reaching that temperature (personal communication, March 2, 2022). The only remaining concern would be if the TRISO fuel was manufactured improperly; however, the NRC has a long and strict process that requires organizations to extensively demonstrate that they can manufacture, transport, insert the fuel into a reactor, and operate the reactor safely, ensuring the TRISO fuel is held to a high standard of quality (personal communication, April 5, 2022).

In the unlikely event these passive safety features don't suffice, there are two alternative ways to safely shut the reactor down. One such mechanism is through the control drum, which controls the level of activity in the reactor; by cutting power to the control drum, the eVinci will passively shut down. If this mechanism fails, a control rod can be inserted into the reactor, stopping the fission reaction and shutting down the reactor. Both of these mechanisms do not require electricity (personal communication, March 2, 2022).

All of these safety features amount to a negligible level of risk on campus under all circumstances. Westinghouse has done extensive hazard analyses for the eVinci model, looking at how the reactor performs under various conditions, and has come to the conclusion that the eVinci's safety features will prevent the release of hazardous fission products for every case they consider, including rare natural disasters (personal communication, April 5, 2022). Westinghouse has also done risk analyses by evaluating, for any event where something goes wrong, what are the likelihood and level of consequences of the event occurring (personal communication, April 5, 2022). The level of consequences are measured by estimating the dose of radiation that people would be exposed to. They found that the risk of every event they considered is far below the level that the regulators set as a baseline for the maximum allowed risk (personal communication, April 5, 2022). In the event that a situation beyond the safety capabilities of the reactor occurs, Westinghouse also has plans for a final resort of releasing radiation into the environment in a controlled manner that minimizes the impacts of the hazardous material on human safety (personal communication, April 5, 2022). Given the eVinci reactor's safety features limiting the impact of a meltdown, combined with the small size of the reactor plant, which is localized to a 0.25 acre building, the eVinci has a very small area that would be impacted by radiation during the final resort (personal communication, March 2, 2022). Previous generations of reactors typically have defined an emergency planning zone with a radius of 10 miles to estimate the area affected if a situation reaches the final resort; however, for the eVinci, this emergency planning zone is far smaller, as only the area within the physical site-boundary itself would be impacted, which covers 0.8 acres (personal communication, April 5, 2022).

Finding 8: The eVinci has simpler operation, maintenance, and security than previous generations of reactors

Because of its passive safety features, simple shutdown mechanisms, and self-operating control systems, the eVinci does not need to be actively operated, but instead can be passively monitored, which can be done remotely on a laptop. Professor Medich noted that the primary concern when operating LWRs is monitoring the coolant levels to make sure that the reactor does not overheat, but the eVinci's cooling systems are designed to function without liquid coolants, leading to much simpler operation (personal communication, March 2, 2022). This simple operation is in stark contrast to previous generations of reactors, which have large control rooms that require hiring additional employees to operate the reactor (personal communication, March 2, 2022). MIT currently hires twelve student operators to run the reactor for experiments, but they are not allowed to operate the reactor for their own experiments due to a conflict of interest. The eVinci would not need as much personnel, and Professor Medich suggested that WPI could hire the minimal additional staff needed to monitor the reactor (personal communication, March 2, 2022).

All aspects of the eVinci's maintenance are handled by Westinghouse, and their processes ensure no one will be exposed to radiation. At the reactor site, there will be 2-meter-thick concrete shielding to keep radiation at a safe level for workers, which is in line with the NRC's regulations for radiation exposure levels (personal communication, April 5, 2022). When refueling, which is only done at most once every 8 years, Westinghouse sets up two bays to allow them to take out the operational reactor and replace it with a new reactor (personal communication, April 5, 2022). This process of replacing the reactor leads to much simpler maintenance than traditional research reactors; MIT's maintenance often requires parts of the reactor to be replaced, and because they don't work with a separate company, those parts need to be specially designed and built on campus (MITK12Videos, 2018). Once the eVinci is replaced, Westinghouse takes the old reactor back to their facilities to handle the radioactive material (personal communication, April 5, 2022). The reactor's high-level waste is ultimately stored in dry casks next to Westinghouse's facilities (personal communication, April 5, 2022). As a result, no nuclear waste is stored on campus. Because Westinghouse handles the eVinci's waste and refueling, WPI does not need to worry about either process.

The design of the eVinci reactor and safety features on the reactor site will prevent bad actors from sabotaging the reactor or from performing proliferation when implemented at a college campus. The remote monitoring system does not allow the reactor to be operated remotely, as it only allows a one-way stream of information from the reactor, keeping it secure from cyber-attacks (personal communication, March 2022). The reactor would also be safe against intruders. The reactor at MIT has lots of cameras monitoring the reactor and has alarms to warn their campus police, who can get to the reactor in 30 seconds to a minute in the event of an emergency (personal communication, February 24, 2022). A similar security system would be put in place if a microreactor is implemented at WPI. The Westinghouse representative noted that the thick concrete around the reactor, in addition to protecting against radiation, increases the difficulty for any bad actor to reach the reactor (personal communication, April 5, 2022). Even if somebody was able to sabotage the reactor by forcing it to overheat, the eVinci reactor's safety systems should prevent it from causing much harm (personal communication, April 5, 2022). Additionally, even if somebody were to steal the reactor's fuel, they would not be able to make any dangerous weapons with it, as the enrichment of the fuel is far too low to do so (personal communication, April 5, 2022).

4.4 Safety on a Larger Scale

Finding 9: Microreactors should only be used for limited applications, as permanent waste storage is an ongoing problem in the U.S.

While the eVinci would be safe to have on a college campus, there are still some inherent safety problems underlying the nuclear industry as a whole that would impact safety if microreactors were more widely adopted. One major issue is the storage of nuclear waste. Legally, the U.S. government is supposed to provide a geological repository for nuclear waste to be stored in permanently, but it does not (Moskowitz, 2021). Previous attempts to site a geological repository have been met with public backlash, and as of now, the U.S. has no plan for how or when a geological repository will be implemented (Ramana, 2017). The Westinghouse representative mentioned the Canadian government is currently making steady progress with creating a geological repository for fuel, which may influence the U.S. to make more progress on its own, but it would be unlikely that the U.S. could rely on Canada for its waste disposal.

Despite geological repositories being considered the best method for long term waste storage and being considered "technically proven," they are still riddled with uncertainties that require more experimentation. The high level waste produced by nuclear reactors needs to be isolated for up to hundreds of thousands of years in order to return to safe levels of radiation, which spawns numerous design problems, such as designing containers that can contain radiation for that long, picking geological mediums that can hold the radiation for that long, and accounting for the many geologic factors that could impact the site on that time scale (Ramana, 2017). In lieu of a permanent waste storage solution, all waste is stored either in pools of water or in dry casks on temporary sites nearby operating or decommissioned reactors. The NRC considers dry casks to be a safe way to store spent nuclear fuel, as two separate studies have found the potential health risks to be very small (U.S. NRC [1], 2017). The NRC suggests that dry casks are safe to use for 120 years, or even up to 300 years, but dry casks have only been in use since 1986, so there is no experimental evidence to prove that they can contain radiation for this long (Alley, 2012). Even then, 300 years is still temporary, and does not replace the need for a permanent solution. The issue of long-term waste storage must be addressed before microreactors are adopted widely, as the waste storage problem will only become larger if more waste were to be produced. For now, microreactor technology should only be used in a limited capacity, such as for use as research reactors at universities, or for powering remote locations, so as not to exacerbate the issue of waste storage.

4.5 Community Receptivity

Survey Results:

Figure 3: Results of Question 1

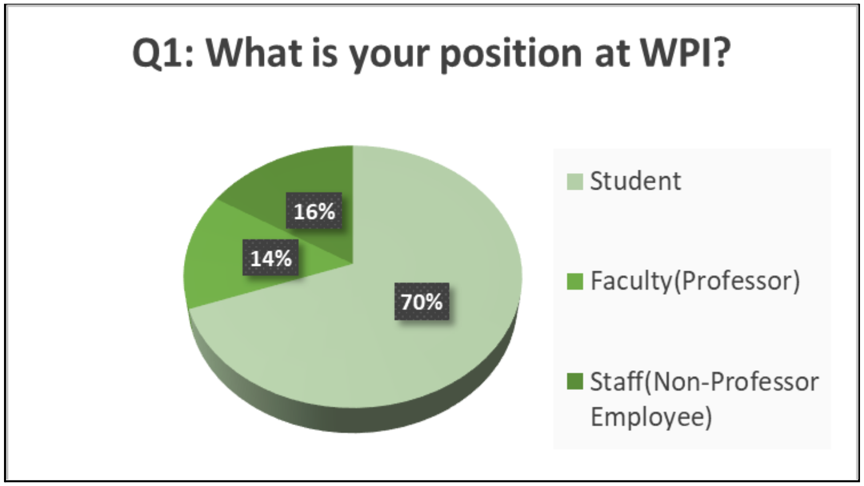


Figure 4: Results of Question 2

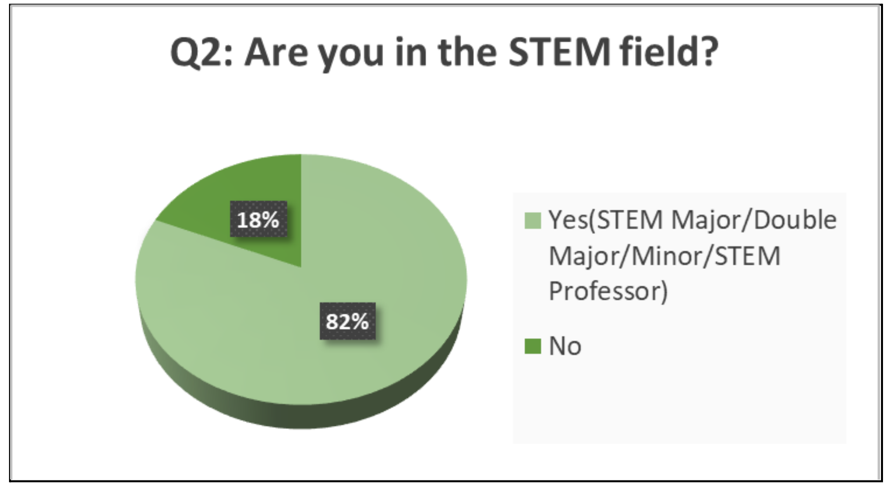
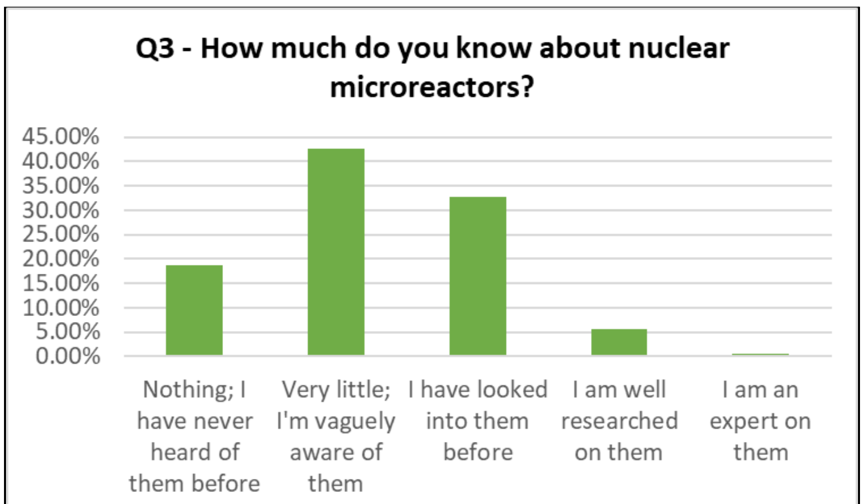


Figure 5: Results of Question 3



Graphics Description: Figures 3, 4, 5 above depict demographic information from our survey. The goal of the demographic portion of the survey was to identify our respondents' position at WPI, involvement in the science, technology, engineering, and mathematics (STEM) disciplines, and prior knowledge of microreactor technology. The figures 6, 7, 8 below depict the number of the total response that answered the question according to our likert scale value. Each of the questions was tailored to gain a broad understanding of interest in nuclear power and performing nuclear research.

Figure 6: Results of Question 4

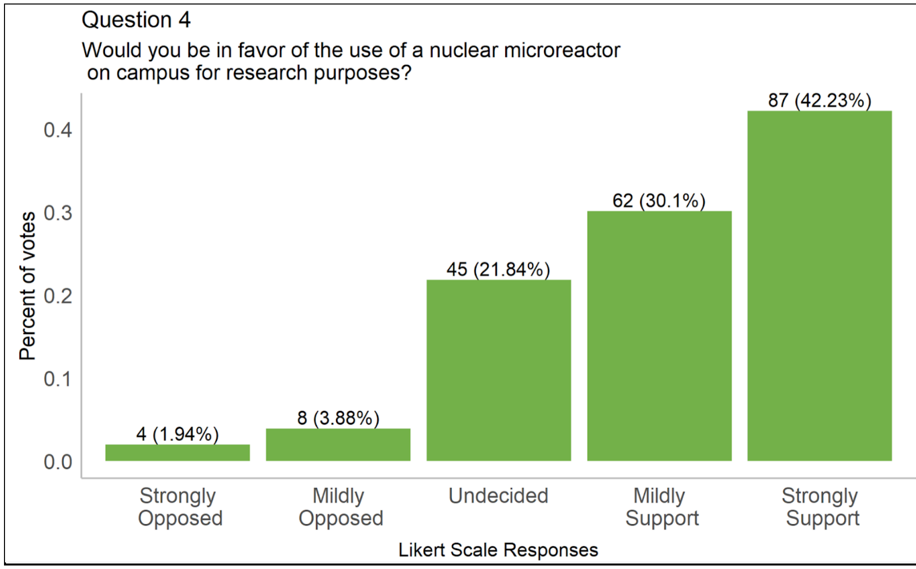


Figure 7: Results of Question 5

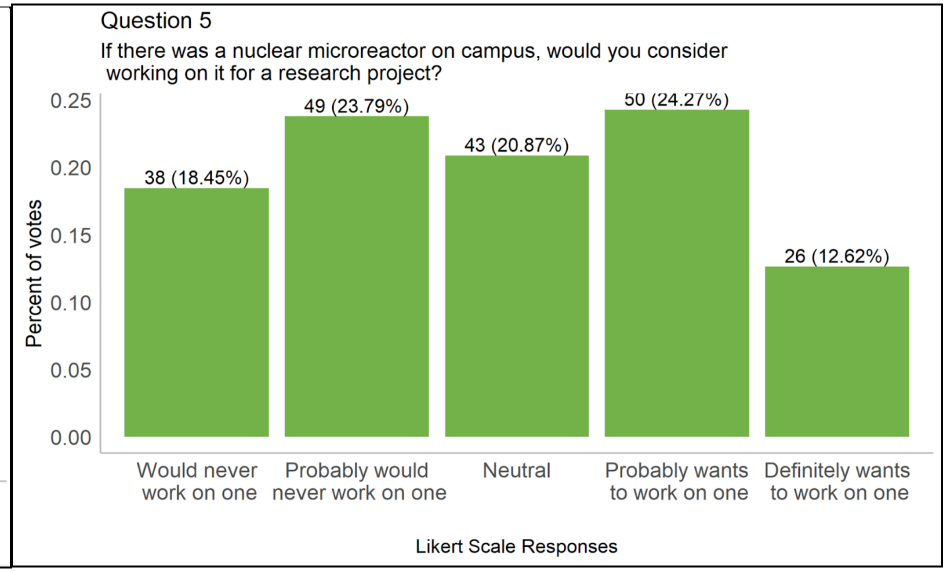


Figure 8: Results of Question 6

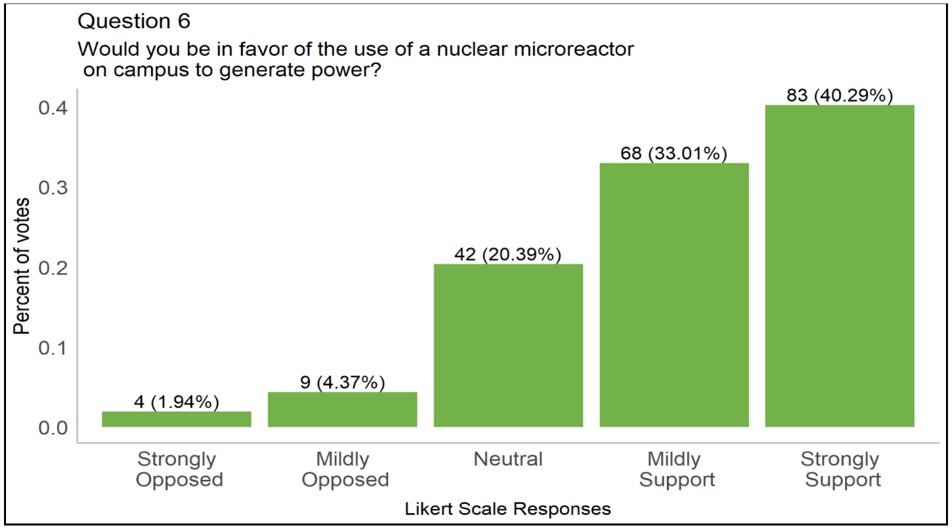


Figure 9: Results of Question 4 categorized by the Results of Question 1

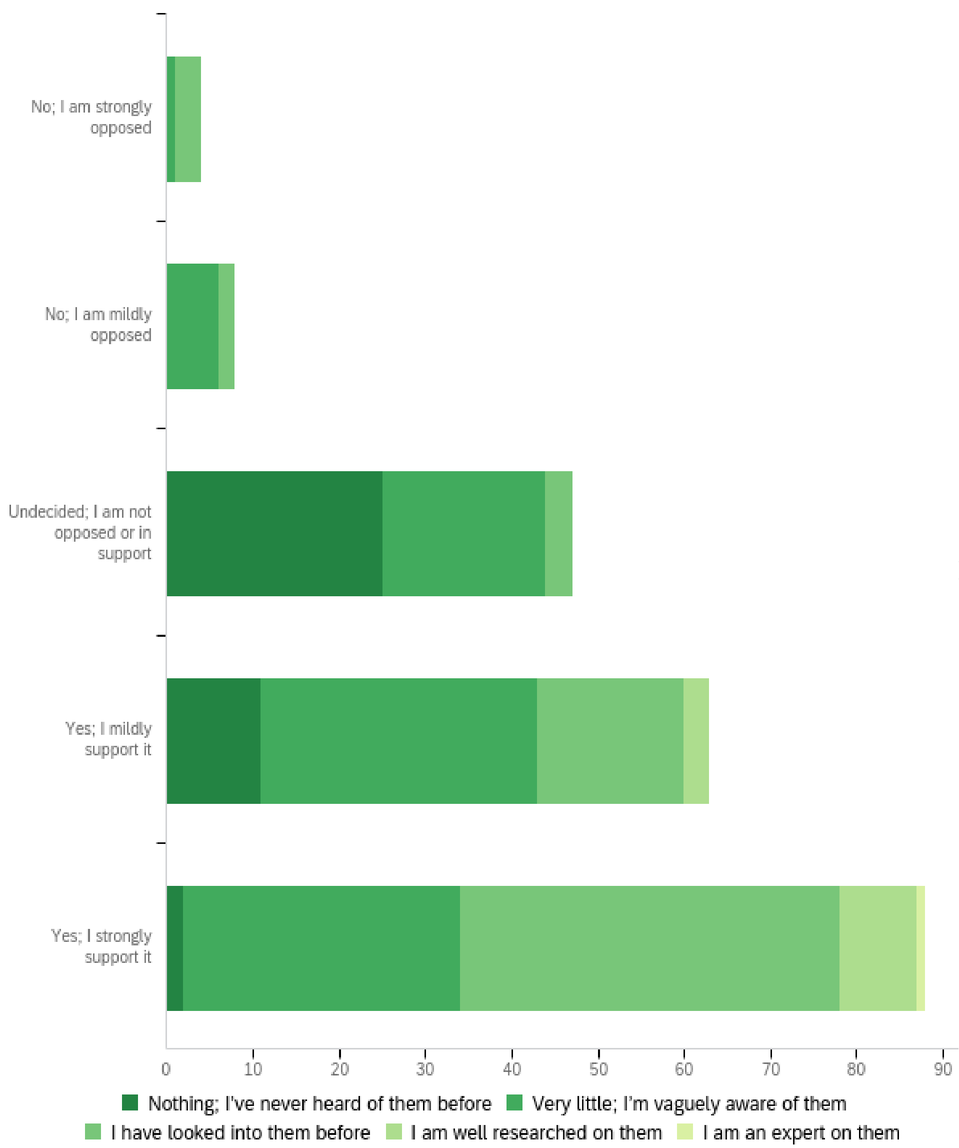


Figure 10: Results of Question 4 categorized by the results of Question 2

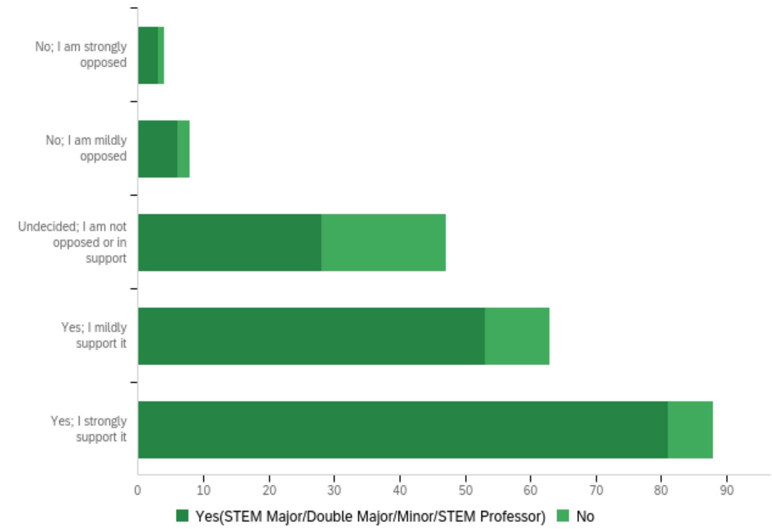


Figure 11: Results of Question 4 categorized by the results of Question 3

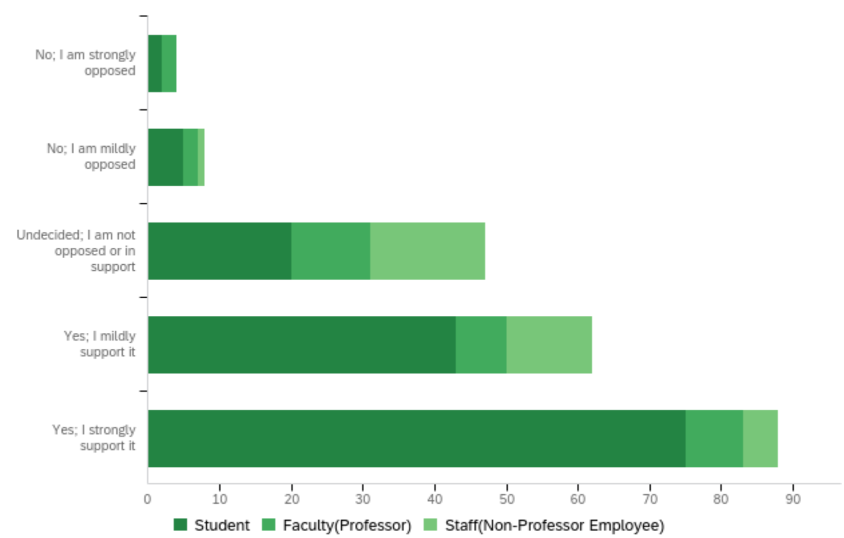


Figure 12: Correlation matrix between all survey questions

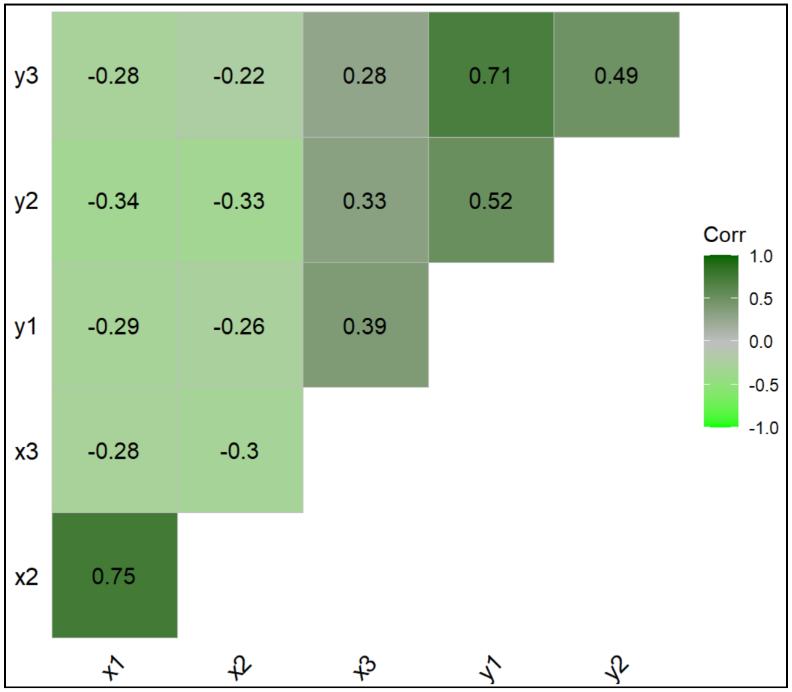


Table 8: Logodds and significance values based on survey responses

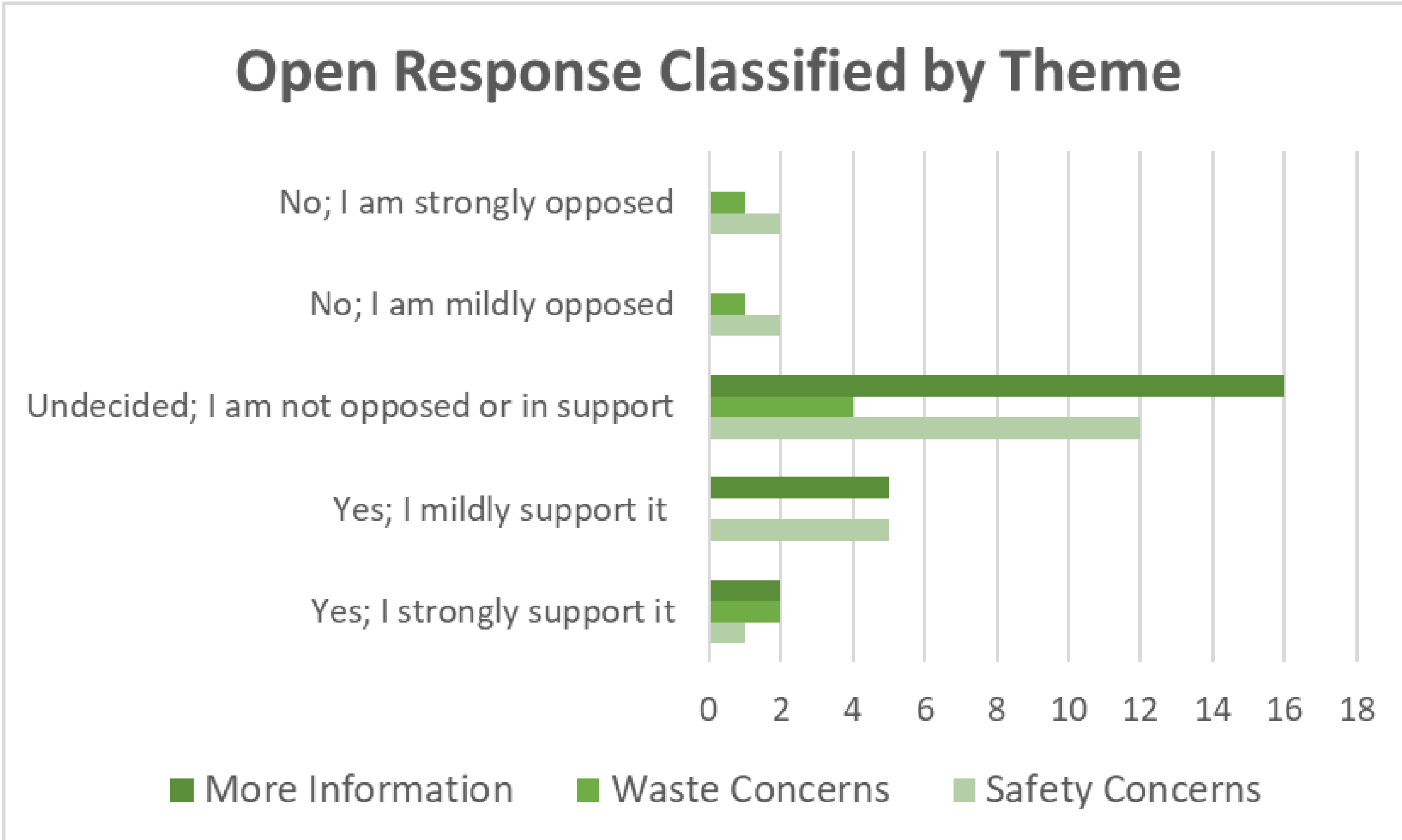
Coeff_label	sig_col	logodds
x1 Faculty (Professor)	•	0.339782911
x1 Staff (Non-Professor Employee)		0.639635735
x2 No		1.068827353
x3 Very little; I'm vaguely aware of them	**	2.711306802
x3 I have looked into them before	***	6.294753381
x3 I am well research on them	•	10.014787442
x3 I am an expert on them		0.000000358
y2 No; I probably would never work on one		1.898567676
y2 I am undecided	**	4.260309421
y2 Yes; I probably would want to work on one	***	4.966456669
y2 Yes; I would definitely want to work on one		73145879913.5

Graphic Interpretation: The correlation matrix, left, provides a visual representation of how much each variable impacted one another. It is important to note that the variables of questions 1 and 2 were categorical, but were analyzed numerically, so this method is not perfect, which is why the only clear finding was correlating knowledge and receptivity. Figure 12, left, is a correlation matrix of the survey responses and depicts the amount of impact each question had on the individual's response to a subsequent question. The variables on the axises in Figure 7 represent a question from our survey and are matched with their respective question below in Table 9. The other calculation Table, right, depicts the significance values(sig_col) of each question and the log odds(logodds column) of each variable's impact to influence the base case of our survey. The significance value essentially says how much each question impacts the individual's level of support in implementing a microreactor on campus. For our analysis the base case was a student in a stem field with no prior knowledge responding to the survey with definitely not wanting to work on a microreactor and it is not represented in the Table. In interpreting the logodds you always subtract 1. If the initial value is above 1 the difference is the likelihood that the base case will move up in level of support. If the logodds are less than 1 the difference is the likelihood the base case will move down in level of support.

Table 9: Variable and survey responses relationship

Variable	Question
x1	What is your position at WPI?
x2	Are you in the STEM field?
x3	How much do you know about nuclear microreactors?
y1	Would you be in favor of the use of a nuclear microreactor on campus for research purposes?
y2	If there was a nuclear microreactor on campus, would you consider working on it for a research project?
y3	Would you be in favor of the use of a nuclear microreactor on campus to generate power?

Figure 13: Results of Question 7



Graphic Interpretation: the open response classification graph above maps responses to Question 4 to feedback provided by respondents in the open response portion of the survey. During the coding analysis, three major themes were persistent. The categories of safety, waste and the desire for more information were extrapolated and mapped across the five possible responses. This analysis helped us understand the underlying mindset of the respondent.

Finding 10: The WPI community is receptive to and mostly supportive of implementing a nuclear reactor on campus

The results suggest that the WPI community will be very receptive to the nuclear reactor if it is implemented. Questions 4 and 6 of the survey asked if the respondent would be in favor of a nuclear reactor for research purposes and if they would be in favor of a nuclear reactor for energy purposes, respectively. They were asked to rate their level of support along a Likert scale, using 1 as the least supportive and 5 as the most supportive. As such, resulting mean values are based on a score out of a maximum of 5 and a minimum of 1. The means for questions 4 and 6 (Figures 6 and 8) were 4.07 and 4.05, respectively, with a sample size of 210, indicating the majority of the WPI community is in favor of the reactor. The similarity of these two means suggests there is no significant difference in support with regard to the function of the reactor, so WPI's support may be independent of how the reactor is used. The logodds model supports this, as it found a correlation of 0.71 between questions 4 and 6, as shown in Figure 12. Based on the responses to question 3 (Figure 5), which asked respondents to rate their knowledge of microreactors on a Likert scale from 1 to 5, there was a mean of 2.27, indicating that they are generally not very knowledgeable, implying that respondents may not know the different uses for the reactor. As such, the similarity in means for questions 4 and 6 may be explained by this lack of background knowledge.

When looking at the level of support among respondents with different levels of knowledge about microreactors (Figure 9), several observations can be made: 1. people who have no knowledge of microreactors tend to be the most uncertain about supporting or opposing them, 2. those who had looked into microreactors only a little bit were the most polarized between supporting or opposing microreactors, and 3. nobody with a self-reported knowledge level of 4 or 5 opposed microreactors. The first observation indicates that the WPI community is receptive to new ideas, which would make implementing the reactor easier. The second and third observations indicate that if the WPI community were more knowledgeable about microreactors, they may support the technology even more, though these observations may not hold much weight because of the small sample size. The responses to question 7, the free response question, also supported these claims. The people who were undecided about implementing the microreactor had the most questions about it, as shown in Figure 13, and many claimed they wanted to know more about the reactor before making a decision. It is noteworthy that some people who were supportive or opposed also said they were open to learning more about the reactor. The main concerns brought up by participants were about the safety of the reactor and its waste. Most of the responses that mentioned safety and waste were questions looking to learn more about it, rather than statements saying that they considered the technology unsafe. Given how receptive the WPI community is, an educational campaign with a focus on the safety of the reactor and its waste would likely be effective at increasing support. While support for the reactor is already pretty high, answering the community's questions would likely lead to a smoother implementation.

While the survey indicates very high support among its participants, it is not fully known if this is representative of the WPI community. The survey was not distributed using a random sampling method, but instead was distributed using posts online asking for volunteers and through word of mouth among some sub-communities.

This introduces bias, as the opinions of the communities surveyed may not fully represent the WPI community. In terms of the ratio between students and WPI employees, the survey was fairly representative; WPI currently has 7,230 enrolled students, including undergraduates and graduates (WPI F&F), and is estimated to have 2,990 employees including faculty and non-instructional staff (Zippia, 2022), meaning around 70.7% of the WPI community is students, and around 69.5% of the survey respondents were students. However, WPI only has 514 faculty (WPI F&F), which is around 5.0% of the WPI community, whereas around 14.1% of the survey respondents were faculty. As such, WPI's faculty may have been overrepresented, and thus the non-instructional staff may have been underrepresented. As a result, we cannot say definitively that the opinions of the respondents are representative of the WPI community as a whole, but given how strong the support was, the survey suggests that the WPI community likely would support the implementation of a microreactor on campus, and that WPI would not face much resistance from them if they were to implement one on campus.

Finding 11: It is unclear whether the position and field of a person are on the support and opposition of integrating a microreactor on campus

Questions 1, 2, and 3 of the survey sought to determine the demographics of the respondents to see if certain groups had different levels of support. Question 4 was used as a basis for comparing different strata under the assumption that it is representative of the support for the microreactor given that its results are not significantly different from those of question 6. For question 4, the students had a mean of 4.27, whereas the faculty had a mean of 3.57 and the staff had a mean of 3.62. This illustrates that students are significantly more supportive of the proposal than faculty and staff. This was also supported by the logodds model, which gave a correlation of -0.29 between question 4 and question 1, suggesting that students are likely to be more supportive than faculty and staff. There was a similar difference in values between people in the STEM field and outside of the STEM field, with people in the STEM field having a mean of 4.19 in favor of microreactors, while people outside of the STEM field had a mean of 3.51, and the logodds model found a similar correlation of -0.26 between questions 4 and 2. The main reason these values mirror the values from the comparison between students and non-students is because 98.6% of students who responded were in the STEM field. This conflation between students and the STEM field is also supported by the logodds model's correlation of 0.75 between questions 1 and 2. As such, it is unclear whether being a student, being in the STEM field, some combination of the two, or some other factor is the main predictor for support level. The data does suggest that being in the STEM field on its own is not the main predictor, because faculty and staff each have very similar mean values for question 4, but 70% of the faculty who responded were in the STEM field, and only 17% of the staff who responded were in the STEM field.

Chapter 5: Recommendations and Conclusion

5.1 Recommendations for WPI's Sustainability Commitment

Through our analysis it has become clear that microreactor technology is a legitimate solution to help WPI reach its sustainability goals. While it is significant that as an academic institution, WPI has been heavily including sustainability in its project work and course material, WPI should also have a stronger focus on operating in a sustainable manner to demonstrate its dedication to combating climate change. And in doing so, WPI should strive to not only meet the goals for the pathway that the IPCC recommended, but to reach carbon neutrality even sooner than 2050 to set a standard for other businesses to follow. WPI should be careful about committing to a long-term agreement that could limit its energy options. While a cogeneration plant may be more efficient than WPI's current practices, it would not reduce WPI's emissions as significantly as a microreactor like the eVinci would. In order to become a leader in sustainable energy, we encourage the administration at WPI to enlist the help of students and faculty in pursuing green energy solutions; solar, wind, and nuclear energy are all potential solutions or could be a piece of the puzzle that makes WPI a leader in green energy. In order to accomplish this, we recommend WPI take the following actions:

1. **Encourage and facilitate student and faculty-led research through IQP & MQPs about sustainable energy sources. Specifically, feasibility studies.**

After the findings outlined in this project and talks with energy experts, it has become clear to our team that there are a variety of solutions capable of providing WPI with sustainable energy. A microreactor integrated with other systems is capable of reaching WPI's sustainability goals, however other opportunities should be explored before coming to a final decision. Many different methods of energy production have a role in stopping climate change.

One of the greatest assets WPI possesses is a wealth of students and faculty passionate and dedicated to science, technology, the future of WPI, and the environment. Based upon the results of our survey, it was clear that a large portion of students support a transition to clean energy and are interested in improving WPI's sustainability. WPI's foundations in project-based learning reinforce the theory taught within its classrooms. WPI has begun to use student projects to further the institution's sustainability; however, more support and action is needed to implement these projects. Based on the current lack of support and action our team recommends expanding the Green Revolving Fund. Expanding support would involve increasing funding and offering direct mentorship from individuals in the green energy industry, entrepreneurship, and business. According to the WPI website the current Green Revolving Fund only provides ~$10,000 of support to one or two on-campus projects annually (WPI [2], 2017). These projects are briefly documented in the WPI sustainability report, but advertisement of this resource and its projects needs to be improved; boosting student funding would allow several teams to perform a small-scale test of their projects and prove the viability of their concepts. Increasing support and encouraging more students to perform IQPs and MQPs will make WPI more sustainable. At the end of the year, these projects should enter the WPI Sustainability Contest held by the WPI Office of Sustainability. It may be beneficial to introduce categories into the contest to allow green energy to compete separately from other sustainability projects. WPI should also invite leading companies from the green energy industries and other investors to meet with teams and transform the competition into a networking event. Projects at the competition should continue to receive funding and present to the WPI administration as a future opportunity for WPI.

2. **Work with WPI and Worcester community leaders, encouraging a commitment to sustainability and transparency.**

For WPI to successfully develop the alternative energy options discovered by students and faculty, it is necessary to have the support of WPI administrators and the Worcester City leadership. This is no different from the sustainability initiative at WPI; members of the WPI Administration and the Worcester City Leadership will have direct control over many of the proposed projects. It is imperative to identify these stakeholders and work with them to accomplish our sustainability goals. Our team recommends that WPI and the City of Worcester establish a commitment to sustainability, with both entities holding one another accountable. It is important that this relationship and the actions of these entities are transparent and communicated to the community. The WPI community is invested in the success of the institution, but very little has been done to communicate WPI's energy infrastructure plans to the student body or faculty. This is evident given we had difficulty obtaining concrete information about WPI's proposed cogeneration plant. This lack of communication may stem from disconnect between high level administrators and the student body and faculty. In order to increase communication between these two groups, monthly meetings or question and answer sessions could allow for the community to be more involved and informed about current plans. WPI students and faculty should have the ability to hold their leaders accountable; transparency is necessary for this to occur.

3. **Conduct detailed surveys of WPI and Worcester communities regarding various kinds of sustainable energy.**

To include the entire Community of Worcester in the decisions made by WPI, our team recommends that WPI distribute a survey to the WPI and City of Worcester communities regarding different energy alternatives. The goal of this survey would be to identify support or resistance to certain types of energy production and to further uncover the reasons for a given response. Reaching a large portion of the community is needed, so working with the City of Worcester to implement such a survey as part of the open response section during an election cycle would be ideal. Using this information, WPI and the City of Worcester could work to educate the community to become more understanding of misunderstood technology and proceed with a project.

4. Select a project and develop an installation/integration plan and timeline for the proposed project.

After completing the above steps and identifying solutions, stakeholders, and community support for different energy alternatives, an action plan should be established. A committee consisting of the WPI Administration, Worcester Community Leaders, and energy experts should evaluate the projects, select which projects to investigate further, and determine which of the energy sources WPI should integrate into campus infrastructure. The chosen projects will then move into a planning and implementation stage where they will determine a plan for installation on campus, in addition to a schedule and budget. These projects can then be used as reference for implementing energy sources on campus.

5.2 Conclusion of Feasibility Assessment

Our findings so far suggest that implementing the eVinci reactor on campus for power generation and research should be technically feasible based on three major considerations: stakeholder needs, infrastructure needs, and financial assessment.

There are various stakeholders for the reactor, and each has different needs to be met. The first major stakeholder is WPI facilities, whose needs relate to campus operations. They will need the reactor to provide enough energy to meet the usage needs on campus. We found that the eVinci could produce enough electricity to meet usage needs. We also found that the eVinci could produce enough heat most of the time, but that it would fall short during the colder months of the year. As such, the eVinci would need to be implemented with backup systems to ensure that energy needs are met. The eVinci will also need backup systems to provide energy when the reactor needs to shut down, but we did not find how backup systems should be designed to account for this. WPI's facilities will also need the reactor to help lower WPI's carbon emissions in order to meet sustainability goals. We found that implementing the eVinci on campus should lower WPI's scope 1 and scope 2 emissions by at least 84%, which would go a long way in helping WPI reach carbon-neutrality.

Another major stakeholder is nuclear researchers. They will need the reactor to enable research opportunities without sacrificing energy production. We found that the eVinci can produce a powerful neutron-beam in its periphery because of its small size. This would allow the reactor to be used for the same research applications as a traditional research reactor of equal power level. Because the neutron beam would be produced on the periphery, the eVinci would not need to shut down to be used for research, meaning that the research applications should not interfere with energy production.

A third stakeholder is the WPI campus residents and the surrounding Worcester residents. They will need the reactor to be exceedingly safe, and to present very low risks to safety. We found that the eVinci has extensive safety features that make it very safe, including passive cooling systems that do not require liquid coolant and inherent protection against overheating because of the TRISO fuel's doppler effect. We also found that Westinghouse has performed risk analyses for the eVinci, and has found that the risk of every event they considered is far below the level that the regulators set as a baseline for the maximum allowed risk. As such, the eVinci should meet the residents' safety needs. We also found that the WPI community is receptive and that they are generally approving of implementing a microreactor on campus, so we do not anticipate that there will be an issue of backlash from the community if information about the eVinci is made transparent and accessible. Additionally, we found that the WPI community would want to perform nuclear research with the reactor, meaning that WPI would need a nuclear research program to allow for this. We did not consider how to run a nuclear research program.

There are a few groups of infrastructure needs that must be addressed for the eVinci to be feasible. The first group is the integration of the reactor on campus. We found that the eVinci could connect to WPI's heating systems by making a connection between the eVinci's Brayton system and WPI's steam pipes to allow heat to transfer. We did not find what electrical infrastructure would be needed for the eVinci, such as whether a microgrid or the central grid should be used, but we did find that the eVinci's systems would have effective load-following to allow its electricity production to match WPI's needs. Most notably, we did not consider finding a site for the reactor on campus. As such, it is still unclear how the eVinci would be integrated with campus infrastructure.

The second group of infrastructure needs is the eVinci reactor's management. We found that the eVinci can mostly operate independently, and that it only needs to be passively monitored, making for very simple operation. We found that WPI could hire additional employees to monitor the reactor and conduct research. We also found that Westinghouse can handle the main aspects of the eVinci's maintenance for WPI, including the refueling process and the storage of waste. Westinghouse's maintenance processes ensure that exposure to radiation will remain at negligible levels, and the high-level waste will not be stored on or near campus. Thus, the eVinci should meet the criteria for management.

The third group of infrastructure needs is the eVinci's safety. As discussed before, we found that the eVinci's safety features make it adequately safe, and that the eVinci presents very low risk of harm. It is also important for the eVinci to have safeguards and emergency preparedness. We found that the eVinci has multiple shutdown mechanisms that act as safeguards to prevent any event from escalating into a meltdown. We found that in the event of an emergency, Westinghouse has developed plans to release radiation into the environment in a way that minimizes harm to human safety. We also found that Westinghouse has found that the emergency planning zone for the eVinci is about the size of the physical site boundary, meaning the eVinci should not cause harm to anyone outside the physical boundary of the reactor site. We have not found any information indicating that the eVinci would be harmful to the environment, and given that we found that it has low carbon emissions, it should have a net-positive effect on the environment. We did find that the storage of waste is an ongoing safety problem in the U.S., but we also found that the eVinci produces very little waste, so it would have a negligible impact if the technology is only implemented sparingly. Thus, the eVinci should meet the criteria for safety.

The fourth and final group of infrastructure needs is regulatory. As the eVinci is still in development, and no microreactors are yet to be used commercially, there are still legal roadblocks that must be addressed to allow for commercial use. We did not consider the specifics of the manufacturing and industrial regulations. One remaining legal issue is that reactors cannot currently be used simultaneously for both power generation and research. We did not find how this legal issue will be addressed. We found that the U.S. places high value on nuclear research, so we expect that this issue will likely be resolved in the future. Additionally, WPI will need a license to use the eVinci, but we did not consider the specifics of this requirement. Thus, it is still unclear how the eVinci will meet the legal criteria.

The last consideration for the feasibility of the reactor is financial. We did not find what the costs associated with the reactor would be. We found that eVinci may be able to generate revenue to offset the cost by using paid research, as we found that there is high demand for performing paid research in the U.S. We also found that the eVinci may be able to sell excess energy for revenue, as the eVinci could produce 75% more electricity and 78% more heat than WPI's average needs, but we did not find how this would incorporate with the electricity infrastructure, and we did not find a definitive answer as to whether this is possible. Thus, it is still unclear whether the eVinci would be financially feasible. However, given that the Department of Energy highly subsidizes other research reactors, like the MIT reactor, it is likely that much of the cost to implement and license the eVinci reactor could be offset through similar funding.

Overall, from what we found about the eVinci's capabilities, the eVinci should meet the needs of relevant stakeholders, but uncertainties remain around the implementation of the reactor on campus. We found no evidence that suggests the eVinci is not feasible without exceptions or alternative measures. As such, we expect that future research into these uncertainties will determine that the eVinci is feasible for implementation at WPI for both power generation and research.

5.3 Future Research

This project has so far established that implementing microreactor technology at WPI is feasible and could benefit WPI and the environment. There are several more topics that still need to be investigated in more depth before a reactor can be implemented.

1. Cogeneration Plant

Because WPI has not made publicly available the details of the cogeneration plant proposals that they have received from various companies, we are currently not able to accurately assess the sustainability of the plant's design in relation to or in conjunction with a research microreactor. While we have obtained information that the plant may use renewable natural gas and may use solar panels as an additional energy source, there are no written plans available to confirm this. WPI has not been forthcoming with the details of the contract they are forming, so we do not know the details of the implementation plan and whether it will be adaptable or restrictive. Since WPI is nearing a final decision, information about the plans may soon become publicly available. Once it is available, the sustainability of the cogeneration plant and whatever other energy systems are included in the plan should be evaluated. The integration of the microreactor also needs to be investigated.

2. Estimating Carbon Emissions

Performing an LCA of the eVinci was outside the scope of this project due to the complexity of the methods involved. Our estimates of the eVinci's emissions rely on LCA estimates of LWRs and on assumptions about the differences between LWRs and the eVinci reactor. Professor Medich voiced skepticism about the methods of previous LCAs for LWRs and was concerned that the emissions estimates seemed unreasonably high. Also, it was difficult to quantify the effects on emissions that the differences between LWRs and the eVinci had. A future group should obtain a more accurate estimate of the eVinci's emissions. One approach to this would be to work with Westinghouse to develop an LCA for the eVinci. Another approach would be to use a more rigorous version of our methods by developing a thorough understanding of the methods used in LCAs for nuclear reactors to conclude whether they are valid, working with Westinghouse to more thoroughly understand the eVinci's lifecycle in comparison to LWRs, and using LCA methods to quantify the difference in emissions compared to LWRs. Also, our emissions estimate for WPI's proposed cogeneration plant is not very reliable because the details of the plant were not publicly available at the time of writing. Once the information is available, a more accurate estimate for the cogeneration plant's emissions should be compared to the eVinci's emissions and evaluated based on how effectively they mitigate climate change.

3. Regulations and Licensing

We did not consider the legal barriers to implementing a microreactor for both research and power generation or the licensing process. A future group should inquire with Westinghouse about the certification for the eVinci, what regulations may need to be changed to allow it, and the NRC's progress on those regulations. The group could also work directly with the NRC to understand the process for establishing reactor requirements.

4. Backup Systems

Backup systems for the eVinci would need to produce energy for two purposes: additional production during peak hours and unplanned shutdowns. In order to get a full picture of how much additional energy the backup systems would need to produce, a future group should obtain data for WPI's peak hour electricity and heating usage. The group should seek to understand the complexities of how energy usage and demand are measured on campus to confirm that the backup systems would meet campus needs. The four options for backup systems that we presented do not directly account for unplanned shutdowns, as we did not obtain information that quantifies how frequently they might occur. As such, Westinghouse should be contacted about how frequently the eVinci reactor would need to shut down to better understand how to plan around providing backup energy so that WPI doesn't lose power. Backup systems for unplanned shutdowns should be further evaluated as to whether or not they can be incorporated into our four options, or if other options for backup energy should be considered.

If the four options remain viable after considering how backup systems will account for unplanned shutdowns, the options will need further research. Of the four options we presented for backup systems, options 3 and 4 incorporate WPI's planned cogeneration plant, while options 1 and 2 are only viable if WPI does not implement a cogeneration plant. For options 1 and 2, for backup electricity, the group should explore the possibilities of using a battery system to store excess energy, buying energy from National Grid, or implementing additional electricity sources on campus, such as solar panels. Additionally, they should explore using the powerhouse on campus to provide extra heating or if another, more sustainable heat source could be implemented. Option 2 also requires further investigation into the eVinci's ability to sacrifice electricity production for additional heating to determine how effective it would be. The group should then seek to evaluate the benefits and drawbacks of each option.

5. Reactor Integration at WPI and Location Selection

We found that integrating the reactor into WPI's current heating system is theoretically possible, but we did not determine the specifics of how to go about integrating the reactor. More research is needed on the technical aspects of the eVinci's open Brayton system and WPI's heating infrastructure. Additionally, we did not explore how the reactor would connect with WPI's infrastructure for electricity distribution. An effective design to integrate the eVinci and its backup systems with the central grid to power the campus needs to be designed. We also didn't investigate how a microgrid could be implemented on campus and how the eVinci and its backup systems would connect to it. It remains to be determined if a microreactor could actually be used in a microgrid system, and if it would be economically viable. The benefits and drawbacks of using either the central grid or a microgrid should also be evaluated. Further, more specific considerations are needed, such as whether the systems would allow the eVinci to provide energy to Gateway Park, and how efficiently heat and electricity can be carried over distances.

This knowledge of how the eVinci will integrate with WPI's energy systems can then be used to choose a location for the reactor on campus. Criteria need to be developed and applied in order to determine a suitable location for the reactor. Possible criteria include: the amount of space available, the environmental risk factors, the ability to connect to both electrical and heating systems, and the ease of security.

6. Financial Impact

A major consideration for the viability of having the eVinci at WPI is its finances. To estimate the eVinci's financial impact, it will be important to weigh the cost of the reactor, the revenue generated from the reactor, funding from grants and subsidies, and the money saved from replacing previous systems. The most uncertain facet is the capital cost of the reactor itself, as it is difficult to estimate before the reactor becomes commercially available. There will also be costs from Westinghouse's services for assembling and maintaining the reactor. Estimates for these costs should be determined once the eVinci is closer to being commercially available. Costs associated with each option for the backup systems should also be considered, as well as any additional infrastructure changes that would be made, such as implementing a microgrid.

While the reactor is expected to have a high initial investment, this cost could be offset by potential savings and revenue. The eVinci's energy and its backup systems would replace the electricity bought from National Grid and the natural gas burned at WPI's power plant. One potential way for the eVinci to generate revenue is by selling excess electricity. We found that if the eVinci were to run at full power, it would produce a substantial amount of excess electricity. We also found that National Grid buys solar energy from its customers through a net metering policy, but they do not purchase electricity from Clark University's cogeneration plant. More research is needed to determine whether WPI could sell the eVinci's energy to National Grid or some other entity, such as the City of Worcester. Another potential way for the eVinci to generate revenue is by running funded research. We found that research reactors are in high demand for funded research opportunities, so a future group should work to estimate the potential for the eVinci to generate revenue from funded research.

Once the financial impact of the reactor is estimated, it should be weighed against the non-monetary benefits of the reactor. In addition to monetary gain, the non-monetary value from the opportunities that the program would provide to the university and its students should be considered.

7. Survey

A follow up survey based on our findings would be useful to develop a deeper understanding of opinions about implementing a microreactor on campus. The survey should be distributed to gather a higher sample size of the WPI community, possibly by working in conjunction with WPI's Sustainability Office. The survey should also be distributed to the greater Worcester community, as their views may become relevant in the discussion of implementing the reactor. To improve upon the previous survey, this survey's questions should be designed with statistical analytical methods in mind to achieve more significant results. Based on the findings of our survey, it may be beneficial to have an awareness campaign about microreactors to better inform the WPI and Worcester communities. More work would be needed to develop an effective outreach effort.

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Appendices

Appendix A: Interview Protocol

Interviews were conducted remotely using the online communication platform, *Zoom*. The interviewee was given a consent form, shown in Appendix B, before beginning the interview, which outlined that they were free to answer the questions to the extent which they were willing and that they could stop answering and withdraw from the interview and the study at any time. The consent form also indicated that we cannot guarantee that the interviewee will be kept anonymous, but that they had the option for the interview to be kept confidential. We intended to accredit the information to the interviewees in order establish credibility for whatever information we used from them in our results, but we would not do so if they wanted confidentiality. We also asked for permission to record the audio of the interview. The recording was not released and was only used to write the transcript for the interview.

During the interview, one member of our team verbally delivered the prepared questions, and one or more other members took notes on the interviewee's responses. One or more members of the team asked unscripted follow-up questions in response to what the interviewee said, not straying far from the topics covered by the scripted questions. After the interview, we sent the interviewee the transcript from the interview, and asked if they had any clarifications or corrections they would like to be made to what they said. We also scheduled follow-up interviews with the interviewees so that we had the opportunity to ask questions based on what we found from other interviews. Protocol written with guidance from (Jacob & Ferguson, 2015).

Appendix B: Interview Consent Form

Primary Investigator:

Derren Rosbach

Contact Information:

Tel: 508-831-5000 / Email: drosbach@wpi.edu

Title of Research Study:

Exploring the feasibility of Small Modular Nuclear Reactors for research and energy at WPI

Introduction:

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks, or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of Study:

The purpose of this study is to analyze the feasibility of a nuclear microreactor at WPI. We are analyzing it from a societal point of view. This includes the environmental and research benefits that would result from the microreactor's implementation, and the support and opposition to the proposal.

Participation:

Participation in this interview is voluntary. You are free to answer questions to whatever extent you are willing. You are free to withdraw from the interview and withdraw your responses from the study at any time before publication. Refusal to participate will not result in any penalty to you.

Confidentiality:

Your responses cannot be guaranteed to be kept anonymous. You are given the option to have us keep your responses confidential so your identity is not explicitly tied to them.

Recording:

The audio of this interview will be recorded for the purpose of creating a transcript. The recording will not be published, and will be discarded after the transcript is complete. You will have the option to edit the transcript before it is published. You have the option to opt out of having the interview's audio be recorded.

Benefits and Risks:

There are no direct benefits from participation in the interview. There may be risk to your employment based on the responses to some questions, but this is unlikely due to the nature of the questions that will be asked.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

Do you want your responses to remain confidential? (yes/no) __________

Do you consent to the recording of the interview's audio? (yes/no) __________

______________________________ Date: ________________

Participant Signature

____

Participant Name (Print)

______________________________ Date: ________________

Interviewer Signature

Appendix C: Interview Questions for Westinghouse

1. It is our understanding that research reactors and power reactors are built differently. Is the eVinci reactor design capable of being used for research?
2. Why did Westinghouse choose to develop a generation IV microreactor instead of a generation III microreactor?
3. What is still preventing generation IV microreactors from reaching the market?
4. What are the main constraints and limitations of generation IV reactors in terms of economic viability?
5. What range of energy can the reactor produce in terms of MW?
6. How long can the reactor sustain maximum uptime?
    a. What percentage of a day can the reactor sustain maximum uptime? e.g. what is the Capacity factor?
7. Could the heat from the reactor be used to heat water to provide heating for campus?
8. How much heat does the reactor produce per MW of electric energy?
9. What percentage of that could be utilized to heat water?
10. What kind of fuel does the reactor use?
    a. How does the fuel differ from other fuels?
11. What process is used to create the fuel?
    a. What type of enrichment process is it?
    b. How does the process differ from other fuels?
12. How much fuel should the reactor need per MW of electrical energy produced? Per year of its lifespan?
13. How does the microreactor refuel?
14. How much waste would the reactor produce per MW of energy produced? Per year of its lifespan?
15. What are the main potential hazards of having a microreactor on a college campus?
16. Should anyone be concerned about their safety due to there being a reactor on campus?
17. How is fuel/reactor designed regarding safety? How does the reactor SCRAM?

Appendix D: Follow-up Interview Questions for Westinghouse

1. You talked about some of the economic benefits of the eVinci design. Were/are there any main struggles in designing a microreactor to be economically viable?
2. You mentioned calculating the levelized cost of electricity. Does Westinghouse have any estimations for the LCOE of the eVinci reactor?
3. You talked about how the eVinci design can produce 5 MW of electric power. Is the eVinci reactor capable of load following, such that it can produce less than 5 MW if needed?
4. You mentioned how the eVinci is capable of heating water for the WPI campus. Can you elaborate on how water is heated with the reactor, e.g. would there be a pipe of water or steam flowing through the reactor, or does the reactor have an exhaust for heat?
5. You talked about TRISO fuels. Can you tell us what enrichment process is typically used for the uranium used in TRISO fuel?
6. You talked about eVinci's quick refueling process. You said that in refueling, the reactor is taken out and replaced by another reactor. To clarify, does this mean that Westinghouse completely replaces the eVinci reactor for the customer when it is in need of refueling, or are we misunderstanding?
7. When talking about the waste and the fuel, you said "the fuel can be separated from the reactor," and we think you meant to say "the fuel can be separated from the waste." To clarify, can the waste be separated from the fuel, and if so, how?
8. Does Westinghouse process the waste? Where does the waste ultimately end up?
9. You talked about how Westinghouse does an internal and external hazard analysis for the eVinci reactor, and how it is made sure that there are mitigations for those hazards. Are the mitigations in the safety features of the eVinci reactor itself, or are there some mitigations that are limited to choosing a specific location for the siting of the reactor? Are there some hazards that cannot be accounted for with the safety features of the eVinci reactor?
10. In a survey we conducted of the WPI community, many people expressed a concern for the safety of the reactor. We do not think the reactor would have much risk associated with it, but we must be sure. Can you tell us about what the baseline for risks and hazards of having the eVinci reactor on a campus would be, if there are any? Or an approximation of what the likelihood of anything going wrong would be in the best case scenario, and what the worst possible scenario would look like?
11. At the end of the interview you mentioned that Westinghouse has calculations for the lifecycle carbon emissions of the eVinci reactor. Could we have access to some of the data, methodology, and results of those calculations?

12. When performing nuclear research, if the core needs to be modified for an experiment, would the reactor need to shut down briefly?

13. You mentioned that some nuclear engineers at Westinghouse had a better idea of what sorts of research can be done with the eVinci reactor. Can you direct us to somebody we can contact to learn more about that?

Appendix E: Interview Questions for WPI Professor

1. What kinds of research can be done inside the core, and which kinds can be done only on the periphery?
    a. Follow Up: Will the reactor be built under power regs?
2. With periphery experiments, how often would the reactor need to be shut down or SCRAM?
3. What areas of nuclear research are you most involved with and interested in?
    a. What about other fields you do not partake in?
4. What sorts of research would you perform with a reactor if there was one on campus?

Appendix F: Interview Questions for MIT Nuclear Research Program

1. What fields of study are involved with nuclear research (materials, medical)?
2. Could you tell us about current experiments being performed at your institution using the reactor?
3. How many students tend to be involved with the reactor every year, between graduate and undergraduate?
4. What about how many students use it for class work or for research projects?
5. Could the reactor allow for more students to be using it than there are currently?
6. How do students feel about the reactor on campus? How has student reception of the reactor been over time?
7. Has there ever been discussion of removing the reactor?
8. What prevents more types of research from being done than there are currently?
9. What is the risk management process of the reactor? What are the processes when the reactor malfunctions?
10. Have safety incidents occurred in the past?
11. Do you have security around the reactor?
12. Is the reactor's spent fuel treated on campus?
13. Where is the waste temporarily and permanently stored?
14. What opportunities does a higher flux neutron beam afford to researchers?

15. Are you familiar at all with generation IV microreactor technology?
16. If yes: Would a Microreactor performing nuclear research have additional benefits beyond a more dense neutron beam?
17. Would using the electricity generated from the reactor to power something impede the reactor's use for research in any way?

Appendix G: Interview Questions for WPI Facilities

1. Where does WPI source its electricity from? Does WPI produce any energy on campus?
2. How is electricity distributed across campus?
3. Where does the campus tie into the city grid and how?
4. How much energy is needed during peak hours and when are peak hours?
5. Are there backup systems for both water heating and electricity on campus? What are they? When are they needed, and how often?
6. What is the current process for heating water on campus?
7. Does WPI store its hot water, or does it produce it based on need?
8. Where is water heated on campus?
9. How much hot water is needed during peak and non-peak usage hours? When are the peak hours?
10. What is all of WPI's natural gas used for? What percentage is for heating water?
11. Would having electricity and hot water generated in the same location cause issues or create benefits?
12. How would the current WPI energy grid handle a new source of power? Would excess energy be used for energy credits?
13. Would the energy infrastructure allow the reactor to simultaneously provide power to the main campus and gateway?

Appendix H: Survey Questions

1.) What is your position at WPI?

1-Student

2-Faculty(Professor)

3-Staff(Non-Professor Employee

2.) Are you in the STEM field?

1-Yes(STEM Major/Double Major/Minor/STEM Professor)

2-No

3.) How much do you know about nuclear microreactors?

1-Nothing; I've never heard of them before

2-Very little; I'm vaguely aware of them

3-I have looked into them before

4-I am well researched on them

5-I am an expert on them

4.) Would you be in favor of the use of a nuclear microreactor on campus for research purposes?

1-No; I am strongly opposed

2-No; I am mildly opposed

3-Undecided; I am not opposed or in support

4-Yes; I mildly support it

5-Yes; I strongly support it

□I don't care

5.) If there was a nuclear microreactor on campus, would you consider working on it for a research project?

1-No; I definitely would never work on one

2-No; I probably would never work on one

3-I am undecided

4-Yes; I Probably would want to work on one

5-Yes; I would definitely want to work on one

6.) Would you be in favor of the use of a nuclear microreactor on campus to generate power?

1-No; I am strongly opposed

2-No; I am mildly opposed

3-Undecided; I am not opposed nor in support

4-Yes; I mildly support it

5-Yes; I strongly support it

□I don't care

7.) Would you like to elaborate on any of your answers to the previous questions? Do you have any additional questions, concerns and opinions? (Open response)

Appendix I: R code for analyzing survey results

The following is supposed to be run in RStudio with all appropriate packages installed. The file path and variable for directory should also be changed to match where the file is on the computer that is running this code.

```
#create variable for working directory, this will be the same location as the R file and should have the csv placed in
the same directory
working_dir <- getwd()

#read in the csv file
data <- read.csv(paste(working_dir, "/IQP Microreactor Survey_April 13, 2022_15.05.csv", sep=""), na.strings = "")

#remove header rows from csv
datasubset <- (data[3:245,11:16])

#remove rows of N/A data and create new dataframe with N/A's removed
finaldata <- na.omit(datasubset)

#replace invalid characters such as Iâ€™m with I'm
finaldata <- data.frame(lapply(finaldata, function(x) {
  gsub("â€™", "'", x)
}))

#during data review it was noticed that at least one response has white space at the end; Q4 "Yes; I mildly support it
"
finaldata <- finaldata %>% mutate(across(where(is.character), str_trim))

#rename the dataframe columns to x1, x2, x3, y1, y2, y3
finaldata <- finaldata %>% rename(x1 = Q1, x2 = Q2, x3 = Q3, y1 = Q4,  y2 = Q5, y3 = Q6)

#all responses are categorical so they should be assigned to factors the following code assigns them to factors
finaldata$x1 <- factor(finaldata$x1)
finaldata$x2 <- factor(finaldata$x2)
finaldata$x3 <- factor(finaldata$x3)
finaldata$y1 <- factor(finaldata$y1)
finaldata$y2 <- factor(finaldata$y2)
finaldata$y3 <- factor(finaldata$y3)

#verify that all factor assignments are accurate
describe(finaldata)

#review current levels to ensure they match survey results
sapply(finaldata, levels)

#upon reviewing we can see that x2, x3, y1, y2, y3 are not number the same as the survey results. Correcting this
may not have an impact on relationships, but does keep the story consistent.
finaldata$x1 <- factor(finaldata$x1, levels=c("Student",
                                              "Faculty(Professor)",
                                              "Staff(Non-Professor Employee)"
                                              ))
finaldata$x2 <- factor(finaldata$x2, levels=c("Yes(STEM Major/Double Major/Minor/STEM Professor)", "No"))
```

```
finaldata$x3 <- factor(finaldata$x3, levels=c("Nothing; I've never heard of them before",
                                    "Very little; I'm vaguely aware of them",
                                    "I have looked into them before",
                                    "I am well researched on them",
                                   "I am an expert on them"
                                    ))
finaldata$y1 <- factor(finaldata$y1, levels=c("No; I am strongly opposed",
                                    "No; I am mildly opposed",
                                    "Undecided; I am not opposed or in support",
                                    "Yes; I mildly support it",
                                    "Yes; I strongly support it"
                                    ))
finaldata$y2 <- factor(finaldata$y2, levels=c("No; I definitely would never work on one",
                                    "No; I probably would never work on one",
                                    "I am undecided",
                                    "Yes; I Probably would want to work on one",
                                    "Yes; I would definitely want to work on one"
                                    ))

finaldata$y3 <- factor(finaldata$y3, levels=c("No; I am strongly opposed",
                                    "No; I am mildly opposed",
                                    "Undecided; I am not opposed nor in support",
                                    "Yes; I mildly support it",
                                    "Yes; I strongly support it"
                                    ))
#validate that factor levels now correspond to survey answers
sapply(finaldata, levels)
describe(finaldata)

#create new dataframe from original finaldata and convert factors to numeric this is to run the correlation matrix
starting at line 141
finaldata2 <- finaldata

finaldata2$x1 <- as.numeric(finaldata2$x1)
finaldata2$x2 <- as.numeric(finaldata2$x2)
finaldata2$x3 <- as.numeric(finaldata2$x3)
finaldata2$y1 <- as.numeric(finaldata2$y1)
finaldata2$y2 <- as.numeric(finaldata2$y2)
finaldata2$y3 <- as.numeric(finaldata2$y3)

fd_corr <- cor(finaldata2)
fd_corr

#visualize the correlation matrix this is a quick visualization of any positive or negative correlations
corrplot(fd_corr, type = "lower")

#visualize the correlation matrix this is a quick visualization of any positive or negative correlations. Recommends
this one. Positive correlation means for every level increase in one the positive increase in another. Negative
correlation for every level increase in one the negative increase in another. This means a linear regression is not an
accurate predictor because you only have a 1 or a 2.
ggcorrplot(fd_corr, type= "upper", title = "Microreactor Correlation Matrix", ggtheme = ggplot2::theme_void, colors
= c("Blue", "Gray", "Red"), lab= TRUE)
```

```
#create an ordered logistic model and return results
m2 <- polr(y1 ~ x1 + x2 + x3 + y2, data = finaldata, na.action = na.omit, Hess=FALSE)
m2

#Check for multicollinearity if a variance factor is greater then 5 there is a high probability of multicollinearity
lm <- lm(y1 ~ x1 + x2 + x3 + y2, data = (finaldata %>% dplyr::mutate_all(as.numeric)))
variance_factors <- vif(lm)
variance_factors

summary(m2)

finaldata2_sum <- as.data.frame(coef(summary(m2)))

# calculate and store p values
finaldata2_sum$p <- pnorm(abs(finaldata2_sum$`t value`), lower.tail = FALSE) * 2

#create a column to highlight significance of p-values
finaldata2_sum$sig_col <- ifelse(finaldata2_sum$p < 0.001,'***',ifelse(finaldata2_sum$p < 0.01,'**',
            ifelse(finaldata2_sum$p < 0.05,'*',
                ifelse(finaldata2_sum$p < 0.1,'.', ''
            ))))


finaldata2_sum$logodds <- format(exp(finaldata2_sum$Value), trim = TRUE, digits = 3, scientific = F)


finaldata2_sum <- setDT(finaldata2_sum, keep.rownames = TRUE)[]
finaldata2_sum <- finaldata2_sum %>% dplyr::rename(coeff_label = rn)

finaldata2_sum %>%
  kable() %>%
  kable_styling()
```

#Your base is 1. The base case for each variable is the one not showing in coeff_label and it is what everything else is compared against. Anything less than 1 is 1-the logodds is the probability that the variable is less. The more * in the sig_col shows you how important a p value is. According to the ordered logistic regression, the logodds can be interpreted as the percent effect for a next level response.

#Positive values(when logodds are greater than 1):
When the logodds are a positive value subtract 1 from the logodds; the result is the percentage likelihood that the identified case will select the next higher level to the question "Would you support a microreactor on campus"

#Negative Values (when logodds are less than 1):

When the logodds are a negative value subtract the logodds from 1 and the resulting value is the percent likelihood that the identified case will select the next higher level to the question "Would you support a microreactor on campus"

Appendix J: Sample Calculations for Energy Usage and Carbon Emissions

- Electricity and heat consumption conversion to average power level

Annual electricity consumption (2019 data):

Consumption in 2019 = $2.50 \cdot 10^7$ kWh

$$\left(2.50 \cdot 10^7\ kWh\right)\left(\frac{1\ day}{24\ h}\right)\left(\frac{1\ year}{365\ days}\right)\left(\frac{1}{1\ year}\right)\left(\frac{1\ MW}{1000\ kW}\right) = 2.85\ MW\ electric$$

Annual heat consumption (2019 data):

Consumption in 2019 = $1.52 \cdot 10^6$ therms

$$\left(1.52 \cdot 10^6\ therms\right)\left(\frac{0.0293 MWh}{1\ therm}\right)\left(\frac{1\ day}{24\ h}\right)\left(\frac{1\ year}{365\ days}\right)\left(\frac{1}{1\ year}\right) = 5.07\ MW\ thermal$$

Monthly heat consumption (February 2019 data):

Consumption in February 2019 = $2.61 \cdot 10^5$ therms

$$\left(2.61 \cdot 10^5\ therms\right)\left(\frac{0.0293 MWh}{1\ therm}\right)\left(\frac{1\ day}{24\ h}\right)\left(\frac{1\ February}{28\ days}\right)\left(\frac{1}{1\ February}\right) = 11.4\ MW\ thermal$$

- Carbon emissions from energy consumption
  - Annual electricity emissions (2019 data):
    Consumption in 2019 = $2.50 \cdot 10^7$ kWh
    $$\left(2.50 \cdot 10^7\ kWh\right)\left(0.0003 \frac{MT\ CO_2 eq}{kWh}\right) = 7{,}500 \text{ MT } CO_2\text{-eq}$$
  - Annual heating emissions (2019 data):
    Consumption in 2019 = $1.52 \cdot 10^6$ therms
    $$\left(1.52 \cdot 10^6\ therms\right)\left(0.0053 \frac{MT CO_2 eq}{therm}\right) = 8{,}030 \text{ MT } CO_2\text{-eq}$$

Percent of WPI's emissions from electricity and heating (2019 data):

Total emissions in 2019: 17,000 MT

$$\frac{7500\ MT\ CO_2 eq + 8030\ MT\ CO_2 eq}{17000\ MT\ CO_2 eq} \cdot 100\% = 91.4\%$$

- Emissions reduction scenarios for implementing the eVinci
  - Percent reduction in total emissions for 12 gCO_2-eq/kWh estimate and no backup heating systems (2019 data):
    eVinci emissions = $(5\ MW)\left(\frac{1000\ kW}{1\ MW}\right)(1\ year)\left(\frac{365\ days}{1\ year}\right)\left(\frac{24\ h}{1\ day}\right)\left(12\ \frac{gCO_2 eq}{kWh}\right)\left(\frac{1\ MT\ CO_2 eq}{10^6 g}\right) = 526$ MT CO_2-eq
    Backup heating emissions = 0
    New total emissions = 17,000 MT CO_2-eq − 15,530 MT CO_2-eq + 526 MT CO_2-eq = 2000 MT CO_2-eq
    Percent reduction in total emissions = $\frac{2000 MT\ CO_2 eq - 17000\ MT\ CO_2 eq}{17000\ MT\ CO_2 eq} \cdot 100\% = -88.3\%$

- Percent reduction in total emissions for 0 gCO_2-eq/kWh estimate and backup heating systems (2019 data):
  eVinci emissions = 0
  Assuming backup heating systems are only needed in February:
  Consumption in February 2019 = $2.61 \cdot 10^5$ therms
  Backup heating emissions =
  $\left(2.61 \cdot 10^5\ therms\right)\left(\frac{11.4\ MW\ thermal - 9\ MW\ thermal}{11.4\ MW\ thermal}\right)\left(0.0053 \frac{MT\ CO_2 eq}{therm}\right)$ = 288 MT CO_2-eq
  New total emissions = 17,000 MT CO_2-eq − 15,530 MT CO_2-eq + 288 MT CO_2-eq = 1760 MT CO_2-eq
  Percent reduction in total emissions = $\frac{1760 MT\ CO_2 eq - 17000\ MT\ CO_2 eq}{17000\ MT\ CO_2 eq} \cdot 100\% = -89.6\%$