Consensus in technology selection for Small Modular Reactors

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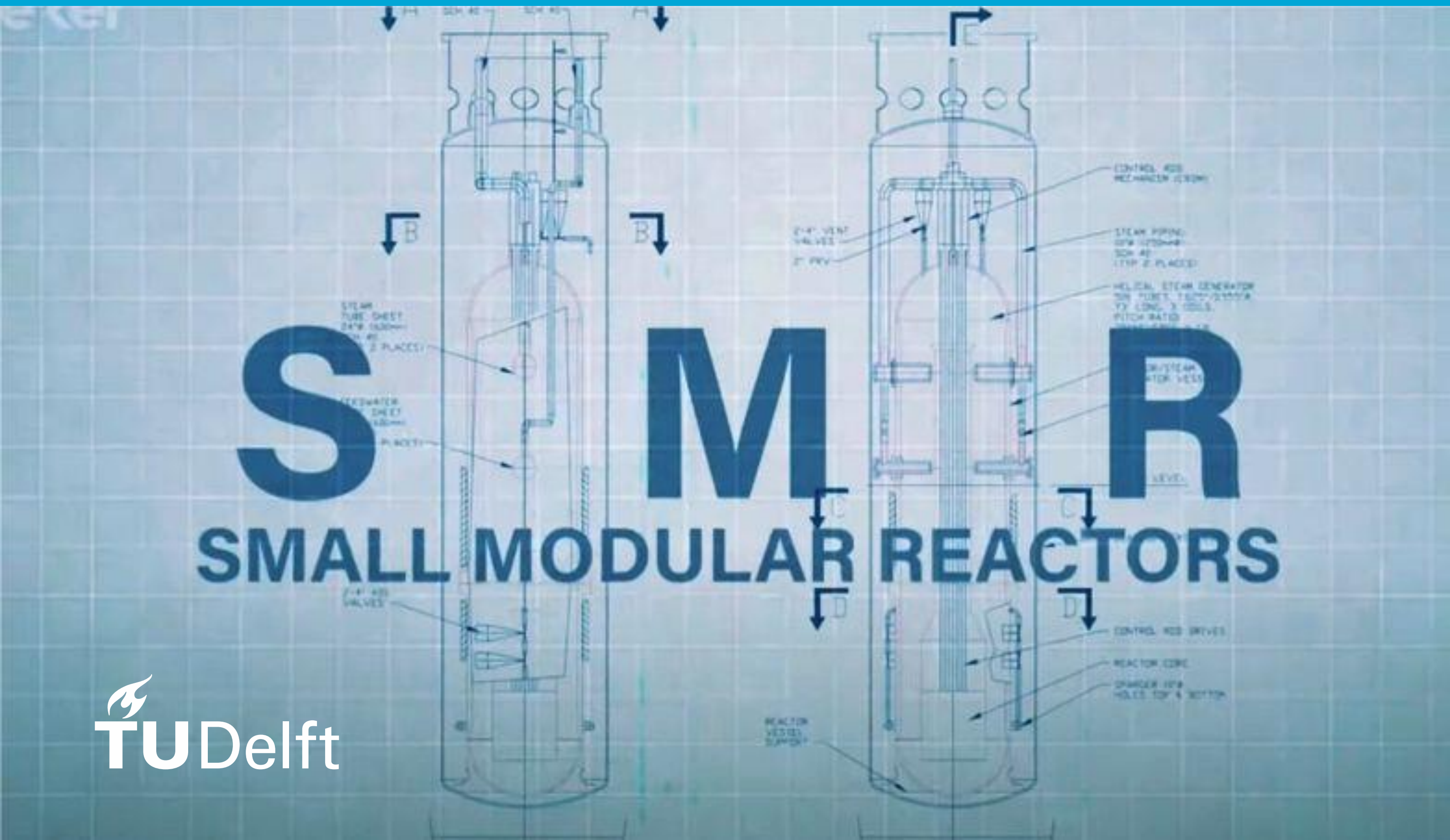

TU Delft

Consensus in technology selection for Small Modular Reactors

by

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Abstract

Small modular reactors are a new type of nuclear reactors with multiple advantages over conventional nuclear reactors. Due to their smaller size, they are safer than conventional nuclear reactors. They can be produced in factories, which solves the problem of nuclear energy projects going over budget due to delays at the installation site. With the increasing demand in energy, small modular reactors can play an important role in the energy transition. Multiple small modular reactors can be coupled together if the energy demand suddenly rises, which reduces the need for a completely new reactor site.

Currently, 72 different models of small modular reactors are being developed. However, this sector faces various challenges, such as safety and standardization challenges. Furthermore, some designs are based on conventional technologies, while others are based on new technologies. These different generations of reactors could pose to be threats to each other and delay the development of reactors. Small modular reactor designs require multiple units of the same design to be deployed in order to be profitable and offer economically competitive energy. Therefore, the sector is highly competitive as not all designs can become successful.

To deal with these challenges, a consensus on technology selection could be beneficial. The Delphi method is used to evaluate if a consensus can be reached. In the Delphi method, experts cooperate by responding to the opinions and views of other experts over multiple rounds of surveys. This creates a sense of understanding of other views which should lead to a consensus on questioned aspects.

Two rounds of the Delphi study have been held. In the first round, 19 participants have filled the survey, while the second round consisted of 14 participants. Participants were contacted via e-mail and LinkedIn. Participants work in the nuclear energy sector as either regulators, advisors, managers or engineers.

This study is based on an idea of the Organization for Economical Cooperation and Development (OECD), which states that the SMR sector could adopt a standardization model used in the aircraft sector. The aircraft sector can be used as an example for successful cooperation to deal with global licensing challenges and development of safety standards. The use of passive safety systems in SMRs could provide safe operating conditions at a fraction of the costs of active safety systems, and thus should be the aim when designing SMRs.

This study finds that cooperation within the SMR sector can lead to a consensus on standardization of parts and standardization of regulations, which reduces the financial risk for stakeholders and improves the chances for a viable global deployment of SMRs.

Preface

In this preface I would like to explain how I came up with this topic and thank everyone who has been involved in the process of writing this thesis, which leads to my graduation and the start of my life as a manager of technology.

During my time at Delft University of Technology, I've seen what impact technology can have on our daily lives. In my Masters, I have decided to focus on sustainability as it is one of the biggest problems of our generation. This had increased my sense of awareness for climate change and has increased my personal desire to contribute in making changes to the rapid decline of our planet. Nuclear energy has always been a sensitive topic in politics, but I believe that nuclear energy could potentially play a big role in our future methods of energy generations. When I was reading the political agenda of the various Dutch political parties, I read that many parties excluded nuclear energy right away. The reasons they gave were badly substantiated. As a student on a University of Technology I knew that there are always solutions to problems, as long as you keep an open mind. Therefore, I decided to dedicate the last months of my time at the Delft University of Technology to this topic.

Before I proudly present my thesis, I would like to thank everyone who has been involved in the research. Katharina Biely for guiding me through the research and providing valuable feedback to my work almost every week. The same is true for Gerdien de Vries, who also provided me with lots of feedback and has guided me through the entire period as well. I also would like to thank you both for calming me in stressful Covid-times and keeping me motivated through this period. I've been on the edge of calling it a day, especially during the period of finding participants, but I'm glad that I continued the research, but probably could not have done it without you two!

Furthermore, I would like to thank the chair of my thesis committee: Udo Pesch, for providing me with a good push in the right direction and for reading and grading my work. I would like to thank Behnam Taebi for giving me feedback on the first questions and sharing the LinkedIn post with his network. In the context of LinkedIn, I would also like to thank Bjorn Hofman for providing me with guidelines for successful LinkedIn messaging.

Last but not least, I would like to thank all participants who have participated in the Delphi study. Without your valuable insights, it would not have been possible to create this thesis. I would like to mention you all by name, to make it more personal but this is not possible due to the anonymous participation requirements of the Delphi method. As you all receive this thesis as a sign of gratitude, I hope you all enjoy reading it, and that it can help the SMR sector to become a viable option in clean energy generation.

Thank you all! Enjoy the thesis!

Luuk van Breugel
Delft, April 2022

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Acronyms

CDF Core Damage Frequency.

FAA Federal Aviation Administration.

FOAK First-of-a-Kind.

FR Fast Reactor.

HTGR High Temperature Gas Reactor.

IAEA International Atomic Energy Agency.

ICAO International Civil Aviation Organization.

IEEE Institute of Electrical and Electronics Engineers.

MSR Molten Salt Reactor.

NOAK N-th-of-a-Kind.

NPP Nuclear Power Plant.

NRC Nuclear Regulator Commission.

OECD Organization for Economic Co-operation and Development.

PWR Pressurized Water Reactor.

SMR Small Modular Reactor.

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1 Introduction

Due to its low carbon energy production (Bruckner et al., 2014), nuclear energy is often an option for replacing fossil fuel power plants. However, nuclear power plant accidents in the past, such as the accident at Chernobyl in 1986, or at Fukushima in 2011, show that nuclear energy production is not completely safe, and humans neglecting safety procedures can cause massive harm (Högberg, 2013). Technological development has led to a different reactor design, that is smaller than conventional nuclear power plants (NPPs). Due to this shrinking in size, the power output of these new reactors is inherently lower. This means less piping and fewer moving parts compared to large NPPs, which simplifies or eliminates the need of active safety systems and other support systems. Without active safety systems, the reactor becomes completely passive safe, thus guaranteeing safety of the entire reactor (Ingersoll & Carelli, 2020). This new class of nuclear reactors are called small modular reactors (SMRs). Small modular reactors are defined as *"advanced [nuclear] reactors that produce electricity of up to 300 MW_e per module. These reactors have advanced engineered features, are deployable either as a single or multi-module plant, and are designed to be built in factories and shipped to utilities for installation as demand arises"* (IAEA, 2016).

With the increasing demand for energy and heat, and the minimalization of CO_2 emissions, the world is looking for alternatives for coal, oil and gas. Because of the low emissions and high availability of nuclear fuel (Bersano et al., 2020), small modular reactors are often considered in the energy transition (Nathaniel et al., 2021). As regions transition to larger shares of renewables such as wind and solar energy, their generated power varies under different weather circumstances. Therefore, nuclear energy can be used together with renewable energy sources as a base load (Jenkins et al., 2018). In order to meet the demand in moments when the weather conditions are not capable of generating enough energy, nuclear energy can be used as alternative. Nuclear energy is not generating direct emissions, and the emissions for supply chain and infrastructure are comparable to wind energy (Bruckner et al., 2014). Another advantage of small modular reactors is the possibility of using the energy and heat they produce as source for hydrogen production in the future, or to use the heat for district heating solutions (Reitsma et al., 2020).

According to the International Atomic Energy Agency (IAEA), 72 different SMR designs are currently available, originating in 15 different countries (Reitsma et al., 2020). Some of these designs are built on existing technologies, that can be found in NPPs that are currently operating. These reactors are so called pressurized water reactors (PWR). These reactors are generation III reactors. Other reactor designs are based on new technologies. Those are called generation IV reactors. Gen IV reactors are either high temperature gas reactors (HTGR), fast *neutron spectrum* reactors (FR) or molten salt reactors (MSR). As different designs are competing to enter the market, policy makers have the choice between the proven technology and the newer technology. These newer reactors have advantages over pressurized water reactors, but might need extra regulations or need different safety requirements. It is likely that only a few of these designs will ultimately be commercialized, but views on why, when and by whom decisions should be made about further development and commercialization differ (NEA, 2021).

Large nuclear power plants benefit from economy of scale in the energy sector (NEA, 2021). Construction costs for a power plant are high, but because of the energy they can generate, the cost of energy is competitive with alternatives. Small modular reactor designs cannot benefit from economy of scale, as they are designed to be small-sized. Therefore, becoming cost effective relies on economy of multiples (Ingersoll & Carelli, 2020) (for explanation, see section 2.4.1). This means that a first-of-a-kind (FOAK) unit, will not be cost competitive, but a few reactors need to be built in order to achieve economic competitiveness. The number of reactors needed at which the design becomes economic competitive is denoted by n, as this might differ per design, construction method and further simplification of the design (Ingersoll & Carelli, 2020). Currently projected construction time of a first-of-a-kind unit is in the order of four years, where an n-th-of-a-kind (NOAK) unit has a construction time in the order of two years.

As international regulations are lacking (NEA, 2021), commercial designers are hesitant to produce FOAK units (Reitsma et al., 2020). The main reason for this is financial uncertainty for companies (Mignacca et al., 2020). However, policy makers prefer to work with several technologies at the same time, until one technology emerges as superior. This is likely to happen after a certain time in which designs have competed for market share. Because of lack of international regulations, national expenditures tend to focus on new technological advances, rather than focusing on building FOAK units. These FOAK units can demonstrate why certain designs are superior. This will lead to less different reactors being built, which is beneficial because nuclear safety regulators do not have the resources to evaluate a large number of designs (NEA, 2021).

While a few governments in Asia have built demonstration units (Reitsma et al., 2020), commercial companies have so far not been able to, due to the financial and regulatory uncertainty (Mignacca et al., 2020). To minimize the risk for all parties involved in the SMR sector, a technology selection is needed. This will decrease the amount of designs that differ on certain aspects. These choices for different technology aspects therefore have to be developed in sync with regulations. This will lead to superior designs, which are in line with demands set by nuclear safety regulators. This will eventually lead to only a few designs with a large market-share that are economically competitive. This economic competitiveness is only achieved if a certain design is built at least N times. This number N is different per design. So far, it is unclear which designs will emerge as superior designs. Therefore knowing which designs have a bigger chance of becoming superior, due to their choices for technology, will lead to less uncertainty for companies involved. This will give the engineers and designers a guidance on why certain choices in the design process are superior over other choices, thus leading to better designs being built. For policy makers, this will result in a selection of designs that will still compete to be the superior design. However, there will be less differences among them, so policy can be implemented for multiple designs. As these designs are more similar when common technology is used, regulatory instances will have less technologies that need to be evaluated. However, making the right choice of technology is not the only factor which impacts the chance of a design becoming superior.

The goal of this research is to create recommendations on the viability of SMRs with different choices of technology. This is done with multiple surveys, based on a Delphi study. In a Delphi study, a group of experts with mixed backgrounds is surveyed over multiple rounds. In between rounds, the experts get to see the anonymized answers given by other experts. By doing this, an understanding of other views is created. This process is repeated until a consensus, or a clear disagreement is reached. These views are related to the underlying values of the experts. These views can be taken as a starting point for the (re)design of a technological system. If a consensus is reached, divergent values are accommodated in the design of these technological aspects. This is the concept of value sensitive design (Correljé et al., 2015).

The Delphi method is chosen because it provides a way of giving feedback to the experts by other experts. A single survey does not have the option for experts to cooperate in answering certain questions. Another option is interviewing experts and using input of previously interviewed experts as a way of cooperating. While interviews could provide more information than a Delphi survey, they also cost more time and require planning. This means that fewer experts could be questioned compared to the Delphi method. However, since the

Delphi method requires participants to type their answers, they are likely to provide less information compared to interviews, and given answers could be hard to understand due to writing mistakes and misinterpretation. However, due to the feedback option and larger group size compared to interviewing, the Delphi method is the preferred method for this research. The surveying is done via Qualtrics. Qualtrics is a platform which hosts surveys, and gives the user a larger variety of question design options compared to other surveying platforms. The platform is equipped with analyzing features and options to export the data set that has been created by participants. A license for using the platform is provided by Delft University of Technology.

This study will focus on three technological aspects of SMRs. The first aspect is safety, because it is a boundary criterion in the nuclear energy sector. The second aspect is standardization. The nuclear energy sector is partly standardized. Throughout Europe, standardization is based on the French model, which is heavily standardized. In the United States of America, there is limited standardization in the nuclear energy sector. The Organization for Economic Cooperation and Development suggests that standardization in the SMR sector should learn from the aircraft industry (NEA, 2021). Both the SMR sector and the aircraft sector are globally oriented and the aircraft industry has shown to be successful. Standardization could potentially be beneficial for the SMR sector, as it could lead to cost reductions and fewer differences among designs. The third aspect is generations. SMRs are designed in two generations, generation III and IV. While both generations have their advantages and disadvantages, focusing on one of them might be beneficial to the amount of different designs and the development of regulations.

This study will focus on these three aspects in the SMR sector. Aspects that are related to politics will not be covered in-depth. Other aspects such as company or design specific aspects will not be covered due to the competitive environment of the SMR sector. In order to focus only on the technological aspects, the following research question and sub-questions have been made:

- How can a consensus on technological aspects within the SMR sector be reached?

- What safety related choices should SMR designers make to guarantee the safety of the reactor?

- How can standardization be beneficial for the SMR sector?

- What can the SMR sector learn from the aircraft sector on standardization?

- How can the SMR sector benefit from making a choice for a specific generation of reactors?

This thesis is written to obtain the degree of Master of Science in Management of Technology. This study uses technological aspects of SMRs as a corporate resource. It shows how firms in the SMR sector can use technology to their advantage, and built potential superior designs. This will increase their economic competitiveness and lead to higher profitability.

This report is structured as follows: Chapter 2 contains the relevant literature that has been used to derive questions for the Delphi study. The Delphi method, as used in this research, is covered in chapter 3. This chapter also contains the questions that formed the first round of the research. These questions can be found in section 3.5. Because the first round results are used as input for the second round, chapter 4 will contain the results of the first round. How these results led to follow-up questions and how these follow-up questions are analyzed is shown in chapter 5. The questions for the second round can be found in section 5.1. The results for the second round can be found in chapter 6. A discussion of the total results can be found in chapter 7. The final chapter contains the conclusions that can be derived from this research, in section 8.1, and recommendations for future research, in section 8.2.

2 Literature review

This chapter will give an overview of the challenges small modular reactors face. There are 72 SMRs at various stages of development (Reitsma et al., 2020). Out of these 72, 31 are water cooled reactors, 14 high temperature gas cooled reactors, 11 fast neutron spectrum reactors and 10 molten salt reactors. Six reactors are micro-sized (< 10 MWe). These micro-sized reactors will not be considered in this review. Micro-sized reactors rely on different technological concepts, and are therefore designed differently compared to other SMRs. They serve a market niche because of their size, off-grid power for remote villages and factories. As described in chapter 1, this study focuses on three areas: safety, standardization and generations. Important literature on those aspects will be discussed in sections 2.1, 2.2 and 2.3 respectively. Section 2.4 will cover financial and regulatory challenges for SMRs. Because these challenges are a part of the necessary background information, are often mentioned by experts in the Delphi study, and are related to all of the three main focal areas, an explanation of these challenges is also provided in this chapter.

2.1 Safety

Conventional nuclear power plants are generally considered to be safe. Yet, nuclear power plants are never completely safe. Safety of a reactor is commonly expressed in the core damage frequency (CDF) (Budnitz et al., 2018). This core damage frequency is the annual probability of an accident which leads to core-damage of the reactor. If a nuclear power plant is well designed and well operated, the CDF is in the order of a few x 10^{-5} per year. The chance of a large radioactive release is a few percent of the CDF, in the order of 10^{-6} per year (Budnitz et al., 2018). These numbers are considered 'acceptably safe' by nuclear regulators around the world (Budnitz et al., 2018). Because this CDF is a numerical expression, it can be calculated and compared for various reactors. It is also widely adopted as an output for safety. Hence, when safety or a safety level is considered in this thesis, it is related to the core damage frequency.

Small modular reactors that are currently being developed promise a CDF that is significantly smaller than the CDF of a conventional nuclear power plant (Reitsma et al., 2020). When this is combined with the smaller radioactive release in case of an accident, the safety level is increased even further. Yet, this is only still a promise because no commercial SMRs are built. In order to reach a higher level of safety, the core damage frequency needs to be lower. However, human errors are a threat to the safety level of all reactors. Major human errors, such as the errors that caused the accident at Chernobyl (Saenko et al., 2011), are always going to have potentially deadly consequences. The human error component in the CDF is dependent on the training of the operators. Less reliable operation of a reactor can increase the CDF by 563% (Karimi et al., 2014). Therefore, SMRs have adopted numerous design simplifications, which makes the reactor easier to operate. Furthermore, SMRs also rely on a higher degree of automation. This decreases the chance of a human error. Perfect operation of a reactor decreases the CDF by 14%, and highly reliable operation decreases the CDF by 13% (Karimi et al., 2014).

These design simplifications are also related to the reduction in power output of small modular reactors. This means a lower thermal energy production than conventional NPPs, making SMRs easier to cool. This reduces the risk of a core meltdown after an accident or shutdown (Budnitz et al., 2018). Another safety related improvement is longer fuel cycles, due to better power consumption. Some reactors are able to reach periods of over 20 years without refueling (Reitsma et al., 2020). This reduces shutdowns of the reactor. Other SMRs are designed to never have spent-fuel on site. The entire reactor core module is replaced by a new one once the fuel cycle is over (Budnitz et al., 2018).

By simplifying the design, different safety systems can be used. Most conventional NPPs rely on active safety systems. Active safety systems involve electrical or mechanical operations (Goldberg & Rosner, 2011), which are activated automatically or manually in case of danger or accident. Automatic or manual activation depends on the allowed period, and therefore does not impact reliability (Sato et al., 1995). However, SMRs are designed to be passive safe. A passive safety reactor has a grace period[1]. If this period is unlimited, a reactor is inherent safe (Sato et al., 1995). Inherent safety depends on the design of the reactor. In case of an accident, the reactor can break down but no damage is done to the outside world. If this period is not unlimited, the reactor can be passive safe. Passive safety relies on natural phenomena, such as gravity, convection and pressure (Sato et al., 1995). As it is not inherent safe, passive safety is no longer safe after the grace period. The advantage of passive safety over active safety is simplicity, which can avoid maintenance of systems outside of the reactor as well as requiring active power sources (Sato et al., 1995).

2.2 Standardization in nuclear power plants and in the aircraft sector as potential blueprint for SMRs

Standardization could potentially be beneficial for the SMR sector, as it can reduce the financial risk for vendors, regulators and manufacturers. These financial risks are discussed in section 2.4.1. It could also speed up the licensing process, which might lead to faster deployment of SMRs. These regulatory challenges for SMRs are discussed in section 2.4.2. In this section, two standardization models in nuclear power plants are discussed: the United States model and the French model. Standardization in nuclear power plants in Europe is based upon the French model, because of the prominence of France in the European nuclear energy sector. These models are compared with the aircraft sector. From these three different models, lessons can be learned for the SMR sector. The standardization models for nuclear power plants are based on historical differences in this sector. The models have not changed in recent years, since nuclear power plants have long operating life-times.

2.2.1 The United States standardization model

In the U.S. nuclear energy sector, standardization is limited. This is mostly related to the way the sector is organized. In the United States, single reactors units are the most common. The largest nuclear utility firm operated nine of these. In 1986 there were 47 different nuclear utilities operating the sector. Because of these different utilities, multiple designs have been adopted, which leads to a lot of variety in the design of light water reactors in the United States (Lester & McCabe, 1993). Because of these differences in the reactors, information sharing has limited potential benefits. Furthermore, information sharing is discouraged by corporate boundaries and limited similarities between reactors.

In order to standardize the sector, four approaches are considered (David & Rothwell, 1996):

1. Streamlining the NRC's licensing of reactor designs with emphasis on combining the construction and operating license
2. Adopting standard procedures for operations and training
3. Standardizing the nuclear steam supply system and related safety systems
4. selecting a single standardized design for all reactor equipment and structures

[1] A period over which safety is ensured without the need for personnel action or an active power source after an incident.

The U.S. Congress Office of Technology Assessment concluded that the first and second point were already being pursued, but the third and fourth could have significant impact on the sector (David & Rothwell, 1996).

2.2.2 The French standardization model

The French standardization model, which is also used in other European countries, is different than the U.S. model. The French nuclear energy sector is highly standardized. In the French nuclear energy sector, the utility company is state-owned. Furthermore, there is only one company for nuclear steam supply systems, and another company for the turbine-generators (Lester & McCabe, 1993). Research and development in the nuclear energy sector is dedicated to a government body. All nuclear power plant construction projects are managed by the state-owned utility company. Because of this, reactors in France are almost identical and mostly have four reactor units operating at the same power plant (Lester & McCabe, 1993).

The United States sector, with multiple utilities, vendors and firms operating it, is therefore completely different from the French sector. However, this is not specific for the country, because the equally diverse aircraft sector in the United States is highly standardized. Aircraft technology has been around longer than commercial nuclear energy production, and the sector is globally oriented. Nuclear energy has always been nationally oriented, but the SMR sector is globally oriented. Therefore, considering the aircraft model is recommended by the Nuclear Energy Agency[2] of the Organization for Economic Co-operation and Development (OECD) (NEA, 2021).

2.2.3 The aircraft model

When the aircraft industry started growing in the early 1900s, it became more clear that aviation laws were necessary. In a time where fatal aircraft crashes were common, aviation laws were needed for the safety of pilots. In 1909, Great Britain was the first country to come up with national laws. When the first successful cross-channel flight showed that aircraft were a threat to Britain's borders, the country insisted on an international conference in Paris. During this conference, problems such as sovereignty of airspace and the spread of diseases via air transportation were discussed.

Due to the first World War, it became clear that aviation was a force to be reckoned with and Great Britain insisted to reform European aviation. A few years prior, Britain had already made laws that limited the entry of foreign aircraft into British airspace. In 1919 at the Paris Peace Conference, the first international laws and regulations were formed, based on British law. These laws contained not only air rules about landing rights and passage prohibition, but also contained ruled on licensing, markings and log books. At the same time, the United States presented state aviation laws, and were not involved in the European cooperation. The American Aviation Mission, a committee comprised of military leaders, presidents of the industry, and the manager of the Manufacture of Aircraft Association, had a goal to keep up with their European counterparts and designing federal regulations and laws. In 1920, the Europeans had international regulations called the International Air Navigation Convention, while the United States were beginning to unify state laws in federal laws.

After the second World War, in 1947 the Chicago Convention on International Civil Aviation marked the start of the International Civil Aviation Organization (ICAO). The ICAO became a specialized agency of the United Nations. This Convention has rules on aircraft safety, registration, airspace, security, sustainability and also contains the rights of those countries that have signed the convention. As of 2019, 193 states have signed the convention. This includes all countries that are part of the UN, except for Liechtenstein, which is covered

[2]In the NEA of the OECD, 34 countries co-operate with the European Comission and the IAEA

under Swiss ratification.

When it comes to specialized regulations regarding development, the SMR industry is behind on standardization. In the SMR industry, no standard parts exists, while for example the FAA (Federal Aviation Administration) has regulations on standard parts (Ausness, 1996). These standard parts can be manufactured by any party and are interchangeable because the manufacturing and design regulations for certain parts are similar. The SMR sector could potentially profit from similar regulations, as standard parts can be developed elsewhere, or can be produced in larger quantities. This contributes to overcoming financial challenges as described in section 2.4.1. Another advantage of standardizing parts is that these parts do not need additional certification. The certification of these parts is done once and the parts can be used in all different SMR designs, which saves cost and time for certification and regulatory instances.

When one looks at the current state of SMR regulations, it can be seen that individual nations have individual regulations, which are guided by the IAEA (Langlois, 2013). Currently these individual nations have started to organize a forum, in which they all come together to discuss guidelines and problems that will arise within these regulatory commissions, and share their issues with the other member states. These discussions are focused on safety, design, licensing, manufacturing, commissioning and operations (Magruder et al., 2018). In comparison with the aircraft sector, the time frame in which SMR regulations develop is much shorter (planned for 2023). Although, it must be said that SMR regulations are adapted from the existing nuclear energy regulations. An overview of the situation is given in Table 1.

Aircraft	**SMR**
Regulations are created at national level	Regulations are created at national level
National level expanded to continental	National regulations expand to worldwide
Conventions lead to international regulations	Conventions lead to international regulations
International regulations overseen by UN	International regulations overseen by UN
Safety is leading in regulations	Safety is leading in regulations
Regulations developed over a large time frame	Regulations still in development. Started in 2015

Table 1: Comparison of regulation process between aircraft and SMR sector

2.2.4 Combining the models

Most safety regulations, in the aircraft industry as well as the nuclear energy industry, have been developed after accidents occurred. In order to prevent the same accident from happening again, the SMR industry needs to think proactive. Any foreseeable accidents must be prevented at all cost. The SMR industry is promoting itself as a safer and cheaper alternative to conventional nuclear power plants. Any incidents that might be harmful to humans, animals or nature, can potentially ruin the entire sector. The choice of using nuclear energy from SMRs will, in most cases, be a political decision, based on safety, sustainability, economics and various other aspects. Therefore any harmful incidents lower the chances of SMRs being chosen as the preferred option for energy generation. Based on the economy of multiples (explained in section 2.4.1), the sector has a low chance of survival if the technology does not get widely adopted. Cooperation and knowledge-sharing are ways to minimize the possibility of accidents, as is currently adopted in the forum.

The SMR sector is a globally orientated nuclear energy sector in which a large degree of standardization can be beneficial. Standardization can reduce licensing time and costs, lower construction costs and improve safety (NEA, 2021). The sector is similar to the old U.S. nuclear model, with various vendors in a competitive environment. This model did not have a high degree of standardization like the French model. To achieve this in a global context, the aircraft model can be used. In this model, standard parts are common. These parts can be manufactured by manufacturers around the world, but do have to adhere to strict regulations regarding safety and reliability. Furthermore, the SMR sector can learn from the aircraft sector that international cooperation might lead to international regulations. These international regulations are needed, so that SMRs around the globe are made according to the same regulations and safety standards. This creates not only a safer environment, but also reduces the licensing time and costs for foreign SMR designs. This can help with the financial and regulatory challenges that are discussed in section 2.4.

2.3 Generations

Small modular reactors can be split in two categories. These categories are evolutionary reactors and revolutionary reactors (Adamantiades & Kessides, 2009). Evolutionary reactors are based upon previously proven successful technology. These are Generation III reactors. Generation III reactors are, similar to large generation I and II NPPs around the world, cooled with water. The technology for generation III is based upon currently active NPPs. Revolutionary reactors are reactors based upon new technology. These revolutionary reactors are Generation IV reactors. Generation IV includes the other reactor types; HTGR, FR and MSR. These reactors are cooled using different cooling substances, which changes various other parameters of the reactor as well. One of these alternative cooling substances is molten metal. Compared to water, molten metals can operate at a much higher temperatures and pressures (Reitsma et al., 2020). This has various advantages: the efficiency of the reactor is increased, higher enriched uranium or thorium can be used, and spent fuel[3] can be burned (Buckthorpe, 2017). These higher temperatures also mean that the construction of the reactor itself will be different, as the materials in the reactor have to be capable of handling these higher temperatures (Klueh, 2009). Because none of these Gen IV reactors have been built for commercial use, the design licensing process will take significantly longer compared to Gen III, because Gen III is based on currently existing technologies. Generation IV reactors are planned to start operating after 2030, while generation III reactors can start operating much faster (Reitsma et al., 2020). National policy makers will decide which reactors will be installed. Many countries are aiming at reducing their carbon footprint as fast as possible (Höhne et al., 2021), which might increase demand for generation III SMRs from countries planning on replacing their coal or gas powered power plants. This could turn out to be a problem for Generation IV reactors, which are not ready for fast deployment. However, recently the EU has labeled nuclear energy as a sustainable source of energy, which may lead to more investments and potentially an increase in development of commercial Gen IV reactors (European Commission, 2022).

2.4 Challenges with small modular reactors

Apart from the three focal areas of this study, the SMR sector still need to face various other challenges. General challenges related to nuclear energy, such as public acceptance and political support. These challenges relate to nuclear energy in general and are therefore not covered in this study. However, there are also SMR specific

[3] Nuclear fuel that has been irradiated in a nuclear reactor. It is no longer capable of sustaining a reaction.

challenges, such as lack of FOAK units and supply chains. As described in chapter 1, these problems relate to financial challenges and licensing issues.

2.4.1 Financial challenges

In the paper "Deeds not words: Barriers and remedies for Small Modular nuclear Reactors" (Mignacca et al., 2020), elements hindering SMR construction are ranked by experts. The findings show that the main elements hindering construction are financial (investment risk, availability of funds) and economical aspects (availability of cheaper alternatives). The results are drawn from a survey, in which experts in the SMR sector are asked about perceived problems for SMRs. However, recently Rolls-Royce has been granted £450 million from the UK government and investors to fund their operations and research (Ambrose, 2021). This investment shows that governments and investors are probably more willing to invest in SMRs as is perceived by experts from the SMR sector. Another explanation can be the timing of the investment. The investment was made during the weeks of the 2021 United Nations Climate Change Conference in Glasgow, where international goals were made on limiting global warming. This investment could serve as an example for other investors, now that the European Commission has approved nuclear energy for their green taxonomy (European Commission, 2022).

Conventional NPPs have used the principle of economy of scale[4] to become competitive energy sources. This means that the high investment costs of the reactor, which are mostly related to the cost of capital (Ingersoll & Carelli, 2020), of a large NPP is covered by the high output of the reactor. However, the final costs of NPPs have been up to two times higher than projected due to associated risks of delays (Berthelemy et al., 2020). Daily construction costs of NPPs are high, due to the on-site construction and large number of parties involved. Delays are caused by various risk factors. According to Berthelemy et al. (2020), these risks are roughly distributed in three categories:

1. Technology; design maturity and innovation
2. Organizational; project management and supply chain
3. Policy framework; safety regulations, financing framework and political support

For a NPP, risk mitigation strategies are crucial for a financial project success, limiting the delays in the construction phase and to start producing energy as soon as possible.

For a SMR, the 'economy of scale' principle does not apply. Due to the inherent lower power, SMRs rely on different financial principles to become profitable. There are various benefits in SMR production compared to NPPs. Smaller investment costs, shorter building times and higher adaptability to the market, all lower the financial risks involved (Ingersoll & Carelli, 2020). A shorter building time leads to more advantages than just a lower financial risk. The reactor construction is completed faster, which means the reactor earns money from sales of generated energy faster than NPPs.

Apart from lowering the risk for investors, SMRs strive to become economically competitive by using a mixture of the following (Boarin & Ricotti, 2011; Ingersoll & Carelli, 2020; Mignacca & Locatelli, 2020):

- Production cost advantage through learning costs[5]
  Cost savings through experience, if more reactors of the same type are build worldwide or on the same factory, improvements and time saving operations allow for better and faster production of units.

[4] Cost benefits obtained from scaling up operations.
[5] Requires multiple units of the same SMR.

- Modularization
  Factory production of reactor units allows for faster construction and less specialized personnel and machinery on-site.
- Multiple units and co-siting [5]
  Cost savings can be achieved through splitting the fixed costs by using multiple reactors on the same site.
- Design benefits
  Cost savings through advantages directly related to the design, such as lack of active safety components and material cost savings. This factor is very dependent on the specific SMR design.

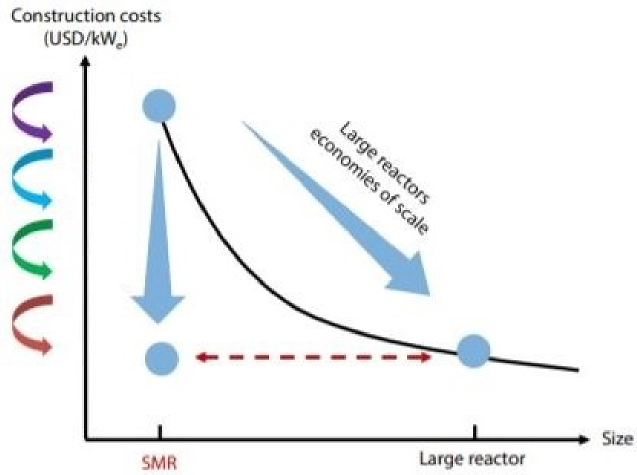

Figure 1: Economy of multiples, adapted from (Berthelemy et al., 2020)

This leads to a levelised cost of electricity (cost per MWh) which is equal to or better than that of NPPs, with less financial risks associated. Therefore, SMRs use the economy of multiples to become cost effective (Boarin & Ricotti, 2011). This economy of multiples is technically also an economy of scale, in which the price per SMR unit drops as more units of that same SMR are built. However, various other effects play a role in this as well, as described above. Therefore a distinction is needed. The name 'economy of multiples' is used in literature (Boarin & Ricotti, 2011; Ingersoll & Carelli, 2020; Mignacca & Locatelli, 2020), and is therefore used in this thesis to indicate all effects related to cost saving in SMRs. The effects are demonstrated in Figure 1.

2.4.2 Regulatory and licensing challenges

When it comes to licensing SMRs for deployment, there are various challenges that need to be addressed. These include, but are not limited to, licensing of SMRs based on existing technologies, licensing of Gen IV SMRs, global licensing and module licensing. These four aspects will be discussed further, as they apply to SMR designs in general. Licensing of aspects, such as site licensing, will not be discussed in this thesis, but do also impact the SMR licensing process.

1. Licensing of SMRs based on existing technologies:
   Because these SMRs are based on existing technologies, the water cooled SMRs, regulations are already available as well as a licensing framework. Companies constructing these are also able to use guidelines

for meeting the regulations. This shortens the licensing process, because these designs can be designed according to these regulations. These SMRs will be subjected to the same regulatory process as conventional NPPs (Ingersoll & Carelli, 2020).

2. Licensing of Gen IV SMRs:
   As Gen IV SMRs are still being designed, no regulations are yet available. Up till now, only guidelines have been developed. As individual components and safety systems must be assessed before licensing, the licensing process of Gen IV SMRs will take more time than SMRs that are based on existing technologies (Ingersoll & Carelli, 2020).

3. Global licensing challenges:
   The licensing process of SMRs faces challenges when it comes to global licensing. As it stands, there are no international regulations or international organizations overseeing the licensing. The first step of the licensing is done by the national regulatory instance. This is the regulator that is active in the vendors' country. Once the SMR is approved, it is produced in that country, but marketed globally. If the SMR is going to be deployed in another country, the regulatory instance of that country needs to approve the design for use in that country. From a technical safety point of view, most countries use the guidelines from the US Nuclear Regulatory Commission (NRC) but have individual regulations for political, economical and social aspects (Ingersoll & Carelli, 2020).

4. Multi-module licensing:
   As SMRs can be expanded into larger power plants when multiple modules are connected, the licensing needs to be done individually. This has to be done because every individual module can be operated, maintained and decommissioned individually as well. The licensing process is therefore more time and resource consuming than licensing a single larger NPP (Ingersoll & Carelli, 2020).

3 Method: The first Delphi round

The following chapter will explain the steps that have been taken to answer the research question stated in chapter 1: *How can a consensus on technological aspects within the SMR sector be reached?*. For this research, a Delphi study has been carried out. The Delphi method will be explained in section 3.1. In this section, an overview of the steps taken can be found in Figure 2. The literature review led to questions, which will be researched in this study according to the Delphi method. Section 3.2, will cover the adaptations that have been made to this method. Furthermore, this chapter will cover the steps that have been taken during this research period in more detail, such as the criteria for expert selection in section 3.3 and the different ways of contacting experts in section 3.4. The questions for the first round are provided in section 3.5. Section 3.6 shows how the given answers are analyzed. The results for the first round can be found in the next chapter, chapter 4.

3.1 The Delphi Method

Originating from the 'Oracle of Delphi', the Delphi method is an explorative research method to forecast future trends in areas where, at the moment, no consensus is reached. In the 1960s, Gordon and Helmer (1964) first used the Delphi method to predict a trend in technology for a period of up to fifty years in the future. A study that uses the Delphi method, has a goal of reaching consensus between experts. The Delphi method consists of a series of questionnaires, split up into different rounds. These questionnaires are sent to a group of different experts, which allows for experts from different parts of the world to collaborate in the research. Answers of individual experts are collected, anonymized and used to create a new questionnaire. This second questionnaire then consists of the results of the previous questionnaire, and gives the option to reconsider the answers a participant has given based on comments from other experts. This process can be repeated as many times as considered necessary. By applying the Delphi method, issues can be clarified, areas of agreement and disagreement can be identified, and an understanding of priorities can be developed (Adler & Ziglio, 1996). A typical panel size for a Delphi study is 20 experts, and the minimum acceptable size is 7 (Dalkey, 1969). Critics of the Delphi method argue that the subjective opinion on who is considered an expert, and the small size of the sample are reasons not to use the method (Murray, 1979; Pill, 1971). In order to deal with the subjective opinion on who is considered an expert, a self-reflection question is added. This does not tackle the problem entirely, as a participant might still misjudge one's level of expertise, but it is a better solution than judging a persons capability based on their job and experience alone. Another given critique is that a single expert might have a better solution than the group of experts (Pill, 1971). It can be true that one expert could have the best potential solution to a problem that is queried in this study. However, the goal of the study is to reach a consensus on technological aspects within the SMR sector. Individual, or company specific ideas, have not led to global construction of SMRs, because of various problems discussed in chapter 2. Therefore, cooperation might be needed. Because experts within the SMR sector are located around the globe and work in diverse jobs, finding time for interviews can prove to be difficult. Neither interviews, nor single surveying, gives an option for feedback and cooperation. Because cooperation could potentially lead to solutions for the challenges discussed in chapter 2, the Delphi method is the preferred research method for this study.

The Delphi method is split up into two phases; the exploration phase and the evaluation phase. In the exploration phase, which is often only the first questionnaire, the subject is explored and extra information is provided by the experts. For this first period, a deadline of three weeks is set. Once this process is completed, the following questionnaires will make up the evaluation phase. In this phase, the experts' views on the subjects are collected and assessed, which might lead to a consensus or disagreement on the subject (Adler & Ziglio, 1996). These phases, including the steps within each phase, are shown in Figure 2. An important aspect of a

Delphi study is that experts are flexible in their cooperation. They can decide when they want to cooperate and they can decide on which aspects they want to focus in their answers, which often is on their area of expertise.

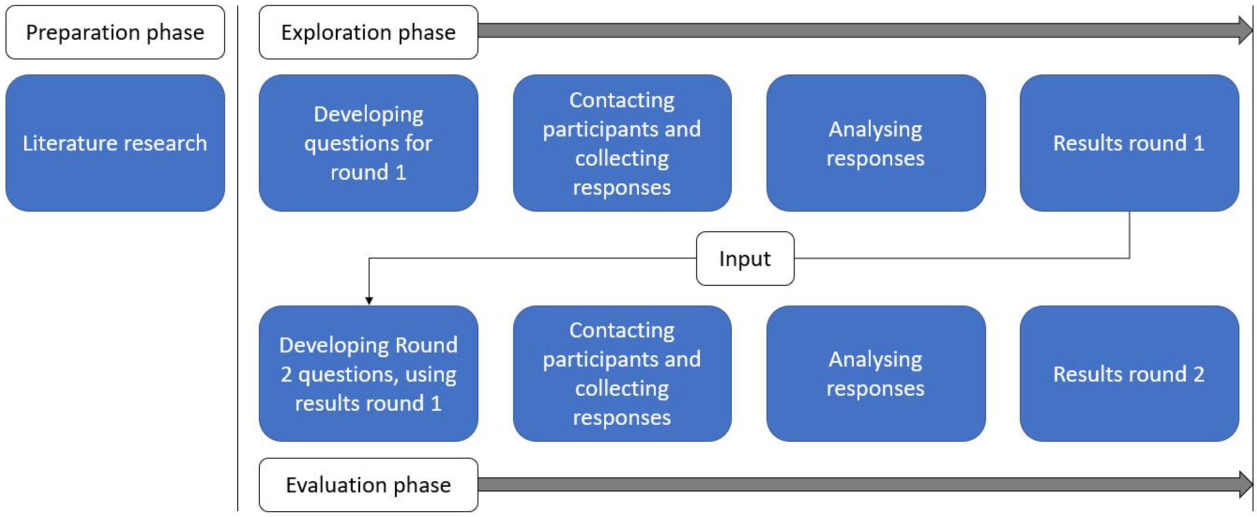

Figure 2: Flow chart covering the steps taken during Delphi study

3.2 Adaptations made to Delphi Method

In the Delphi method , the group of experts should ideally remain constant. However, in most Delphi studies, this is not the case (Bradley & Stewart, 2003; Scholl et al., 2004). This study is no exception. For this study, a constant group of expert is preferred but likely not possible. In order for a participant to cooperate throughout the study over various rounds of questionnaires, it is likely that some sort of incentive is needed. Due to the lack of financial resources or sponsoring, no monetary compensation could be offered. Instead, a participant is offered this thesis and the results obtained in the study as a way of thanking the participant for their time and effort. Between the first and the second round, a total of five participants dropped-out. Two new participants have joined the panel for the second round. The first round contained 17 participants, while the second round contained 14 participants. One participant indicated that finding time to answer the questionnaire was the reason for not answering. A complete overview of participation numbers can be found in section 3.4.

As stated in section 3.1, the panel should be able to review the anonymized responses of other participants after every round. Due to time restraints for the thesis research, and the effort required from participants, this has been changed. After analyzing the answers from the first round, a selection of important statements is made and questioned in the second round. In order to make this selection, first the similarities in the answers had to be found. Differently formulated answers might contain the same message. Once this was completed, differences in the responses were explored. Then, other interesting statements were noted. If these statements were within the scope of the research, they were included for the second round. An example is that two participants, both engineers, mentioned: "Because there is a lack of public support, there is no incentive to standardize". This statement is aimed at standardization, and mentioned by multiple participants. It is interesting to see how other people feel about this statement, especially participants that have a different job than engineering. Because these statements are pre-selected for the participants, the research can be kept within boundaries. This also greatly decreases the time required from every participant. It also makes sure that participants do not spend a lot of time and effort on subjects that are outside of the scope of this research, such as political reasons for certain decisions. The decision to not include reasons outside of the scope has its downsides. As described in section 3.1, participants are likely to answer based on their own expertise. Excluding these statements from the following rounds, limits the possibility of receiving insights based on specific expertise available in the group of experts. These experts are later asked to elaborate on the selected statements only, which might not cover their area of expertise.

3.3 Criteria for Expert Selection

In order to select which experts to contact, I made a list. All names found in relevant literature, such as reports, studies and IAEA conferences, have been added to the list. This contained names of people, companies and regulatory instances. In order to keep the level of expertise on small modular reactors as high as possible, the choice has been made to not include people or companies with no direct link to SMRs (e.g. consultancy firms, climate researchers) in this list. The authors of other relevant studies regarding SMRs in which surveys were held, were contacted as well. Due to privacy reasons, details of the participants for those surveys could not be shared.

To reach the right people at SMR vendor companies, searches on LinkedIn were done. Most searches for company names provided a list of people who work at that company. People with job titles which included *'engineer', 'manager', 'regulatory', 'licensing'* or any other related job were selected and added to the list. The process has been repeated for regulatory instances and agencies.

According to the Delphi method illustrated in section 3.1 the panel should consist of a group of experts. For this study the word 'expert' is ambiguous (Murray, 1979). A participant is considered to be an expert because of their experience with nuclear technology and small modular reactors in particular. At the start of a questionnaire, a multiple choice question is included in which participants self-reflect on their expertise. The question is: *"Do you consider yourself an expert in Small Modular Reactors?"*. The participants had the following options: *"Yes"; "No"; "No opinion"*. If the participants considered themselves experts, they received the role of "expert". Participants that did not consider themselves experts, by selecting either *"No"* or *"No opinion"*, received the role of "no expert". The answers of both groups are considered equally, but the different groups are shown in the figures with results, which can be found in chapters 4 and 6.

3.4 Contacting Experts

For the people on the list, an online search for contact details such as e-mail addresses was done. When searching online, most of the times either an e-mail address or LinkedIn profile was found. Some contact details could not be found. The reason for this is likely that these people do not have contact details online or use a different script on their personal LinkedIn profiles, such as Russian (Cyrillic), Chinese (Hanzi) or Korean (Hangul). Therefore two ways of contacting experts were selected: e-mail and LinkedIn. Because e-mail does not have a limit to the amount of text, e-mail is preferred over LinkedIn. Some e-mail addresses were found and those people were contacted via their e-mail addresses. The e-mail that was sent can be found in appendix A.1. If no e-mail address could be found, people were contacted via LinkedIn. This was done by sending a connection request which included a short text with a link to the survey. Due to LinkedIn's maximum of 300 words, this text could only include a greeting, some short information on the project and a link to the survey[6].

[6] In order to be compliant with privacy and ethical regulations, this research has previously been approved by the Human Research and Ethics Committee of Delft University of Technology. The submitted forms can be found in appendix B.1. An informed consent message was included on the introduction page of the survey, which can be found in appendix B.2.

If the connection request got accepted, a more detailed explanation of the project was send via chat message. The LinkedIn connection request text and detailed explanation can be found in appendix A.2. A total of 19 people were contacted via e-mail. Out of these, a total of three surveys have been filled, which equals a response rate from the e-mail messages of 15.8%. Another 143 people have been contacted via LinkedIn. Out of these, a total of seven surveys have been filled, which equals a response rate from the LinkedIn messages of 4.9%.

After contacting 162 people, 10 surveys have been filled. The ideal group size is not a predefined number, but rather a combination of expertise and diversity in the group of experts. Drop-outs in future rounds were also taken into account. Because these conditions were not yet met, more participants were needed. The limitations of LinkedIn became clear when searching for participants. LinkedIn limits the amount of search results once a certain number of searches have been done that month. It hides profiles for people that are not second degree connections[7] of that profile, and only a certain number of connections that can be made each month. To overcome this problem, a LinkedIn post has been made, so that it could be shared by my supervisors and other people in my network. For this post, it is important that it contains project information and a call-to-action, so that readers can enter the survey directly. The original post, which is available in appendix A.3, had a reach of 1,023 views. This reach was expanded beyond my personal network by tagging relevant stakeholders with a bigger network. The actual reach of the post has been a lot higher than the statistics for the original post show. This is due to sharing. The post got shared by ten people, which then made the post visible for their network. These numbers are not included in the reach of the original post.

The numbers on LinkedIn are much higher than the amount of people that were contacted personally. However, most people that have seen the post do not have any affinity with nuclear energy. The original post and shares combined have led to seven responses. This brought the total for the first round to 17 participants. This is close to the typical size of 20 participants in a Delphi study, and significantly more than the minimum panel size of 7 (Dalkey, 1969). One of the potential participants replied to the e-mail with feedback on the survey. The feedback contained valuable information and answers to the questions in the questionnaire. These answers have been manually added. This participant is included in the 17 total responses.

By posting on LinkedIn, a degree of randomness in participant selection is introduced. Anyone who saw the post was able to enter the survey. This method has its positive and negative points. Increased visibility of the post is beneficial, if participants that match the profile are seeing the post. If the post did not define the profile of potential participants, there is a chance of receiving responses from people that do not have the specific knowledge required to answer the survey. Another downside is that open surveys can attract bots and people who fill surveys purely to receive the incentive (Perkel, 2020). This is common for surveys that offer money or gift cards as incentives. By offering this thesis as incentive, receiving these type of responses is highly unlikely. All responses were checked for validity, such as unique IP address and content. All responses were valid.

3.5 Questions for round 1

From the information gathered in the literature review, three main focal areas have been identified. These areas are <u>safety</u>, because it is a main priority and boundary criterion for success of the sector, and <u>standardization</u>, because it can be potentially beneficial for the licensing process of the reactors, reactor economies and SMR safety. The last area is <u>generations</u>, because currently multiple generations are researched and designed alongside each other.

[7] Connected to a connection of the user, i.e. a friend of a friend.

Safety

From section 2.1 it became clear that the SMR sector faces multiple safety related challenges. If accidents happen with the first commercial SMRs, the entire sector is likely harmed. Therefore, safety is the number one priority. Engineers and designers have to choose the preferred way of guaranteeing safety for the reactor. The following questions have been developed to gather insights from SMR experts:

- Question: Accidents with nuclear power plants are uncommon, and small modular reactors are even safer than conventional nuclear power plants. However, potential accidents with SMRs could still be dangerous. Some SMRs (mainly Gen III) are equipped with safety systems that have shown their worth on older conventional reactors. Other SMRs (mainly Gen IV) will be developed with completely new safety systems. These systems are still in development and have not yet shown their capabilities. Should the sector prefer the older safety systems over new safety systems, if both options would be available for the SMR?

When the financial aspects of SMRs are considered, the principle of economy of multiples holds for SMRs. But as technological knowledge is gained over time, it can happen that a certain SMR design is improved after numerous years. Previous units of the same design might not be equipped with the same safety systems. Therefore, it can be that the specific SMR can be made even safer. The following question is developed to gather insights on safety when financial aspects are considered:

- Question: SMRs rely mostly on the economy of multiples to make them profitable. Therefore, more than one unit of a successful design needs to be built. This design can change over time, as technology advances. However, many SMRs are designed to run for a long period without having to shutdown for refueling. This period can be up to 30 years. In these years, the safety systems of a reactor design can be improved. If we want to upgrade these safety systems, the reactor has to be shutdown outside of the refueling period. This also brings added costs, which might decrease the economic competitiveness of the SMR. If we want to guarantee the highest possible form of safety, how should we deal with this problem?

Standardization

Countries use different strategies on standardization or nuclear reactors. The United States and French models are discussed in section 2.2. According to the NEA, the SMR sector could benefit from the standardization model as used in the aircraft sector. The comparison with the aircraft sector, in section 2.2.3, shows that standardization might also be beneficial for the SMR sector. The two sectors can be compared with each other because:

- They are both high-tech sectors in which safety is a main priority
- Both are complex technologies made of different sub-technologies
- Both technologies, SMR now and aircraft in the past, are/were developing faster than regulations on the technology
- Individual countries have set regulations, and international regulations are created at UN Conventions. (e.g. IAEA SMR Regulators' Forum and the Chicago Convention on International Civil Aviation)

As stated in section 2.4.2, regulatory instances need to evaluate several different SMR models. This is resource consuming. In order to save resources, the aircraft sector has gone for standardization. A standard part can be constructed by any manufacturer, as long as the part is made in accordance with the regulations, dimensions and specifications that are set for the part. These parts therefore do not need to be evaluated by regulatory instances anymore. This might yield potential advantages but there might also be disadvantages to this. In order to gain this information from different perspectives, the following question is queried:

- Question: What are, according to you, the main advantages and disadvantages of using standard parts in SMR production?

Generations

There are also differences between Gen III and Gen IV reactors. While it takes longer for Gen IV reactors to get licensed, they also have more advantages in their applications. Some groups of participants might have a preference for a certain generation of reactors. This might mean that the sector prefers to focus on a specific generation. In order to gain this information, the following question is asked:

- Question: One of the differences between the two generations, is that the operating temperature of Gen IV reactors is higher than Gen III reactors. This leads to more applications (e.g. Hydrogen production, process heat). On the other hand Gen III reactors are safer versions of the Gen II technology, which means that the technology used in Gen III reactors is highly available. What are, according to you, the biggest advantages and disadvantages of Generation IV compared to Generation III?

3.6 Analyzing results

Once the deadline passed (6-DEC-2021), the 17 responses were analyzed. For this procedure, the export option in Qualtrics[8] is used. This option generates an excel file with all responses. The exported file contains all responses, including unfinished responses. This is then filtered, so unanswered questionnaires are hidden from the results. In the end, an excel file containing responses from people with at least one question answered is left.

In order to process the data, a new file is created. Four job categories were created: Regulator, Advisor, Manager and Engineer. Every participant was included in the group that fit their job title. This creates smaller groups of people that have the same type of job. The downside of clustering is that participants in a group might have different backgrounds (e.g. a reactor engineer and a safety engineer are both engineers but might have different backgrounds and interests). However, clustering makes it more difficult to trace multiple statements back to the same person. Another advantage of this is that it can easily be seen once a certain group is the only group that makes certain statement. Then, expertise was considered. For every category, an "experts" and "no experts" subcategory was made. Eight categories were available. After the distribution, six categories remained. All regulators and advisors selected that they considered themselves experts, so the "no expert" subcategory was removed. The total participants per category can be seen in Table 2.

Job Title	Regulator	Advisor	Manager	Manager*	Engineer	Engineer*
Number of Participants	3	2	3	1	3	5

Table 2: Distribution of participants. "No expert" subcategories are denoted with asterisk (*)

For every question, the answers are analyzed. One answer can contain multiple statements on different aspects related to the question. For every statement, the participants that mentioned it were counted. As example, the

[8] Platform for experience management and surveying. Qualtrics is used to design and host both surveys.

round 1 question 1 answer (Figure 3, statement 4): "The type of safety system is irrelevant, but it must be safe over its lifetime" was given by 2 regulators, 1 manager and 1 manager*. This does not have to be in exactly the same words. Answers similar to this, but in different words, such as: "To me it does not matter, but it must be tested and qualified to achieve the objective" are counted as the same answer. Once this process was completed for every question, the results were ordered by number of appearance. The results of the first round can be found in chapter 4.

4 Results of the first Delphi round

In this chapter, the results from the first round are shown. The first round of the Delphi study contained the four questions that have been derived from the literature review. These questions can be found in section 3.5. In this chapter the results of these questions will be discussed one-by-one. The first two questions are related to safety, question three is related to standardization and question four is aimed at differences among Gen III and Gen IV reactors. The goal of the first round is to gain information on the covered topics and identify similarities and differences among expert groups. All questions in this round are open-ended questions, which is typical for the exploration phase of a Delphi study, as described in section 3.1 on page 13. This chapter will first cover the safety related questions in section 4.1, followed by a question related to standardization in section 4.2 and afterwards a question about differences between SMR generations in section 4.3.

4.1 Safety

The first question is about the choice of safety system:

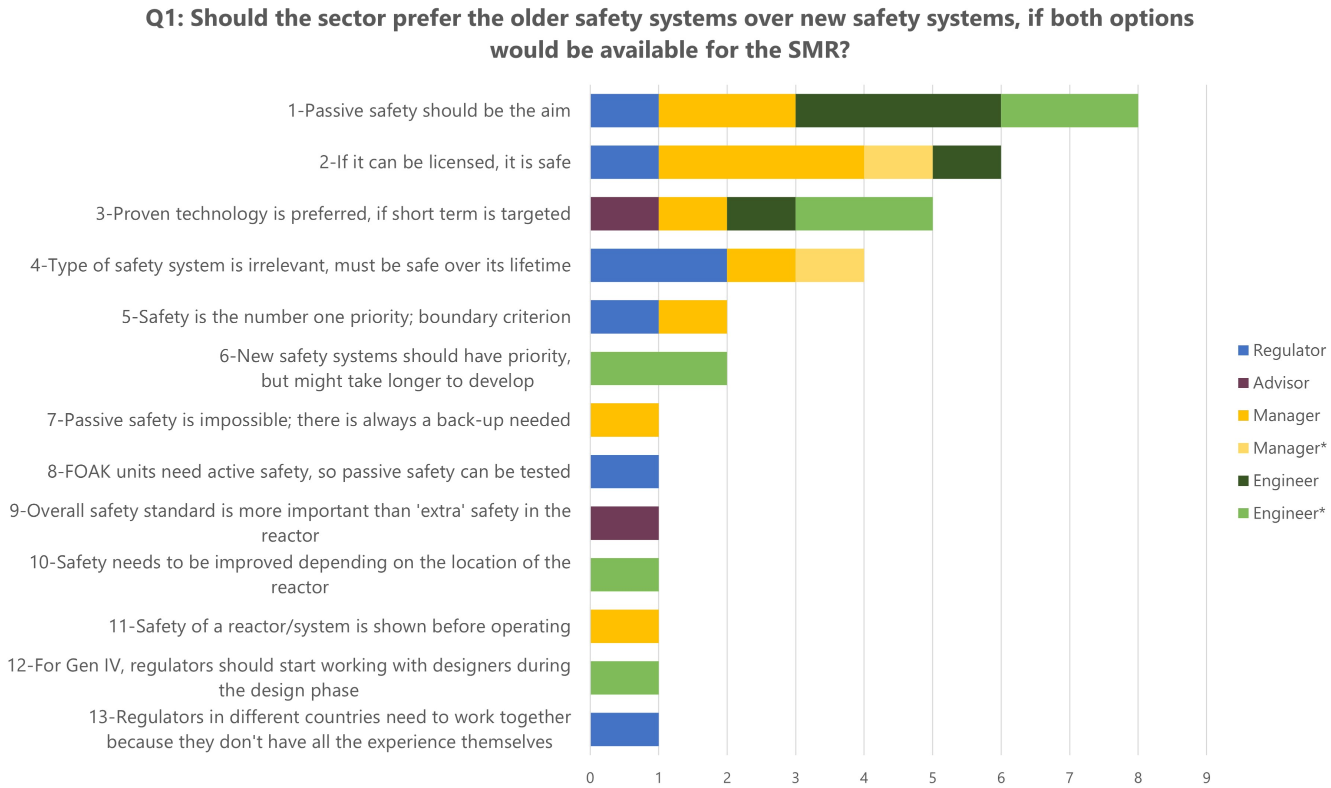

Figure 3: Results for question 1 of round 1

Figure 3 shows the results from the first question. The experts have been divided into groups according to their job title and expertise, as described in section 3.6. Every group is shown by their own color in the results. The results are extracted from the answers given by the experts. Not all answers are provided in exactly the same words, but similar answers are combined under one collective answer. E.g. the answer “Passive safety should be the aim” is combined with similar answers such as “The main focus should be passive safety”. On the X-axis of the figure, the number of respondents is shown. The given answers are shown on the Y-axis of the figure, together with the number of participants from a certain group that have given that answer. The answers are ordered from most given, to least given. This graph style is similar among all open-ended questions, which all questions in this round are. In this section, the answers that have been given by three or more participants will be discussed. Answers that have been given by fewer than three participants might be discussed if clarification is required.

In question one, most experts indicate that the type of safety system, whether these are newly designed -, or existing safety systems, does not matter. This is supported by statement 2: “If the safety system can be licensed, it is safe” and statement 4: “The type of safety system is irrelevant, it must be safe over its lifetime”. The most given answer, statement 1, which is given by eight respondents: “Passive safety should be the aim”, is not directly related to old or new safety systems, as passive safety is used in NPPs for decades already (Aksan et al., 2009). However, this has always been to a limited extend, as there are no NPPs completely passive safe.

When statement 3, which is given by five experts: “Proven technology is preferred if short term is targeted” is combined with the main take-away from the answers, “The type of safety system does not matter”, it can be said that the safety system is a matter of design choice. If short term deployment of a reactor is preferred, using a safety system that is already in use in different reactors might reduce the required licensing time significantly. Using a new safety system does not have this advantage, but it might have different advantages, such as being a better fit to the SMR design. Another aspect to note is that older safety systems might not be suitable to Gen IV reactors, as these reactors have completely different properties. The downside of using newly designed safety systems is that these systems might require more frequent updates. This requires shutting down the reactor, which might make it less economically competitive. This dilemma is covered in question two.

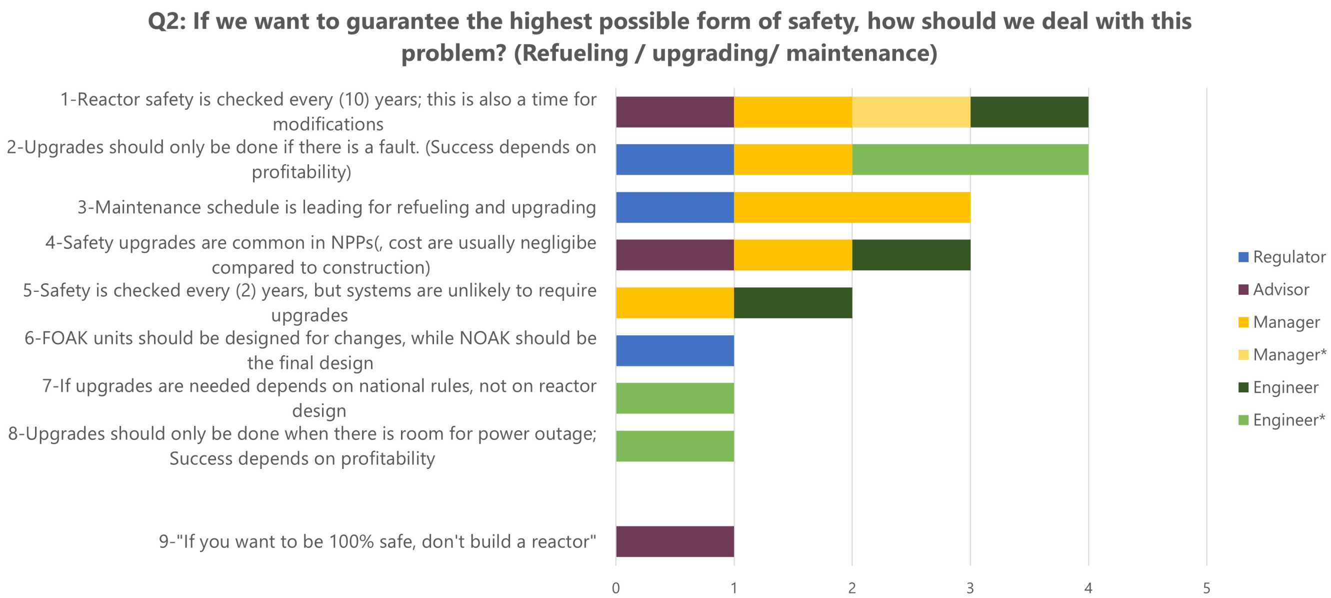

Figure 4: Results for question 2 of round 1

Figure 4 shows the results for question two. In this question, the answer: “Reactor safety is checked every (10) years, this is also a time for modifications” (statement 1) is given by four participants. The number 10 is placed in parentheses, because other numbers were also mentioned. Differences among national legislations are the reasons for these other numbers. This answer is related to the periodic safety review of the reactor, which is ten years in most countries. Participants indicate that during this period, the reactor is not running for a longer time than during the regular maintenance checks. This makes the periodic safety check a better occasion for updates and maintenance to the reactor.

Another answer that was given four times is: "Upgrades should only be done if there is a fault" (statement 2) Some participants added that the success of the reactor is depending on the profitability. Spending additional funds on not required upgrades would only increase the cost of electricity. Other participants mention that upgrades are common in NPPs and the costs of these upgrades usually negligible. For SMRs, these costs might not be negligible. The construction costs of SMRs are usually lower (see section 2.4.1). Therefore, the costs for upgrades will relatively be higher for SMRs compared to NPPs. This might impact the economic competitiveness of SMRs.

Three participants indicated that the maintenance schedule is leading for refueling and upgrading (statement 3). Maintenance is usually done every two years. This maintenance is usually completed faster than the full periodic safety check. Therefore installing large upgrades or refueling would only increase the downtime of the reactor. Because SMRs do not require to be refueled every two years, this maintenance can only include minor upgrades, as these can be done during the maintenance period.

One participant mentioned: "If you want to be 100% safe, don't build a reactor" (statement 9). Safety can never be completely guaranteed, but the chance of an accident happening can be minimized, as described in section 2.1. The current situation in Ukraine accentuates this even more. During this war, attacks on Zaporizhzhia Nuclear Power Station, and on the Chernobyl Nuclear Power Plant have happened, that posed potential threats to the safety level of these nuclear power plants. One can build the reactor according to the highest safety standards, with a well trained staff on site, but in case of extreme events, safety cannot be guaranteed anymore.

4.2 Standardization

The third question is about standardization. As discussed in section 2.2, standardization can potentially be beneficial for the SMR sector. Therefore, question three focuses on gaining insights on the advantages and disadvantages of standardization of SMRs.

Figure 5: Results for question 3 of round 1

Figure 5 shows the results for question three. In this question, three participant indicated that supply chain predictability (statement 1) is an advantage of standardization. Two participants mentioned cost reduction (statement 3). These advantages can help with the financial challenges the SMR sector faces, as described in section 2.4.1. Three managers also note that certified parts are already available for NPPs, and that they probably will become available for SMRs as well (statement 2). However, some participants indicate that even if a part is standardized, a regulator still needs to check the part (statement 4). This is because the regulator is responsible for the safety of the SMR.

Two different participants note the scenario of a fault being discovered in a standard part that is in multiple plants. One participant gives the disadvantage of this scenario (statement 9): “All plants have the same fault”, and the other participant notes the advantage (statement 10): “All plants with that part can be stopped”. Whether it is seen as an advantage or a disadvantage depends on the point of view of the participant. When it is seen from a safety perspective, all plants with that fault can be stopped, which would be beneficial to the safety of these other plants. When it is seen from an economical perspective, it would mean that all plants probably would require maintenance or inspection, because one part in another plant has an error. This would lead to downtime and additional costs. This could be a waste of money if it is not a common manufacturing error.

A few participants gave their thoughts on the standardization process. Some indicate that the industry should design the standardization process (statement 18), while others indicate that the IAEA needs to be more proactive (statement 24). This leads to a question in the next round about who should be responsible for standardization, which can be found in Figure 11, section 6.2. Two engineers indicate that the lack of public support gives no incentive to standardize and work together (statement 5). It would be interesting to see if this thought is shared among other participants, because they have not mentioned it themselves. This statement is discussed in round two. It can be found in Figure 13, section 6.2.

4.3 Generations

The last question in the first round was aimed at the differences between the two generations. When the generations are compared, they might have unique advantages and disadvantages over one another.

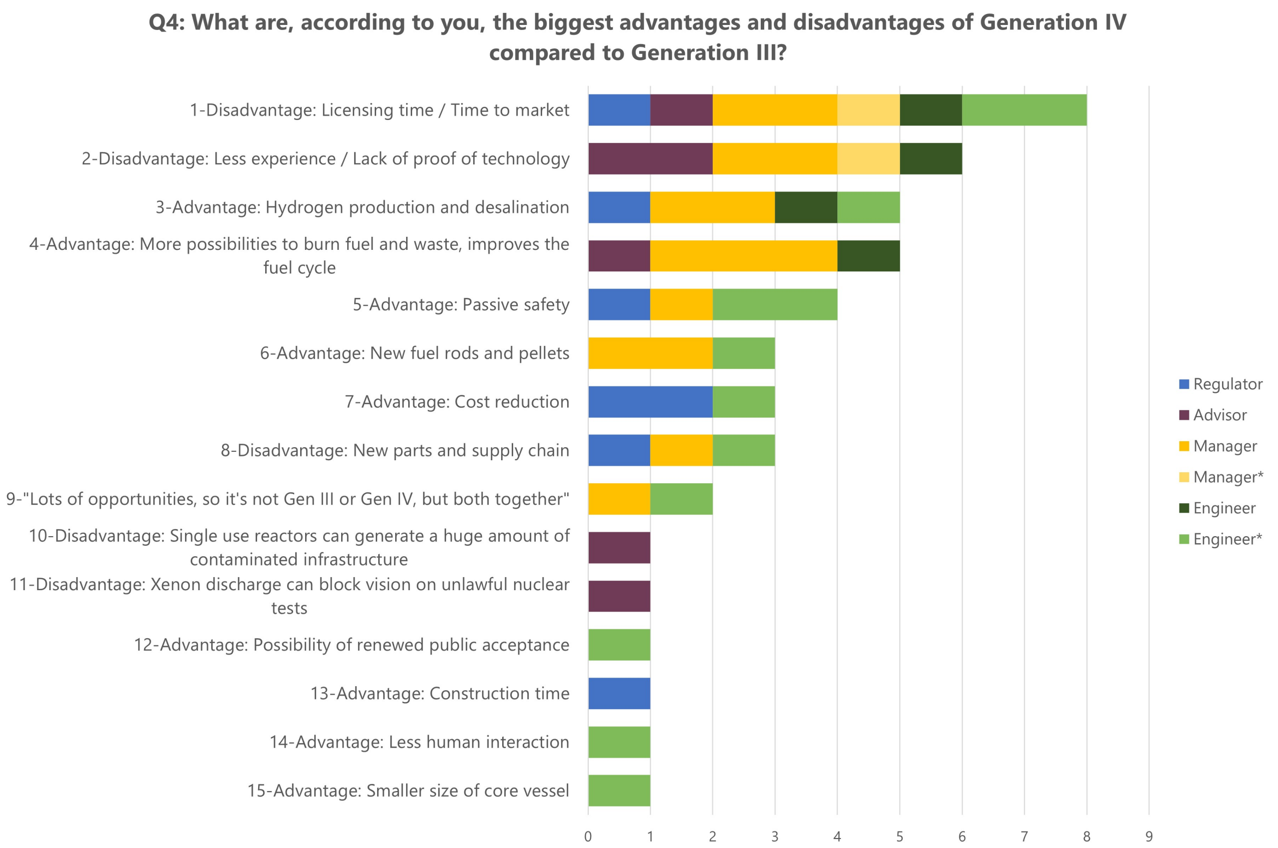

Figure 6: Results for question 4 of round 1

In Figure 6, the results are shown. The most mentioned disadvantages of Gen IV reactors are the long licensing time required (statement 1) and the lack of proof of technology (statement 2). It takes a long time for a completely new reactor to go through the licensing process, making the time to market for this generation the biggest disadvantage. Because both disadvantages are related to technological maturity, these disadvantage will disappear once Gen IV is a commonly used technology.

Participants also give many advantages of generation IV. These advantages are mostly improvements compared to generation III. Among these are: fuel cycle improvements, hydrogen production and desalination, cost reductions and passive safety. Participants have mentioned nine different advantages of generation IV, and five disadvantages. However, the two most mentioned statements are both disadvantages. The long licensing time / time to market (statement 1) is mentioned by participants from all groups, which might mean that this disadvantage is commonly known across the SMR sector.

Two participants also mention that because of the opportunities, there should not be a choice between Gen III and Gen IV. For the many different requirements and needs around the world, different reactor types and generations can be used. As statement 1 suggests, the time to market for generation IV is longer than that of generation III, but generation IV reactors have more applications, such as hydrogen production and desalination. In order to meet the 2050 CO_2 reductions, generation III SMRs might be a better choice because of the faster deployment. If hydrogen is commonly used as fuel, or as the need for sweet water rises, generation IV reactors might be a better investment.

5 Method: The second Delphi round

The results of the first round provided (partial) answers to the questions, but also called for clarifications. In round one question one (Figure 3, page 20), most participants indicated that passive safety should be the aim. From this, the question arises how passive safety should be achieved. This led to a follow-up question for the second round. In the second round, not only open ended questions are asked. Some participants answers contain contradicting statements. In round one question one, a participant indicated that a back-up safety system is always needed, which makes complete passive safety impossible. Another participant indicated that active safety should be available in FOAK units, so the passive safety systems can be tested for later builds. These contradicting statements are queried in the second round to investigate if others agree or disagree. Therefore, these statements are visible for everyone in round two.

Statements do only require answers on a Likert scale[9]. The choice to include statements by participants as closed questions, makes sure that all opinions on interesting statements can be asked. The process of answering these statements is faster compared to open-ended questions. By including closed questions, participants can answer more questions in a shorter period. This comes at a cost of potentially losing out on extra information. However, increasing the amount of questions in the second round would also extend the time needed to answer the questionnaire. In a Delphi study, participants should be able to review statements by other participants, as described in sections 3.1 and 3.2. By adding statements, more questions can be answered in the same amount of time, hence the choice has been made to include closed questions. Section 5.1 shows the questions that formed the survey for the second round. In section 5.2 the analyzing method for second round is discussed, and section 5.3 gives an explanation on why the research ended.

5.1 Questions round two

This process is repeated for all four questions. The following questions and statements were included in the second round:

Safety

In the first round, various participants indicated that passive safety should be the aim for SMRs. Someone noted that passive safety can't be guaranteed over a longer period and therefore active safety is always needed.

- Question: What is, according to you, the best way to achieve passive safety?
- Statement: Passive safety can't be guaranteed, some form of active safety system is always needed.
- Statement: Passive safety should be extensively checked in FOAK units so passive safety can be guaranteed for NOAK units.

In the first round, many of you indicated that the leading time frames are the maintenance schedule of the reactor and the full periodic safety check. This periodic safety check is set to be every ten[10] years for nuclear power plants.

- Question: What do you think about this time interval for SMRs? Do you think it should stay like this, or can it be shortened/extended? Please motivate your answer.

[9] A Likert scale contains intervals based on level of agreement: Completely disagree, Somewhat disagree, Not agree nor disagree, Somewhat agree, Completely agree

[10] Most countries use ten years, fixed by law. If your country uses a different time interval, you can use that interval (please indicate in your answer). If you are not sure how long the periodic safety check interval is, please assume ten years.

Standardization

The most given advantages of standardization are the availability of parts and predictability of the supply chain. Many of you supplied me with a lot of extra information. When it comes to which stakeholder should be responsibility for standardization, the results are mixed.

- Question: According to you, which stakeholder(s) should be responsible for standardization and why? (e.g. Vendors, Clients (purchasing countries), Regulators, IAEA, etc.)
- Statement: Standardization of parts between vendors is possible.
- Statement: The lack of public support gives no incentive to standardize and work together.
- Statement: I feel that there is a lack of public support for SMRs.

Generations

From the first round it became clear that the biggest disadvantages of Gen IV are the time to market and lack of proof of technology.

- Selection: What are, according to you, the main reasons for this? Please select only the important reasons and not the unimportant reasons.
- Rank: Please rank the reasons of the disadvantages "time to market" and "lack of proof of technology". Start with the most important reason and go down to less important. You do not have to include all the reasons, only include the ones that you think are important (the ones that you have selected in the previous question).

In the last question (What are, according to you, the main reasons for this? Please select only the important reasons and not the unimportant reasons.) participants are required to select reasons which they find important reasons for the given disadvantages "time to market" and "lack of proof of technology". A preselected list of choices is given to the participant. These choices are a selection of reasons which have been discussed in "Deeds not words: Barriers and remedies for Small Modular nuclear Reactors" (Mignacca et al., 2020). Participants are also allowed to add reasons which they find important and are not on the list. In the second part of the question, participants are asked to rank the reasons that they have selected. By ranking these reasons, a comparison can be made with literature. If the results are similar, the reliability of answers is increased. Because Mignacca et al. (2020) used a larger sample, similar results for this question might also be generalizable to a larger sample.

5.2 Analyzing the second round

For the second round, 17 participants were invited. This includes 15 participants who participated in the first round and indicated that they wished to receive an invitation for the second round, and two participants who did provide their contact details after the deadline passed. All potential participants were invited by e-mail. The e-mail sent can be found in appendix A.4. The second questionnaire contained the questions as shown in section 3.6. Furthermore it contains the same first questions as in round one in which their job title is asked, how many years they have had that job, and their self-reflection on SMR expertise. In this round, there was also only one participant who selected "no opinion". This participant is also added to the "no expert" group, to be consistent with the first round. At the end of the questionnaire a question is added in which participants are asked if they would like to participate in a third round.

The deadline for the second round has been a week shorter compared to the first round. The participants were invited for the second round by e-mail. Most participants responded in the first week. After this week, a reminded was sent. 14 out of 17 invited participants filled the survey. This equals a drop-out rate of 17,6%. The distribution of participants for the second round can be seen in Table 3.

Job Title	Regulator	Advisor	Manager	Manager*	Engineer	Engineer*
Number of Participants	1	1	2	4	2	4

Table 3: Distribution of participants. "No expert" subcategories are denoted with asterisk (*)

5.3 End of research

After the results for the second round were made, conclusions could be drawn from all questions. At this point, saturation is reached. This means that the Delphi study will remain a two-rounded study. Further questioning of participants will not yield new insights. Interesting follow-up questions will, from this part onwards, deviate too far from the scope of the research. From the 14 participants in the second round, 13 participants have indicated to join the third round. However, the group of participants does not contain multiple participants per role. By continuing, answers can easier be led back to individuals. Follow-up questions that can be drawn from the results will be discussed in section 8.2. In this section, possible future research will be discussed.

6 Results of the second Delphi round

As explained in chapter 5, the second round contained open questions and statements, which will be discussed below. The open questions in the second round were analyzed in a similar way as the first round. This method is described in section 3.6. For the statements a different method is required. The available data for statements is a predetermined value from the Likert scale: Completely disagree, Somewhat disagree, Not agree nor disagree, Somewhat agree, Completely agree. These values are plotted in bar diagrams, which can be found in section 6. These diagrams show a possible trend in the group of experts. Furthermore, the average value is calculated. This is done by assigning a numeric value to the Likert scale, based on the positive or negative values belonging to each answer. An example is shown in Figure 8. The corresponding numeric values are shown in parenthesis behind the answers, ranging from -2 to +2, with neutral being 0. Then, the average value is calculated. A neutral answer would score close to 0. A positive number would indicate the level of average agreement with the statement, while a negative number would indicate the level of average disagreement with the statement. The open questions are displayed in a similar way as in the first round. The figures show the number of participants that gave a similar answer on the X-axis, while the synthesized statements are found on the Y-axis. The questions are discussed per topic, which was also the order of appearance in the survey. Firstly, section 6.1 will contain the safety-related questions and statements, secondly the standardization-related questions and statements are covered in section 6.2, and thirdly the question and ranking exercise related to generations is covered in section 6.3

6.1 Safety

The first question in the second round is a follow up question based on the first question in the first round, as shown in Figure 3. Most participants indicated that passive safety should be the aim for SMRs. To follow-up on this specific result, the means to achieve passive safety were queried.

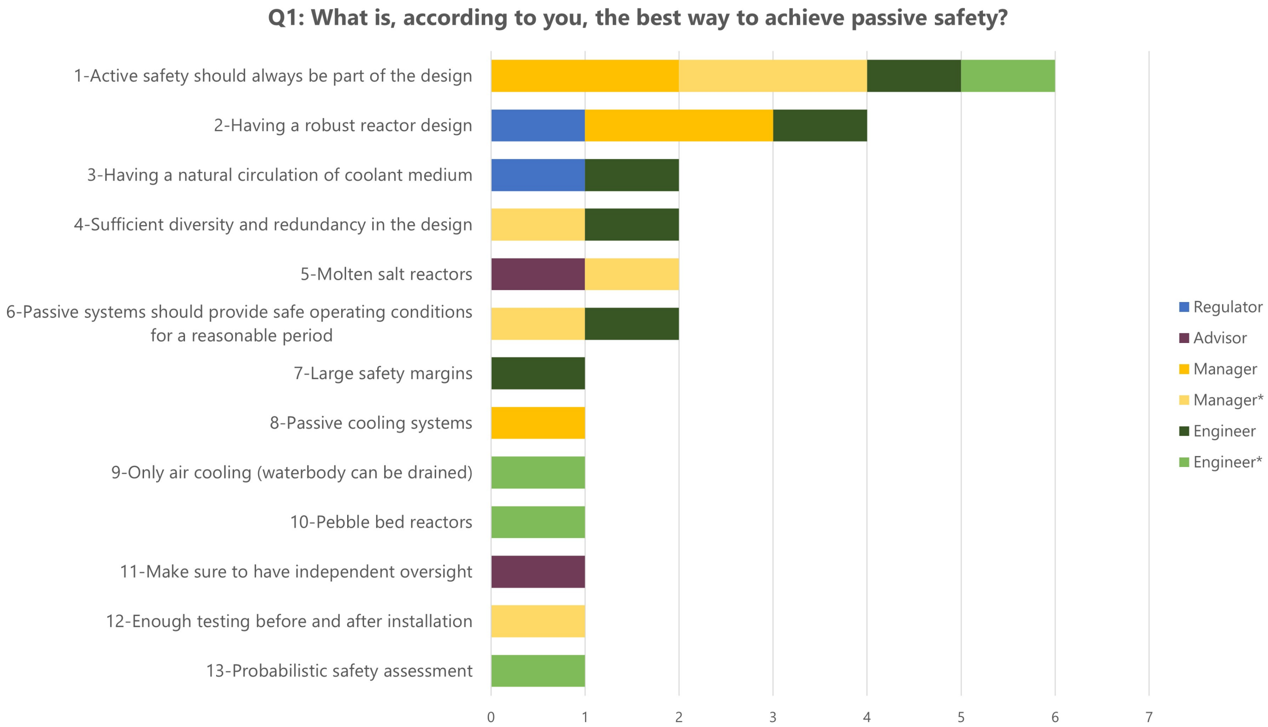

Figure 7: Results for question 1 of round 2

Figure 7 shows the results of question one. In the first round, participants indicated that passive safety should be the aim. However, in this round the participants note that there is always some form of active safety needed. Two participants argue that the passive safety only provides safe operating conditions for a limited time, and therefore there is always back-up needed. This is also questioned in the first reflective statement, Figure 8. This conflicting result can be explained because passive safety should be the aim, but a complete passive safe reactor is difficult. For very small modular reactors, this might be possible, but as power increases for SMRs, accidents can have large consequences. Passive safety can only be guaranteed for a limited time. If the issue is not fixed within this period, there needs to be a back-up. This back-up can be provided by an active safety system.

Participants also note that to achieve passive safety, a reactor should have a robust design (statement 2), with sufficient diversity and redundancy in the design (statement 4). The reactor should have a natural circulation of the coolant medium (statement 3). One participant adds that a water body can be drained, so air cooling should be preferred (statement 9). However, using only air as coolant could prove to be difficult. The heat transferring properties of air are lower than those of water. Therefore, cooling with circulating water is easier. If the basin of water is sufficiently large, with a negligible chance of draining, using water as a coolant medium for the SMR should be possible.

Two participants indicate that molten salt reactors have the best design opportunities to become passive safe (statement 5). Molten salt reactors are generation IV reactors, that use a molten salt as coolant, in which the fuel has been dissolved. By dissolving fuel in the coolant, the molten salt serves as fuel for the reactor. This also means that no meltdown can occur, since the fuel is already in molten state. This leads to a low operating pressure, which makes the use of passive safety systems easier (Elsheikh, 2013).

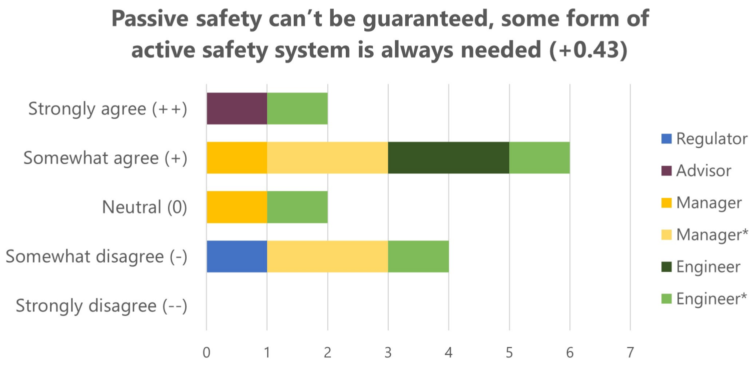

Figure 8: Statement 1

Figure 8 shows the results to the first reflective statement. While most participants agree with the statement, four participants answered "somewhat disagree". The average of +0.43 shows that the group of experts does not have a similar view on the statement, but is, on average, quite neutral. This can be explained because some very small modular reactors can in theory, be completely passive safe. For other reactors, it is likely that, even if it would be theoretically possible, legislators will not allow it. Following this statement, another statement was asked. This statement is also aimed at passive safety. The statement asks if passive safety should be extensively checked in first-of-a-kind units, so it can be guaranteed once the designs are matured. The results are shown in Figure 9.

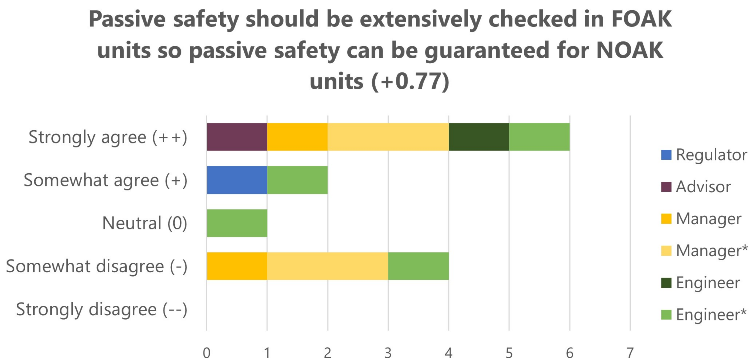

Figure 9: Statement 2

The results to this statement show that most participants agree with the statement. The average of +0.77 show that the group of experts somewhat agrees with the statement. Six participants do strongly agree with the statement, and another two participants do somewhat agree. However, four participants do somewhat disagree. Participants did not have an option to explain their choice in the statements, as this would increase the required time for the survey. The given answers in the first statement, Figure 8, do not indicate that participants who think passive safety can't be guaranteed, disagree with this statement. Therefore, disagreement to this statement does not come from agreeing with the first statement. An explanation to disagreeing could be found in round one question one, Figure 3 statement 11. A participant mentioned that safety is shown before operating, so passive safety should already be tested and guaranteed before FOAK units are operating.

The following question is related to the periodic safety check of SMRs. In question two of round one (Figure 4) most participants answered that reactor safety is checked every ten years, which is also a period for modifications. However, this is for reactors at NPPs. Because SMRs produce less power and have different safety systems, this periodic safety check might be shortened or extended. Question two is aimed at getting insights on this periodic safety check for SMRs.

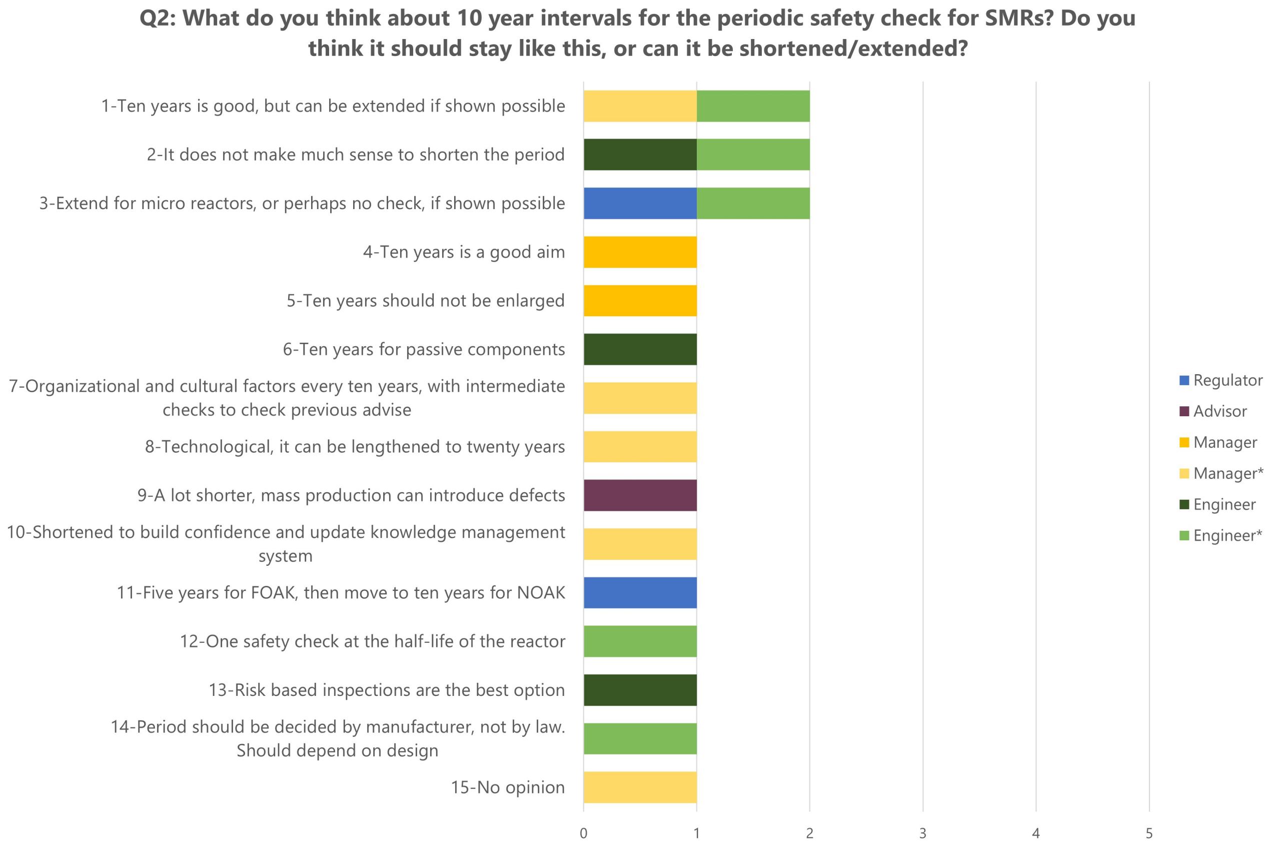

Figure 10: Results for question 2 of round 2

The results in Figure 10 show mixed opinions. Some participants note that a ten year period is a good aim, but it can be extended if shown possible. Because of the lower power output of SMRs compared to NPPs, some participants also note that it does not make much sense to shorten the period, as SMRs are generally safer than NPP reactors with a higher power. Another participant notes that in theory, this period can be extended to twenty years. For very small micro reactors, the period of ten years can be extended, or if tests show that a periodic safety check is not needed, there should be no checks. This correlates with the answer given by an engineer who indicates that inspections should be based on risk.

There are also participants who think that this period should be shortened. Because SMRs are mass produced, defects might be introduced to the reactors. This would mean that more safety checks are needed. More safety checks might also help with building confidence and with gaining more knowledge about the reactor once it is operating. One participant also notes that for FOAK units, safety checks should happen every five years. If these safety checks show that it is possible to extend the period to ten years, this can be done in NOAK units.

One participant indicates that perhaps these safety checks should not be based upon a period that is decided by law, but rather on the period the manufacturer sets. An advantage of this is that perhaps this could increase the profitability of the reactor, as it should not be interrupted for a unnecessary safety check. On the other hand, in case of an accident within this period which might lead to release of radioactive material, that might have been prevented otherwise, the manufacturer could be responsible which might have consequences for all other SMRs produced by this manufacturer. This is a scenario related to political consequences of certain decisions, which will not be covered further in this research.

6.2 Standardization

The third question in this second round is focused at standardization. In question three of round one, which is shown in Figure 5 on page 23, multiple participants noted that standardization might be beneficial. Some participants showed mixed opinions about who should be responsible for the standardization process. Question three is therefore aimed at responsibility for the standardization process.

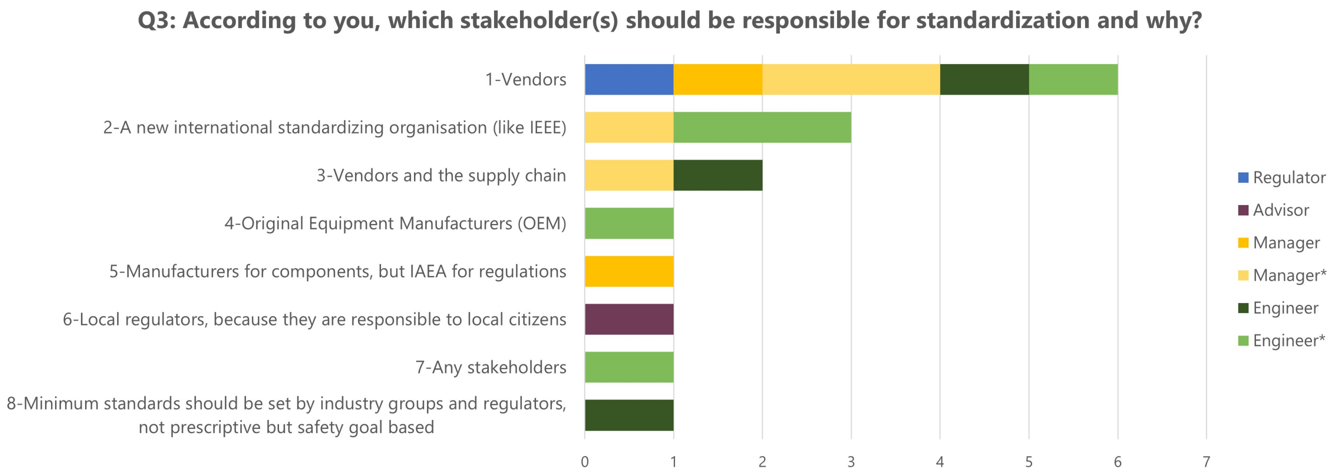

Figure 11: Results for question 3 of round 2

Figure 11 shows that most participants think the SMR vendors should be responsible for the standardization. Two participants also include the entire supply chain. One participant indicates that only the OEM should be responsible for standardization. One participant indicates that manufacturers should be responsible for parts, and the IAEA should be responsible for standardizing regulations. So far, the IAEA only provides guidelines for safety. This is something that is also mentioned by other participants. They do not think that the IAEA should be responsible as this is not one of the goals of the IAEA. These participants indicate that a new organization should be formed, that is completely dedicated to creating standards within the industry. This is done in the electronics sector by the IEEE, the Institute of Electrical and Electronics Engineers, which is included by one of the participants as a successful example. The most common standards that have been created by this institution are Ethernet, WIFI and Bluetooth. A global organization like IEEE, consisting of researchers, engineers and other relevant stakeholders could be formed for the SMR sector, to enable standardization among different manufacturers.

Another participant mentioned that local regulators should be responsible for standardization because they are responsible to local citizens. This could be implemented in a global standardizing organization. Local regulators do not have sufficient influence and knowledge to standardize a global sector, especially not if these regulators have different interests and operate according to their local laws set by national governments. This would require extensive cooperation between them. A new international standardization organization might be the ideal place to cooperate, as it would serve the common good. A recommendation for further research on this topic can be found in section 8.2.

In question three of round one, some participants made statements which are discussed with the group of experts in this round. One participant mentioned that standardization of parts between designs is unlikely (Figure 5, statement 15). This is followed up on in the following statement in a slightly different manner: Standardization of parts between vendors is possible. By changing the statement, it becomes better suited for the Likert scale, as it does not include the vagueness of the word 'unlikely'. The results are shown in Figure 12.

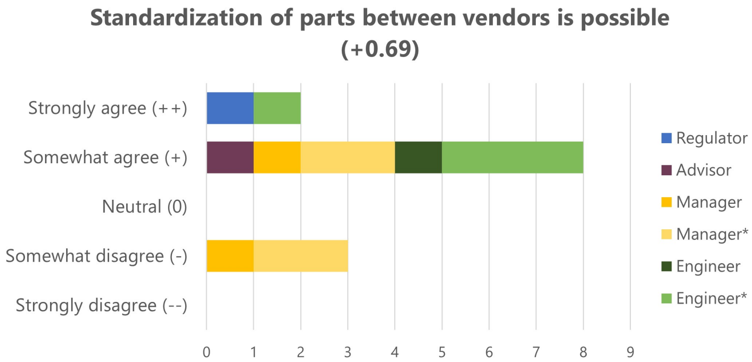

Figure 12: Statement 3

Two participants do strongly agree with the statement. The largest group, consisting of eight participants do somewhat agree with the statement, while three participants do somewhat disagree with the statement. The average score of +0.69 implies that the group of experts does somewhat agree with the statement. An interesting aspect to note here is that all participants who disagree with the statement are managers. Managers might have a more general overview of the project and their competitors, which could mean that they do not think it is possible. Since they answered "somewhat disagree", it might also mean that they think it would be very difficult or impossible to standardize among vendors, in the current state of the SMR sector, but there might be a possibility in the future.

The next statement is also made in question three of round one (Figure 5, statement 5): The lack of public support gives no incentive to standardize and work together. This statement was made by two engineers. Giving all participants this statement can show if this thought is shared among other expert groups as well. The results are shown in Figure 13.

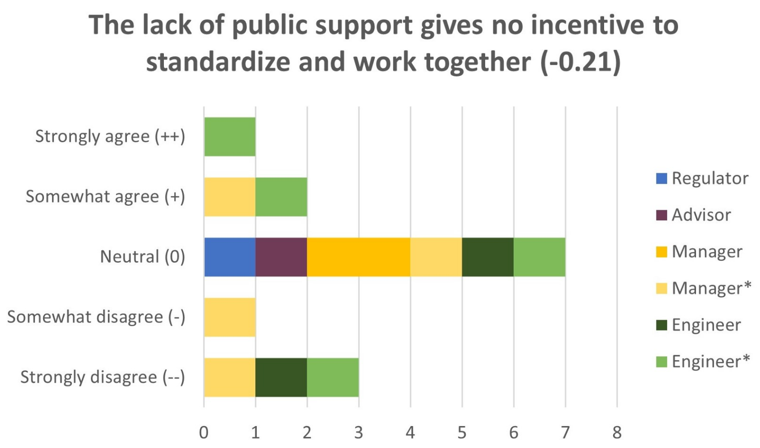

Figure 13: Statement 4

The results of this statement show that most people do not have a strong opinion on this. The average score of -0.21 implies that the group of experts is neutral. Two engineers do strongly disagree with the statement, which shows that it also is not shared among all engineers in this sample.

The last statement in this round is aimed at the personal opinion of the experts pertaining public support for SMRs. Participants are asked their opinion on the following statement: I feel that there is a lack of public support for SMRs. The results are shown in Figure 14.

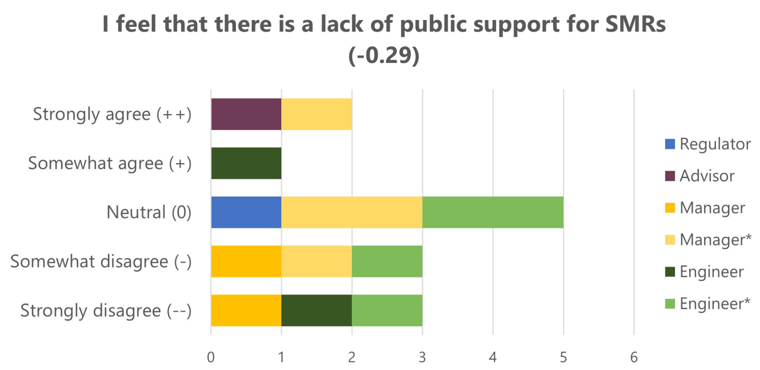

Figure 14: Statement 5

The results show differences between participants. The average score of -0.29 implies a neutral group response, but the answers are more spread out among participants. However, as only 3 out of 14 (21.4%) do agree with the statement, it seems that the lack public support is not commonly felt among the experts in this study.

6.3 Generations

The last question of this round follows up on question four of round one, which is shown in Figure 6 on page 25. From this question it became clear that the biggest disadvantages for Gen IV SMRs are the time to market and the lack of proof of technology. Based upon previous research by Mignacca et al. (2020), possible reasons for these disadvantages are given. These reasons are provided to the participants as predefined choices. Participants were also able to manually add reasons.

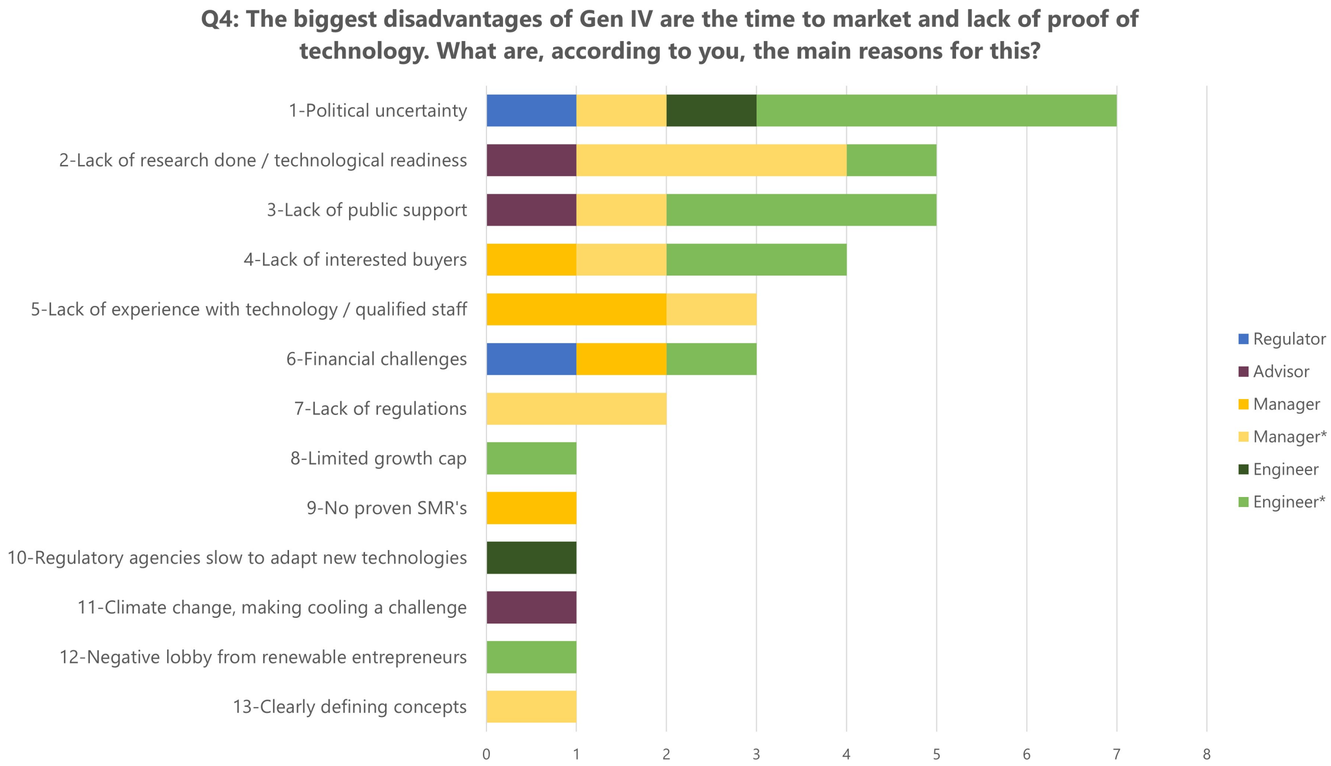

Figure 15: Results for question 4 of round 2

The results in Figure 15 show that most participants think that political uncertainty is a main reason for the given disadvantages. The lack of research done and public support are also chosen often as important reasons. There is likely an effect of the predetermined choices, as those form the top seven reasons, which are all selected more than once.

The selection of important reasons is then carried over to the next question, in which participants were asked to rank the reasons they have selected. This shows which of the main reasons are the most important, according to the participants. The results of the question are plotted together with the results of the selection. To be able to compare the results, the values are normalized. The results are shown in Figure 16. The number of selections is shown in red, while the green bars show the results when the main reason is prioritized. The priority is made according to the distribution shown in Table 4. When the results show that the red bar is longer than the green bar, the participants have not given that reason a high ranking (on average). If the green bar is longer than the red bar, the participants have given that reason a high ranking.

Rank	Points
1	6
2	3
3	2
4	1

Table 4: Rankings with corresponding point values

Participants selected between two and four main reasons. If a participant selected only two reasons, 6 and 3 points were awarded to the first and second ranked item. If a participant selected three reasons, 6, 3 and 2 points were awarded. If a participant selected four reasons, points were awarded according to table 4. One participant did not make a selection but mentioned the reasons were equally important. In this case, both reasons received 4.5 points. Other distributions, with 4, 3, 2, 1 (normal ranking) and 5, 3, 2, 1 (bonus point for the most important reason) yielded similar results. However, because most participants selected two reasons, the relative difference between the most important reason and second reason is smaller when 4 or 5, and 3 points are awarded. Therefore it has been chosen to double the points of the most important reason, compared to the second choice. The outcome of the results did not change, but the relative difference between the red and green bars is increased, allowing for better visualization.

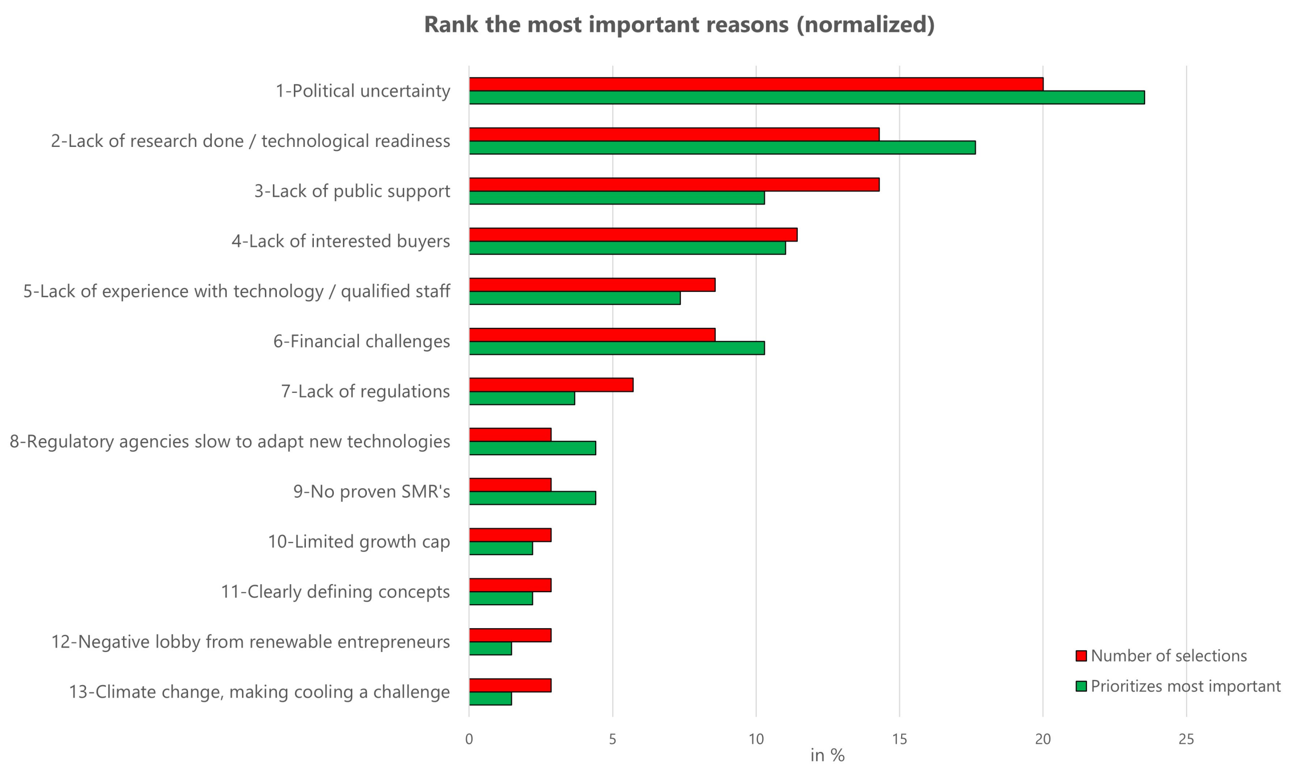

Figure 16: Ranking of reasons

The results show which reasons are often chosen as most important reasons for the disadvantages "time to market"and "lack of proof of technology" . Reasons that are often chosen as most important reason have a green bar that is longer than the red bar. This does not mean that these reasons are more important than the other reasons, but it indicates that experts have chosen these as most important reasons. These reasons are:

- Political uncertainty (1)
- Lack of research done (2)
- Financial challenges (6)
- Regulatory agencies slow to adapt new technologies (8)
- No proven SMRs (9)

One of the reasons, no proven SMRs (statement 9), corresponds with the disadvantage mentioned in the question (lack of proof of technology). It is still included as it might have been given as reason for the disadvantage: time to market. Many of the given reasons might be related to each other. An example of this is lack of public support, which might be related to lack of interested buyers. Another example is negative lobby from renewable entrepreneurs, which might be related to a lack in public support. More of these relations can be found in these reasons.

Reasons with a green bar shorter than the red bar, are selected as important reasons but not often, or not at all, chosen as most important reason. These are:

- Public support (3)
- Lack of interested buyers (4)
- Lack of experience with technology / qualified staff (5)
- Lack of regulations (7)
- Limited growth cap (10)
- Clearly defining concepts (11)
- Negative lobby from renewable entrepreneurs (12)
- Climate change, making cooling a challenge (13)

The reason "clearly defining concepts" is mentioned without further explanation. This reason is manually added by a manager. It can relate to the disadvantage time to market, as a lack of clearly defined concepts lead to a longer time to market. The reason climate change, making cooling a challenge, is likely related to different choices policy makers can make. Gen IV reactors are not available yet, which means renewables are more likely to be chosen as option to fight climate change.

The most important reasons will be compared with the results from the study by Mignacca et al. (2020) in section 7.3.

7 Discussion

This study investigated three main focal areas for the SMR sector. These are safety, standardization, and generations. Within these areas, various aspects were researched by using the Delphi method. In this section, the results found in the Delphi study are discussed. These results will be connected to the literature study, which is shown in section 2. As any study, this study also has it limitations. These limitations are discussed per section. Upon these limitations, recommendations for future research are made, which can be found in the following chapter, section 8.2. This chapter will discuss the results for the safety related questions in section 7.1, results for standardization related questions in section 7.2 and results for generation related questions in section 7.3.

7.1 Safety

This section will contain a discussion of the results found in the Delphi study and their connection back to the literature. The safety related questions focused on two subjects: Safety systems and safety over the lifetime of the SMR. To finalize this section, the limitations of the safety related questions are discussed. This final section also includes general limitations to the Delphi study, which hold for the other questions as well.

7.1.1 Safety systems

In the first round of the Delphi study, question one was related to passive safety, and question two focused on guaranteeing safety over a longer period. The results from question one, which can be found in Figure 3 on page 20, show that eight participants indicate that passive safety should be the aim. This is an interesting result as this answer does not directly answer the question whether older -, or newer safety systems should be preferred. However, other answers that were given do answer the question. The choice of using a newer or older safety system is shown to be a design choice. If the safety system can be licensed, it is shown to be safe. This therefore means that it does not matter which system is used. A generation III SMR might be better suited for older safety systems, as these reactors are based upon existing technology. Generation IV reactors use newer technologies. These reactors can reach different operating conditions than generation III reactors, which might imply that a different safety system is required. The downside of using newer safety systems is not that these are potentially unsafe, but the process of licensing such a new safety system is longer than an existing system. If it is possible to use an existing safety system, one can argue that this is the better choice. This would decrease the time needed for licensing the reactor, as well as mitigate the R&D costs that come with designing a new safety system, thus making the SMR more economically competitive.

However, as the most given answer is related to passive safety, this should be further discussed. Passive safety systems can provide the same reliability as active safety systems, but at a fraction of the costs. Given the difficult economics of SMRs, which are shown in section 2.4.1, passive safety might be an important part of the solution. Question one of round two (Figure 7, page 30) is aimed at a further discussion on passive safety. This question finds that there are multiple ways of maximizing the passive safety of SMRs. These include, but are not limited to, a robust reactor design, natural circulation of coolant medium and sufficient diversity and redundancy within the design. For natural circulating coolant mediums, water and air are often used. Air cooling is the preferred method, as water bodies can be drained. The downside of using air as coolant is that it has a lower heat transfer coefficient than water, thus making it less capable of cooling the reactor. This would imply that a larger area is needed to provide the same change in temperature. For SMRs with a compact design, this might be difficult to implement. However, aiming for a high level of passive safety in every reactor, could reduce the need for maintenance, as described in section 2.1. A reduction in maintenance intervals, in combination with the longer fuel cycle of SMRs leads to fewer shutdowns. This increases the economical competitiveness of the reactor.

In this same question (Figure 7) the most given answer is that active safety should always be part of the design. Passive safety is aimed at providing safe operating conditions for a set period of time after an accident. A back-up safety system is always needed to cover the period after which passive safety does not guarantee the safety of the reactor. It is also likely that regulatory or government bodies do require this back-up method, to ensure the safety of their citizens. In the first statement of the second round (Figure 8), the group of experts does not have an unanimous opinion on whether active safety is always needed. This might be explained by the fact that some very small modular reactors can be completely passive safe due to their very small power output. However, most participants indicate that active safety is always needed. Another explanation can be that different reactor types are considered. As described in section 6.1, Figure 7, a Molten Salt Reactor can be made passive safe. However, only 10 out of 72 SMR designs are molten salt reactors. Because these Gen IV reactors are not commercially operated yet, it is unlikely that these are the only considered designs. If the question would have focused on molten salt SMRs, the answers could have been different. However, the sample used in this study contains experts on SMRs, not specifically on molten salt reactors. Therefore, it could be that this sample of experts is not suited for such a question on a specific type. This is also discussed in section 7.1.3.

In the second statement (Figure 9), most participants agree with testing passive safety in FOAK units, so it can be guaranteed for NOAK units. This would increase the knowledge about the passive safety features for the first reactors of a certain design. Four experts do somewhat disagree with the statement. This can be because they either do not think that passive safety can ever be guaranteed, or that passive safety should not be tested in FOAK units. Testing can also be done during the design phase, which does mean that FOAK units do not require many tests. Testing in FOAK units decreases the economical competitiveness of the reactor, while a FOAK unit is already likely to not be profitable.

7.1.2 Safety over the lifetime of the SMR

The financial aspect proves to have a significant impact on the way the expert think about upgrading, as is shown in question two of round one (Figure 4 on page 21). When it comes to upgrading safety systems, experts bring up the costs associated with doing such upgrades. If upgrades are not necessary, the experts indicate that these would only harm the profitability of the SMR. When a reactor is still proven to be safe, the safety systems do not require any upgrades. Even if these upgrades can increase the safety of the reactor, and thus decrease the CDF (as described in section 2.1), they are not needed. Core damage frequencies of SMRs already promise to be significantly smaller than those of NPPs, which means a higher level of safety is already achieved. Therefore SMRs should not upgrade their safety systems if these upgrades are not necessary. If upgrades are required, most experts indicate that doing these during the periodic safety check of the reactor is the best moment. This is of course only a viable moment if there is no direct threat to the safety of the reactor. If there is a direct threat, which does not guarantee safety, the reactor does require to be shut down and the upgrade should be installed, so that safety can be guaranteed again.

Opinions on how long this periodic safety check interval should be, differ between experts. Currently, a ten-year interval is common in NPPs, but there are countries that use other intervals. For the SMR sector, various experts think that this ten-year period is a good starting point. If it is shown possible, this period can be extended. However, there are also experts that think this period should be shortened for SMRs. A reason that is provided for this choice is that mass production can introduce defects. This is possible but it does not need to require a change to the periodic safety check interval, as SMRs are checked upon installation, and monitored and maintained in the meantime. If a defect is introduced due to mass production, it is unlikely that it is not noticed during testing or during regular reactor maintenance moments. Another reason provided is that shorter intervals build confidence and that it increases the knowledge about the reactor. It is likely that there will be multiple units of the same design, and therefore more knowledge is already gained. Knowledge sharing between clients with the same reactor and manufacturer of that reactor can be beneficial for all stakeholders. Therefore it is possible that the periodic safety check will vary for different stages of the reactor design. FOAK units could require more safety checks than NOAK units, but if these early safety checks show that this period can be extended, it is likely that these will be extended.

7.1.3 Limitation on safety related questions and the Delphi method

Safety should be the number one priority of the SMR sector. However, the definition of safety is difficult. What is considered "safe"? Where literature is mostly related to the core damage frequency, as described in section 2.1, this only covers the safety of the reactor design. Many more aspects relate to the overall safety, such as the location of the reactor, the quality of the staff and mechanics, and the treatment of nuclear waste. These factors are all not considered as they are different in every case. A well designed reactor with a low CDF is not safe if it is operated in the wrong manner and located in the wrong area. Regulators do keep all these aspects in mind when licensing a reactor. Therefore the answer given in Figure 3 statement 2 might be the most important answer. If the reactor can be licensed, it is safe. Following-up on this statement would however be difficult with this sample, as there are no universal regulations yet (section 2.4.2). If such a question is queried, it could lead to statements that are based on local legislations, something that is not covered in this research. Since this research is only aimed at technological aspects, passive safety and the periodic safety check are chosen as subjects for the second round.

Due to time limitations in the Delphi study, there could be no feedback round in between round one and round two. Therefore, it is chosen to go with statements. As these statements were multiple choice questions, something that is uncommon in the Delphi method, participants could only answer predetermined answers. The Likert scale used in these statements does not clearly define intervals. Where one participant might somewhat agree with the statement, another participant that feels exactly the same might select neutral or somewhat disagree. Over a large sample, this would likely even out. However, since only 14 experts participated in the second round, this degree of randomness might have a significant influence on the results. Because participants were unable to provide a written answer on these statements, answers could not be synthesized into groups. Therefore, the average score found in statements could have a significant degree of uncertainty. The low number of participants also creates low external validity. The results from a Delphi study represent opinions of the participating experts, but can not be generalized to all experts in the SMR sector.

These statements as a way of giving feedback, limit the amount information experts receive. It pushes their answers in a certain pre-determined direction that corresponds with the scope of the study. This is not ideal, because an open discussion on certain aspects could prove to be more effective. This solution limits the content validity of the research as it ignores important aspects that relate to SMRs. However, due to the political and competitive nature of certain statements, including these could arouse suspicion of a bias towards political views or favor a certain company. By excluding these aspects, the focus of the study remains on the technological aspects only.

While the respondents should ideally cover the entire population of experts, this was not the case in this study. Russia and multiple Asian countries, such as Korea and Japan, have a significant influence in global SMR production. As discussed in section 3.4, experts from these countries have not been contacted. This limits the coverage of the group of experts views to only the following three continents: Europe, North America and Africa. This could potentially influence the outcome of the results. Furthermore, the group of experts is, especially in round two, not equally covering all four groups. In this round, only one regulator and one advisor have joined the panel of experts. Therefore, results are based mostly upon answers of managers and engineers, which could inflict a certain bias in the results.

7.2 Standardization

This section will focus on the discussion of the questions related to standardization and their limitations. First, question three of round one is discussed, and then question three of round two is discussed, together with the derived statements from round one. Furthermore, this section will also discuss the limitations of these questions.

7.2.1 Advantages and disadvantages of standardization

From the literature research, it became clear that standardization can be beneficial for the SMR sector, as shown in section 2.2. The SMR sector can be standardized in two ways. The first one is standardizing parts. As manufacturers of parts can make more copies of the same part, this is likely to drive prices per part down. Question three of round one, which is shown in Figure 5 on page 23, is aimed at standardization of parts. In this question, advantages and disadvantages of standardization of parts are asked. The following advantages are mentioned: supply chain predictability, cost reduction, reductions in licensing time, common failure, performance history, consensus on quality and reliability and better availability of parts. These advantages are either aimed at reducing the financial risks for parties involved, or at increasing safety and reliability. Disadvantages that are mentioned are: local effects, chance of cheap copies and common failure. Local effects can have an effect on parts, but SMR vendors do need to get their designs licensed by local regulators. These local regulators do keep local variables in mind when licensing a SMR for a certain site. Furthermore, it is likely that even if a part is standardized, not all SMR designs will use that standardized part, as there are still differences between designs. A chance of cheap copies is also unlikely, as standardized parts are constructed according to regulations that are set for the part, as is the case for standardized aircraft parts. Independent quality checks and inspections are likely to happen at manufacturing sites. Common failure is mentioned both as an advantage and as a disadvantage. This is depending on the point of view on the situation. From a safety perspective, common failure is beneficial as it leads to early detection of potential incidents. From a financial perspective it is seen as a disadvantage, because the part needs to be inspected, and probably replaced, in all designs leading to unscheduled downtime in SMRs around the globe.

7.2.2 Standardization and the responsibility for standardization

In this question experts also indicate that standardization is needed, but that there are still many aspects that need to be considered. A participant mentions that standardization of parts between vendors is unlikely, and two engineers mention that the lack of public support gives no incentive to standardize and work together. These views are shared with the group as statements in the second round. These statements can be found in Figures 12 and 13 on page 34. The statement standardization of parts between vendors is possible provides a positive outcome. Within the group of experts, most participants think that this is indeed possible. However, the group is not unanimous. It is likely that it can be done for certain parts, when vendors cooperate in their designs. This is something that might be difficult, given the profitability of reactors, especially in early stages. It is likely that designs need to be adapted and costs might increase in the early stages, thus requiring larger investments. In later stages, costs will decrease due to the advantages of standardized parts. In the second statement, most participants show a neutral opinion on the lack of public support. Therefore, it is difficult to draw a conclusion from this statement. What can be said is that, within this sample, it is not a commonly shared thought, but other experts might agree that there is a lack of public support. Perception of public support is investigated in another statement, which is shown in Figure 14 on page 35. Within this sample, the lack of public support is not commonly felt. The size of the sample, which is only 14 participants, is also to small to generalize over a larger population. Perhaps, because SMRs are still in early stages, the broad public does not have a clear opinion. Furthermore, it is likely that differences in public support for SMRs can be linked to national and political views on nuclear energy in general.

The second way the SMR sector can standardize is in the licensing process. The aircraft model serves as successful example in this case. This sector has dealt with global licensing problems, and aircrafts that are developed in the United States are airworthy in Europe, as well as the other way around. Licensing challenges for the SMR sector are discussed in section 2.4.2. These are global challenges, and attempts of finding solutions via cooperation are currently being investigated by the SMR Regulators Forum of the IAEA. As these problems are not limited to regulators only, but do also include global politics, this study is not the right place to investigate these challenges. This study is only aimed at general technological aspects of SMRs, and not at politic aspects. Although participants in this study cover multiple continents, many areas of the world are not covered. Another notable aspect is the group distribution in the second round, as shown in Table 3 on page 28. The results in the second round do cover mostly views from engineers and managers, as 12 out of 14 participants in the second round come from these two groups. Therefore, results for advisors and regulators do not cover the views of a group, but only those of one person and are thus to be interpreted as such. However, this study shows that cooperation can be beneficial for the SMR sector, and that agreements can be reached among experts with different backgrounds. Therefore, it should be possible to find a proper solution to global licensing of SMRs.

When it comes to responsibility in the licensing process, view differ on who should be responsible. Question three of round two (Figure 11 on page 33) is aimed at which stakeholder(s) should be responsible for standardization. Most participants mention that vendors should be responsible, perhaps with the whole supply chain involved as well. This might be the most obvious solution. Vendors create designs, and are likely to enjoy most benefits from standardized parts. Most participants also think that standardization of parts between vendors is possible. As previously described, this situation might require more cooperation between vendors, preferably in early design stages. However, due to collusion among vendors, not all types of cooperation might be allowed. In the beginning, standardization might increase costs, due to changes in designs. In later stages, the positive effects of standardization will be noticed by the vendors. As it is likely that certain vendors will benefit more from this process than other vendors, some participants indicate that a new international standardization organization should be formed. This could create a fair environment, because such an organization should favor the common good, rather than specific vendors. The structure of such a standardization organization is something that should be researched. This is not done in this study. The reasons for this can be found in section 7.2.3. A potential research idea is covered in 8.2.

7.2.3 Limitations of standardization

Question three in the first round covered the advantages and disadvantages of standardization. In this question, the most mentioned advantage is supply chain predictability (statement 1, Figure 5). This advantage is only mentioned by three participants, so it is hard to conclude if this is the most important benefit. Furthermore, the question only focuses on standardized parts, while the sector might benefit more from standardized regulations.

Due to the diversity in the group and the current efforts in the SMR Regulators Forum of IAEA, this is not questioned in this study. Standardized regulations might lead to standardized parts, which in turn might lead to the advantages mentioned by the experts. In the aircraft sector, it is shown to be possible to deal with global challenges. The SMR sector might have more issues, as certain countries, such as Germany, decided to stop with nuclear energy in general. Due to the cooperation in the European Union, this might also have an effect on other countries nearby, such as France, that do want to use nuclear energy. Due to the political background of these challenges, these are not to be investigated in a study on technological aspects.

Standardization is also covered in statements. Due to the high degree of randomness and the small sample size, this might not have been the best method. This is covered in section 7.1.3. The sample size and distribution between groups, proved to be a problem for a potential third round. A new international standardization organization, might, when ran in the right way, be a potential solution to standardization of parts. This organization should not prefer certain vendors over other vendors, and cover all aspects of the SMR sector. A third Delphi round may not do justice to investigate such a potential solution for the standardization of the SMR sector. The total group of experts is not sufficiently sized to draw conclusions from findings in a next round, especially if further drop-outs between surveys are considered. Furthermore, the group of experts is not sufficiently diverse enough to cover group opinions. Therefore, it is recommended to investigate this topic in a future research. Such a potential research idea is covered in section 8.2.

7.3 Generations

This section will cover question four of the first and second round in section 7.3.1. These questions were aimed at differences between the two generations. It will also discuss the limitations of these questions in section 7.3.2.

7.3.1 Advantages and disadvantages of Generation IV

Generation III SMRs differ from generation IV SMRs. Because of the higher operating temperature in generation IV reactors, these SMRs can be used for more applications than generation III SMRs (see section 2.3). Question four of round one covers the advantages and disadvantages of generation IV compared to generation III. This question can be found in section 4.3. The advantages of generation IV that are mentioned are: More applications, fuel cycle improvements, passive safety, new fuels, cost reductions, possible renewed public acceptance, lower construction times, less human interaction and smaller size of core vessels. The effects of many of these advantages differ among types of generation IV reactors, and are for now not proven as there are no generation IV SMRs available. This lack of proof of the technology is commonly seen as a disadvantage for generation IV reactors. Other disadvantages that are mentioned are: Time to market, new parts and supply chain, contamination of single use reactors and xenon discharge. Xenon discharges happen in molten salt reactors, and can block vision on unlawful nuclear tests. This problem should be considered, but since it is specific to molten salt reactors and includes political views, it is not further covered in this study. Single use reactors are also a specific type of reactors, which do not suit the broad technological focus of this study. As new parts and supply chains are a direct cause of increased licensing times, the increased licensing time and lack of proof of technology are chosen to further investigate in the second round.

In question four of round two (Figure 15 on page 36), reasons for these disadvantages are asked. Participants received predetermined choices, based on findings from Mignacca et al. (2020). In this paper, the authors researched general elements hindering SMR construction. Figure 17 shows the elements that hinder the construction, which essentially equals the disadvantage "time to market" (most given disadvantage in Figure 6).

The findings in Mignacca et al. (2020) relate to SMRs in general and do not relate specifically to generation IV SMRs. However, the element hindering SMR construction that are found in this research are given as predetermined reasons for experts in this study. These reasons have been categorized in this survey, to better suit the question. E.g. financial challenges contains elements such as the perceived investment risk and availability of funds. Participants were also able to add reasons they found important to the list, but other participants did not see the manually added reasons of previously answered surveys.

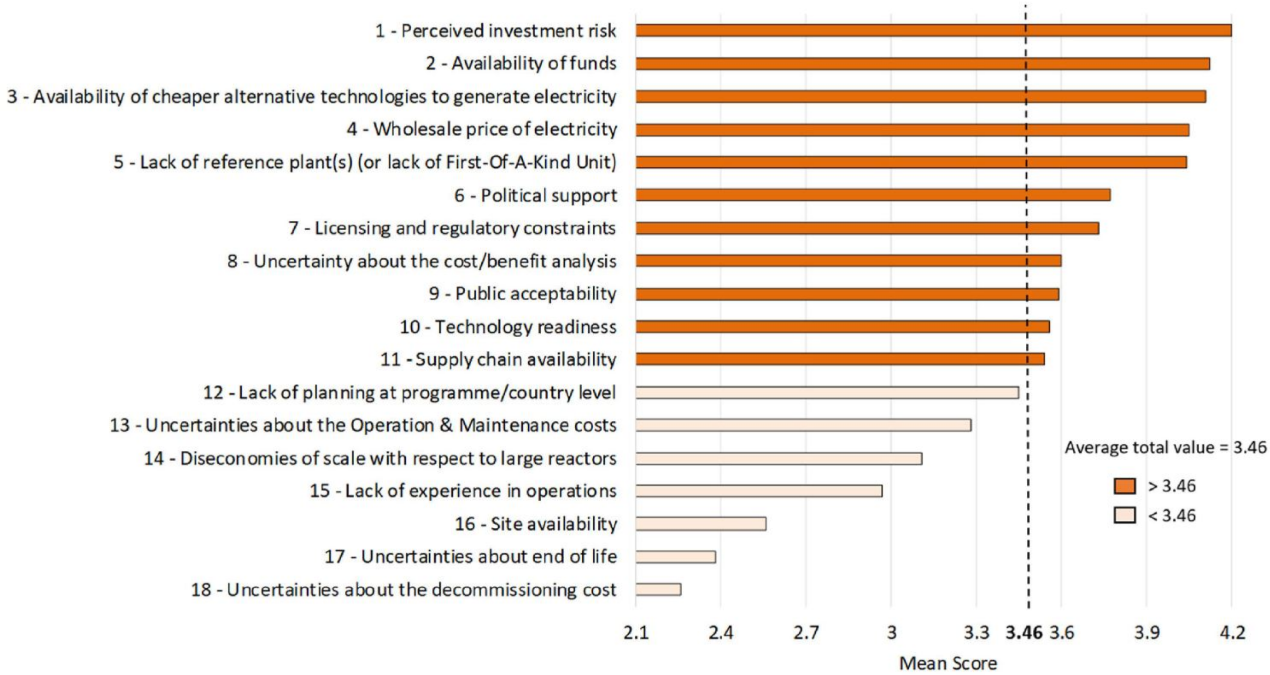

Figure 17: General elements hindering SMR construction (Mignacca et al., 2020)

While in this study, participants were asked to select only the most important reasons, the study by Mignacca et al. (2020) used a different method. In their study, participants were asked to give points between 1 and 5, with 5 being the highest. The study finds that financial challenges, economic challenges, technological readiness, policy and regulation readiness, and public acceptability are the most important reasons hindering SMR construction. This study finds that political uncertainty, technological readiness, financial challenges, regulation readiness are the most important reasons for the generation IV disadvantages "time to market" and "lack of proof of technology". To get these results, points are given to statements based on ranking, as shown in Table 4. If these point values were chosen differently, the most important reasons might vary. In this study it is chosen to only prioritize the first ranked item, by a factor two over the second ranked item, because most participants did only select two reasons.

7.3.2 Limitations of generation-questions

This question, as asked in round two, should have been better formulated in hindsight. The question should have only focused on one single aspect: time to market, because two aspects are queried in one question. Answers to this question are reasons based on one aspect, while they are portrayed as reasons for multiple aspects. The correct aspect that should have been queried should be: "time to market" instead of "lack of proof of technology". This is because lack of proof of technology is also a reason for the slow time to market. Furthermore, including two reasons in one question introduces a bias in the answers, as there is no way is knowing if an answer relates to one disadvantage or if it relates to both disadvantages. An example of this is the answer: No proven SMRs. This answer is manually added by a participant, but is a similar answer as "lack of proof of technology", for which reasons are being researched in that same question. Other manually added reasons however, are interesting. The reason climate change, making cooling a challenge is likely related to different choices policy makers can make. Gen IV reactors are not available yet, which means renewables are more likely to be chosen as option to fight climate change. With recent development within the EU, nuclear energy is now classified as green energy, once it meets certain requirements. This provides options for countries willing to invest in nuclear energy. If a country has clear plans and funding for dealing with nuclear waste, the EU will classify nuclear energy as sustainable energy, to reach the goal of becoming climate neutral by 2050. This will perhaps lead to opportunities for the SMR sector. The EU plans are heavily criticized by green parties and ministers throughout Europe (BBC, 2022).

8 Conclusions and recommendations

This chapter will highlight conclusions that can be drawn from the insights of experts that have been gathered during two rounds of surveys according to the Delphi method. It will also contain the conclusions that can be drawn from the literature review in section 2 and comparison with the aircraft sector in section 2.2. These conclusions will answer the research questions stated in section 1. Section 8.1 contains conclusions, while section 8.2 contains recommendations for future research.

8.1 Conclusions

This research aimed to create recommendations on the viability of SMRs with different choices of technology. The main research question was: *How can a consensus on technological aspects within the SMR sector be reached?* During the literature study, three main focal areas have been identified. These areas are safety, standardization and generations. Surveys have been designed, which were answered by experts within the SMR sector. Based on qualitative research, the following conclusions can be drawn:

1. Cooperation within the SMR sector can be beneficial for all stakeholders.

Perhaps the most important conclusion that can be drawn from this study is that cooperation within the sector can be beneficial for all stakeholders. As is shown in this study, there are many different views within the SMR sector, which makes it difficult to achieve a general consensus on technological aspects. What this study shows is that there is always a common ground between people from different backgrounds, and experts are willing to cooperate to help the SMR sector out of the state that it currently is in. This cooperation can lead to standardization and knowledge sharing, two important factors that will effect the economic competitiveness of SMRs in general. Although a direct consensus on technological aspects within the SMR sector is not reached in this study, it shows that experts are open to cooperation. Finding a consensus on specific technological aspects, whether it be in the form of standardization or in choice of specific SMR design elements is likely possible due to this cooperation.

The answer to the research question: *How can a consensus on technological aspects within the SMR sector be reached?* is therefore: Through intense cooperation between different stakeholders, a consensus on technological aspects within the SMR sector can be reached. It is likely that not all technological aspects will reach a consensus, due to the differences in designs and design specific aspects related to a certain type of SMRs. Due to the financial challenges covered in section 2.4.1, it is likely that not all designs will eventually reach the market, as there is simply not enough demand for multiple units of 72 different SMR designs. Specific investments in the designs, such as the UK government investment in the Rolls-Royce SMR, might lead to a shorter time to market for these designs. This will mean these designs serve as a basis for regulations and are therefore more likely to be successful. However, if the sector finds a consensus on certain aspects, this might lead to a development of regulations on those aspects. Designs that have made different choices will then be harder to license. In the end, a consensus could lead to more investments in the SMR sector, especially because of the green taxonomy of the European Union.

2. It does not matter if old or new safety systems are used, as long as reactor safety can be guaranteed.

In order to answer the first sub-question: *What safety related choices should SMR designers make to guarantee the safety of the reactor?* research is done on safety systems. SMRs generally are safer than conventional NPPs. The safety systems used in SMRs can be the same as in these NPPs, but can also be newly designed specifically for that SMR design. The choice for safety systems should only depend on the goal: guaranteeing the safety of the reactor. The choice for which safety system to use is a design choice. Using older safety systems might save licensing time and R&D costs. Newer safety systems, on the other hand, might be more suitable in certain reactor designs. Generation IV reactors have higher operating temperatures for which older safety systems might not be suited. Newer safety systems might also be smaller and thus a better fit to smaller scale of SMRs.

3. Passive safety should be the aim, but some form of active safety is needed.

Passive safety can provide the same reliability as active safety systems, but at a fraction of the cost. Some ways that contribute to passive safety are robust designs, with enough diversity and redundancy in the design and natural circulation of coolant mediums. However, passive safety is (for most reactors) only guaranteed for a limited time after an accident, so some sort of active safety is needed to guarantee SMR safety. The safety related choices SMR designers can make to guarantee the safety of the reactor are therefore the choices of safety systems. A SMR should be aimed at a high level of passive safety, but is likely to also require an active safety system. This safety system should be chosen to fit with the design. If calculations for multiple combinations of safety systems show that safety is guaranteed, the choice of safety systems is a free design choice.

The periodic safety check and choice of upgrading are not design choices. The periodic safety check is a choice made in legislations. Therefore, the SMR sector needs to prove that extending this period is possible and safety is guaranteed, so that SMRs can operate without interruptions for longer periods, so that the economic competitiveness is increased. This also is a major aspect in the following conclusion.

4. Upgrades to safety systems should only be done when they are absolutely needed.

Financial aspects play an important part in the SMR sector. When unnecessary upgrades are installed, they reduce the profitability of the SMR. The success of SMRs depends on the ability of providing economically competitive energy. The preferred moment of installing upgrades is during the periodic safety check, for which the intervals should be extended when possible.

5. Standardization can be beneficial for the SMR sector, if implemented in the right way.

Standardization of parts can lead to cost reductions, faster licensing and better parts availability. These advantages can be beneficial for the economic competitiveness of SMRs. The standardizing process should be, according to most experts, the responsibility of vendors. Other experts indicate that a new standardization organization should be formed. The advantage of such an organization is that it operates towards a common good. How such an organization should be formed, should be researched in future work. An example of such a study is given in section 8.2. Standardization in the licensing process is currently being investigated by the SMR Regulators Forum of the IAEA. As SMRs face various challenges within the licensing process (section 2.4.2), standardizing can help with overcoming these challenges. This answers the second sub-question: *How can standardization be beneficial for the SMR sector?*

Which way exactly should be chosen is a difficult subject, due to the many stakeholders that are involved. The ideal way of implementing standardization is not covered in this study, but a comparison with the aircraft sector is made. This subject in covered in section 2.2.3. The third sub-question: *What can the SMR sector learn from the aircraft sector on standardization?* is therefore answered based on this literature research:

6. The aircraft sector can provide an example of successful global licensing and safety standards.

The aircraft sector has proven that international cooperation might lead to international regulations. These international regulations are needed, so that SMRs around the globe are made according to the same regulations and safety standards. This creates not only a safer environment, but also reduces the licensing time and costs for foreign SMR designs. This can help with the financial and regulatory challenges that are discussed in sections 2.4.1 and 2.4.2.

7. Political uncertainty, technological readiness and financial challenges are the main reasons for slow development of generation IV reactors.

A main disadvantage of Gen IV is slow time to market. Political uncertainty, technological readiness and financial challenges are chosen often as most important reason for this. Lack of public support and lack of experience with the technology are also often mentioned as important reasons. Current developments within the EU might lead to a decrease in political uncertainty and an increase in investments for the nuclear energy sector, as the EU has classified nuclear energy as sustainable energy source if certain conditions are met (see European Commission, 2022). However, due to large number of opportunities, both generations have their advantages and disadvantages. The fourth sub-question: *How can the SMR sector benefit from making a choice for a specific generation of reactors?*, therefore has a difficult answer. The SMR sector could benefit from making a choice for a specific generation as it might lead to quicker development of regulations and less financial risk. However, this is likely not the best choice for the sector and for society as a whole. Deciding on a specific generation or even a specific type of SMRs would reduce the amount of designs significantly. As both generations have their advantages, this is not beneficial for society. A choice for generation III would mean that SMRs are likely deployed sooner, which might help with reducing CO_2 emissions. Generation IV is not ready for commercial deployment yet, but has more applications such as hydrogen production and desalination. These applications might become necessary in the coming decades. Therefore, from a societal aspect the SMR sector should not make a choice, but let both generations develop and exist together. The choice of which reactor generation, has to be made according to the needs of a specific country or region, and not be decided from within the SMR sector.

An overview of the conclusions can be found in Table 5 below:

Conclusions
Cooperation within the SMR sector can be beneficial for all stakeholders.
It does not matter if old or new safety systems are used, as long as reactor safety can be guaranteed.
Passive safety should be the aim, but some form of active safety is needed.
Upgrades to safety systems should only be done when they are absolutely needed.
Standardization can be beneficial for the SMR sector, if implemented in the right way.
The aircraft sector can provide an example of successful global licensing and safety standards.
Political uncertainty, technological readiness and financial challenges are the main reasons for slow development of generation IV reactors.

Table 5: Overview of conclusions that can be drawn from this study

These conclusions lead to the main take-away of the research:

Cooperation within the SMR sector can lead to a consensus on standardization of parts and standardization of regulations, which reduces the financial risk for stakeholders and improves the chances for a viable global deployment of SMRs.

8.2 Recommendations for future work

From this study, recommendations can be made for the industry and policy makers. These recommendations will focus on how cooperation within the SMR sector can be achieved. Furthermore, recommendations for future research can be made in a scientific context. This section will discuss these recommendations.

8.2.1 Recommendations for the industry

This study focuses on three areas. Safety, standardization and generations. For each of these areas, recommendations can be made towards the industry. On the focal area safety, the following recommendation can be made: Maximize the safety level of the reactor by increasing the passive safety of the reactor. When designing a reactor, a robust design should be chosen with natural circulation of coolant medium and enough diversity and redundancy in the design. This will maximize the passive safety level of the reactor, which minimizes the need for active safety. This could be achieved at a fraction of the costs of only equipping the reactor with active safety systems.

As described in the conclusions, section 8.1 the main recommendation of this research is that cooperation can lead to a consensus in technological aspects of reactor designs. In turn this might lead to standardization. The industry should be responsible for standardizing according to most experts, but as other experts indicate, a new international standardizing organization could also be formed. It is likely that the industry plays a big role in this, pro-activity from the industry might be required.

When it comes to choices between the two generations, it is recommended to not make such a choice. Making this choice could potentially be beneficial as it might lead to quicker development of regulations, but it decreases the potential for global adoption of SMRs. Due to the large potential in the energy-generation market, both generations can be used alongside each other. Generation III SMRs can be deployed in the coming years, and replace conventional fossil fuel power plants. Generation IV reactors can be deployed in the coming decades, and serve more potential applications. Production of hydrogen and desalination might be crucial advantages of generation IV reactors over other ways of CO_2-free energy generation in the future.

8.2.2 Recommendations for policy makers

There are also recommendations for policy makers that can be drawn from this study. The first recommendation is a general recommendation that helps the SMR sector: Invest in the SMR sector. This recommendation is based on the significant impact of financial challenges on all three aspects: safety, standardization and generations. Various answers that are given in the Delphi study relate to becoming financially competitive with alternatives. Investments in the SMR sector lower the financial risk for companies involved. It does not matter much in which areas these investments are made, as long as they could benefit the entire sector. Examples of investments that benefit the entire sector are investments in research & development, standardization, regulators and nuclear waste management locations. If research & development and the standardization process are financially supported, it could lead to cooperation between firms on these aspects. Although it is likely that these investments do not lead to any return on the investment apart from the possibility of deploying SMRs in the region, and thus the ability of replacing polluting power plants. Investments that are likely to make returns are investments in specific SMR designs, such as the investment of the United Kingdom in the Rolls-Royce SMR, described in section 2.4.1. Now that the EU has classified investments in nuclear energy as a sustainable energy investment, there are more possibilities for such investments. As these investments mainly benefit a certain vendor, they might also benefit other vendors as regulations are likely to be derived from FOAK units.

This could lead to less financial risk for other vendors.

The second recommendation is to keep an open mind in selection of energy-generation methods. Ruling out nuclear energy could lead to not reaching the global CO_2-reduction goals. Both generations of SMRs might be useful. Gen III SMRs could assist in reaching the climate goals, and Gen IV SMRs have multiple extra advantages. They could provide sweet water in locations with large salt water bodies, and produce hydrogen, a clean fuel for the future.

8.2.3 Recommendations for future scientific research

Two recommendations for future research can be made. Both scientific studies are related to standardization in the SMR sector, as this shows to be a promising improvement for the viability of the sector. These studies will be described in this section.

The first recommendation is to research how a new standardizing organization can be formed. As mentioned in section 7.2, a third round with this group of experts is not going to be conclusive, as the group of experts is mainly consisting of managers and engineers. Therefore a new study is recommended. The IEEE standardizing organization can be taken as a starting point for literature research. The Delphi method could be used for this research as it facilitates cooperation between experts with different background in the SMR sector. Other research methods that can be used for such a study are interviews and surveys. Interviews can provide insights that can not be gained via the Delphi method, as questions can change depending on the answers that are given. This is a time-consuming method, which lowers the number of experts that can be interviewed. Interviews also require more planning than the Delphi method, as the Delphi method gives experts more time to answer questions. The disadvantage of doing a single survey is the lack of feedback of different views, but single surveys do have a lower threshold for experts to participate. This might generate more responses than the Delphi method, since experts might not want to participate in multiple rounds. Possible research questions can be, but are not limited to:

1. Which factors play an important role in the creation of a new standardizing organization for the SMR sector?
2. How can a new standardizing organization in the SMR sector contribute to fair standardization?
3. What should be the main focal areas of a new standardizing organization dedicated to SMRs?
4. What are the effects that a new standardization organization can have on SMR designs?

The second recommendation is one that is a more quantitative research. In this research, it can be investigated which parts can be standardized between designs and vendors, so that an overview is created on the benefits of standardization in the sector. It can be said that this is a difficult subject to research, as this requires a lot of knowledge on different SMR designs. Furthermore it would require data and designs provided by vendors, which is likely difficult to acquire due to the competitiveness of the sector. Due to collusion of vendors, a good starting point for this research might be a literature research on legislations regarding cooperation. Only vendors that might be interested in cooperation with other vendors might provide data of their designs, under strict confidentiality agreements. Therefore, such research is likely to happen on multiple designs of a single vendor only, as this does not lead to disclosed information to competitors and does not include legislation on cooperation between vendors. This research can be best be conducted as an internship at a company, by a student that aspires an engineering job in the nuclear energy sector. Possible research questions for this research might be:

1. Under what circumstances are vendors allowed to cooperate?
2. Which parts of design X can be used in new design Y?
3. Which parts of design X by company 1, can be used in designs Y and Z by companies 2 and 3?

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Appendices

A Contact messages

This appendix contains e-mails and LinkedIn messages that have been sent to participants.

A.1 E-mail message

The following e-mail was sent to invite participants:

Dear NAME,

For my master thesis at Delft University of Technology, I am researching technology choices for the viability of small modular reactors (SMRs). The SMR sector is currently at a breaking point. Regulatory instances want to derive regulations of the first running SMRs, but the companies building them are being hold back by the high investment cost and uncertainty. Policy makers and the public have their concerns about safety. So the three parties are waiting for each other to make the first move.

The goal of this research is to create recommendations on the viability of SMRs with different choices of technology. This survey is answered by experts from different companies and instances. The given answers from every individual expert will be used to create follow up questions for a new survey. Therefore this survey will be followed up by a new survey. The results will be sent to the email addresses of everyone who participated in the research, and shared their email address in the end of this first survey. The research is part of my Master thesis for Management of Technology at the Delft University of Technology in The Netherlands and is not affiliated with, or sponsored by, any company or instance.

This survey will take approximately 20 minutes. The survey does not need to be completed in one go. The link can be accessed as many times as needed to complete the survey. This survey will close at 6 DEC 2021. The data will be anonymized and used for this thesis and might possibly be used for future studies related to SMR development.

As you are an expert on the topic, I would appreciate if you give me your insights by filling in this short survey! LINK

If you have any further questions before or while filling in the survey, do not hesitate to contact me!

Best regards,

Luuk van Breugel
Master Student Management of Technology
Energy Transition Lab & Faculty of TPM, TU Delft
l.vanbreugel@student.tudelft.nl

A.2 LinkedIn message

The following message was sent via connection request on LinkedIn:

Dear NAME,
For my master thesis at TU Delft, I am researching technology choices for the viability of SMRs. As you are an expert on the topic, I would appreciate if you give me your insights by filling in this short survey! LINK

Best,
Luuk

When the connection request was accepted, the following message was sent:

Hi NAME,

Thank you for accepting my request. In my survey I am looking for the personal opinion of different experts. The survey focuses more on the concepts and dilemmas related to technology, than on the specific technology itself. I am a master student in Management of Technology, which is more aimed at the management and consultancy side of technology rather than the engineering itself.

I'm interested in seeing possible differences between the given answers of engineers and regulators. The survey takes roughly 20 minutes. If you have any questions, do not hesitate to contact me.

Best regards,
Luuk van Breugel

A.3 LinkedIn post

The post, as appeared on LinkedIn, is shown in figure 18. On the left, the timeline view is shown. On the right, the full text is shown. This full text only became visible when someone clicked on the post.

A.4 E-mail message round 2

The following e-mail was sent to invite participants for the second round:

Dear NAME,

Thank you for your participation in my research on technology choices for the viability of SMRs for my master thesis at Delft University of Technology. I would like to invite you to participate in the second round of the survey, which can be accessed via the following link:

LINK

For this second round, I have used the given answers of the first survey as input for the questions in this survey. I have received many great insights from people with different backgrounds. Therefore it is possible that you recognize some of your previous answers in questions or statements in this survey. Compared to last time, this survey contains not only open questions but also some statements and a question in which you are

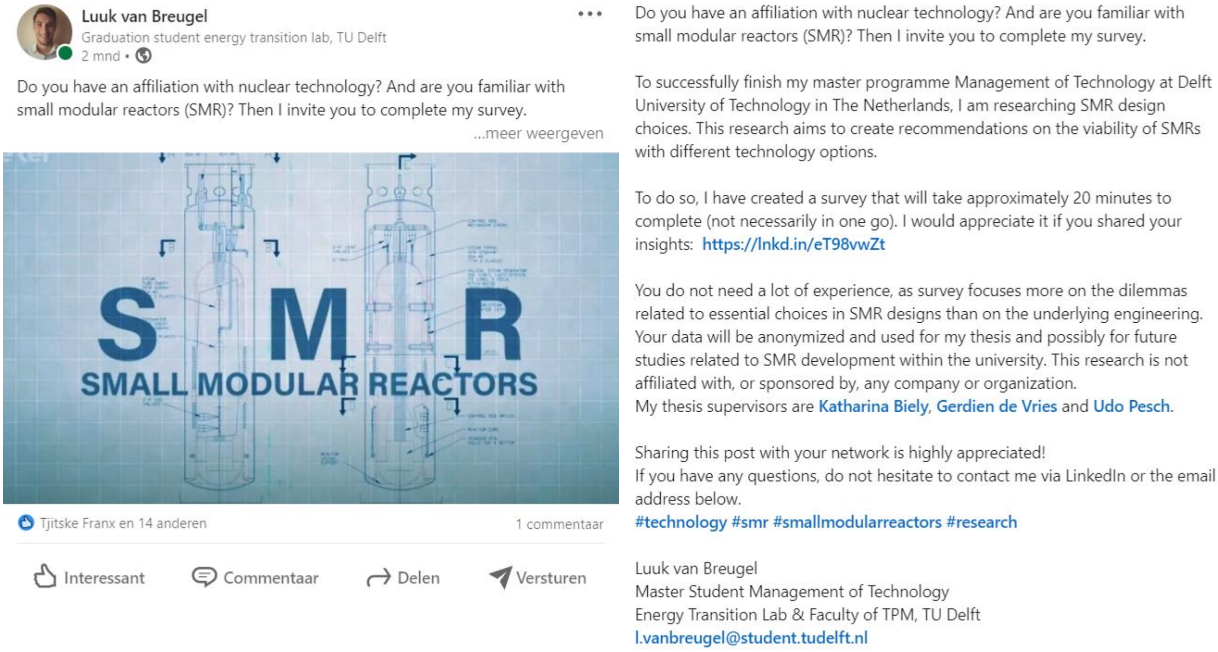

Figure 18: LinkedIn Post

asked to rank certain items. There are a few more questions, but the time needed to complete the entire survey is, again, approximately 20 minutes. It is also possible to take the survey on mobile devices.

Your participation in the survey is entirely voluntary and you are free to omit any question. This survey will close on 17 JAN 2022. The data will be anonymized and used for this thesis and might possibly be used for future studies related to SMR development.

If you have any questions before, during or after the survey, do not hesitate to contact me!

Best regards,

Luuk van Breugel
Master Student Management of Technology
Energy Transition Lab & Faculty of TPM, TU Delft
l.vanbreugel@student.tudelft.nl

B Forms for research ethics

The following forms were submitted to, and approved by, the Human Research and Ethics Committee of the Delft University of Technology.

B.1 HREC Forms

Delft University of Technology
ETHICS REVIEW CHECKLIST FOR HUMAN RESEARCH
(Version 12.03.2021)

*This checklist should be completed for every research study that involves human participants and should be submitted **before** potential participants are approached to take part in your research study.*

All submissions from students doing their Master's thesis need approval from their research supervisor (responsible researcher) who indicates their approval of the content and quality of the submission through signing and dating this form (or providing approval via email).

Additional elements of research compliance:
There are various aspects of human research compliance which fall outside the remit of the HREC as follows:

1) **The Data Steward of your faculty and/or the TUD Privacy Team** privacy-tud@tudelft.nl can help you with any issues related to the protection of personal data – including how data are processed and stored, and the informed consent that is required for legal compliance with GDPR.
2) **Research related to medical questions/health may require special attention**. See also the website of the CCMO before contacting the HREC.
3) **Your faculty HSE representative** should provide advice on any health, safety and environmental requirements including non-CE certified experimental devices, covid regulations, liability and insurance etc
4) **Your faculty/departmental contract managers** may also provide advice on, eg: procurement and working with third parties
5) **Professional standards/best practice** – there may be professional standards determined within different research disciplines with which you are expected to comply.

Submission and additional Information:
You can find more instructions and additional information on your application here.

IMPORTANT NOTICES:
*1: Please ensure that this form is properly signed and dated **by the responsible researcher** before submission. In the case of a student research project the responsible researcher must be the project supervisor.*
*2: Please note that incomplete submissions (either in terms of documentation or the information provided therein) will be returned for completion **prior to any assessment by the HREC.***
3: Please note that participants should always direct queries and complaints regarding their participation to the responsible researcher(s) and not the HREC. Please therefore do not list HREC as a point of contact for participants in your research documentation (e.g., informed consent form).

I. Table 1: Basic Data

Project title:	**Consensus in technology selection for Small Modular Reactors**
Research period (planning):	**07/2021 – 01/2022**
Faculty:	**TPM**
Department:	**O&G**
Level of the research project: Eg: Masters, PhD, Postdoc, Tenure Track, Permanent Researcher, Organisational	**Masters**

Funder of research: Eg: EU, NWO, TUD, other (in which case please elaborate)	**-**
Name of corresponding researcher (if different from the responsible researcher):	**-**
E-mail corresponding researcher (if different from the responsible researcher):	**-**
Position of corresponding researcher: Eg: Masters, PhD, Postdoc, Professor	**-**
Name of responsible researcher: Note: all student work must have a named supervisor who must approve, sign and submit this application	**Gerdien de Vries**
E-mail of responsible researcher: This must be an institutional email address (ie: not google etc)	**G.deVries-2@tudelft.nl**
Position of responsible researcher : Eg: PhD, Posdoc, Professor	**Associate Professor**

II. Summary Research

Please summarise your research very briefly (100-200 words), stating:

a) What the research aims to explore/demonstrate
b) Who will participate, how many participants there will be, how will they be recruited and what are they expected to do?

Please avoid jargon and abbreviations.

The objective of this thesis will be to achieve a consensus between specialists (designers, researchers and policy makers) on technology selection, to find out which developments and innovation are superior and why. A consensus is needed to lower the financial risk for companies that build "small modular reactor" designs, leading to a smaller amount of technologies to be evaluated by regulatory instances, while maintaining competitiveness between them for policy makers. This is done by delphi study. Participants will be experts in the field of "small modular reactors"; designers, engineers, researchers and policy makers. The aim of the research is to have roughly 10 participants, who are asked to fill in various questionnaires and give their personal opinion. They will be recruited through e-mail.

III. Table 2: Risk Assessment Checklist

Note: *if you answer "yes" to any of the questions in this checklist, please ensure that you summarise and confirm how these will be dealt with in Section IV (Risk Management and Informed Consent) below. Where appropriate please include the relevant advice/approval (eg: from the Privacy Team, Data Steward or HSE representative) as an additional attachment to this application.*

Potential Risk	Yes	No
1. Does the study involve participants who are particularly vulnerable or unable to give informed consent? (e.g., children, people with learning difficulties, patients, people receiving counselling, people living in care or nursing homes, people recruited through self-help groups).		x
2. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children or own students)?[1]		x

[1] **Important note concerning questions 1 and 2.** Some intended studies involve research subjects who are particularly vulnerable or unable to give informed consent. This includes research involving participants who are in a dependent or unequal relationship with the researcher or research supervisor (e.g., the researcher's or research supervisor's students or staff). If your study involves such participants, it is essential that you safeguard against possible adverse consequences of this situation (e.g., allowing a student's failure to complete their participation to your satisfaction to affect your evaluation of their coursework). This can be achieved by ensuring that participants remain anonymous to the individuals concerned (e.g., you do not seek names of students taking part in your study). Please ensure that you include such risks – and how you will mitigate against them in your risk section.

Potential Risk	Yes	No
3. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		x
4. Will the study involve actively deceiving the participants? (For example, will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		x
5. Will the study involve discussion or collection of personal sensitive data (e.g., financial data, location data, data relating to children or other vulnerable groups)? Definitions of sensitive personal data, and special cases are provided on the TUD Privacy Team website.		x
6. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants? *If yes see here to determine whether medical ethical approval is required*		x
7. Will blood or tissue samples be obtained from participants? *If yes see here to determine whether medical ethical approval is required*		x
8. Is pain or more than mild discomfort likely to result from the study?		x
9. Does the study risk causing psychological stress or anxiety or other harm or negative consequences beyond that normally encountered by the participants in their life outside research?		x
10. Will you be offering any financial, or other, inducement (such as reasonable expenses and compensation for time) to participants?		x
Important: if you answered 'yes' to any of the questions mentioned above, you **MAY** be asked to submit a full Research Ethics Application.		
11. Will the experiment collect and store any personally identifiable information (PII) including name, email address, videos, pictures, or other identifiable data of human subjects? [2]	x	
12. Will the experiment involve the use of devices that are not 'CE' certified? *Only, if 'yes': continue with the following questions:*		x
➢ Was the device built in-house?		
➢ Was it inspected by a safety expert at TU Delft? *(Please provide a signed device report)*		
➢ If it was not built in house and not CE-certified, was it inspected by some other, qualified authority in safety and approved? *(Please provide records of the inspection).*		
13. Has this research been approved by a research ethics committee other than this one? *If yes, please provide a copy of the approval and summarise any key points in your Risk Management section below.*		x
14. Is this research dependent on a Data Transfer Agreement with a collaborating partner or third party supplier? *If yes please provide as a copy of the signed DTA and summarise any key points in your Risk Management section below.*		x

IV. Risk management and Informed Consent

A: Risk management

Please summarise what specific steps you will take to minimize any risks you have identified (as "yes") in the checklist above. Risks can range from physical or emotional well-being (including

[2] Note: You have to ensure that collected data is safeguarded physically and will not be accessible to anyone outside the study. Furthermore, the data has to be de-identified if possible and has to be destroyed after a scientifically appropriate period of time. Also ask explicitly for consent if anonymised data will be published as open data.

covid), to privacy/reputation (including professional standing, student grading or social impact). In each case please note the numer of the potential risk you are referring to.
Where appropriate please include in this application any advice or approvals from the TU Delft Privacy team and/or Faculty HSE advisor that confirm legal compliance with these dimensions of your research.

Email addresses, names and job titles will be collected. Data used will be anonymized. Email, names and job titles will only be used for communication purposes. Privacy related details will be kept separate from files that require sharing or processing. Further information can be found in the DMP.

B: Informed Consent
The key function of the Informed Consent (IC) process is that this is where you (as the responsible researcher) come to an agreement with your participants about what they will do for your research and what you will do, both legally and ethically, to ensure their physical, emotional and reputational security. It is key that they know exactly what – and particularly what potential risks – they are agreeing to, and that this is clear in your agreement.

In most cases your IC process should include an opening statement or participant information which outlines the purpose of the research, what participants will do, what kinds of risks – including of identification – are involved and what steps you will be taking to mitigate against those risks. In general, good practice determines that IC forms should be granular, providing separate consent points as separate tick boxes.

Please note that by signing this checklist list as the sole/responsible researcher you are providing approval of the content and quality of the submission, as well as confirming alignment between GDPR, Data Management and Informed Consent requirements.

V. Signature/s

Name of corresponding researcher (if different from the responsible researcher) (print)

Signature of corresponding researcher:

Date:

Name of responsible researcher (print)
Gerdien de Vries

Signature (or upload consent by mail) responsible researcher:

Date: July 26, 2021

VI. Additional enclosures

Please, tick the checkboxes for any additional submitted enclosures as follows:

- A data management plan reviewed by a data-steward.
- (If requested by the HREC) a full research ethics application
- An Informed Consent form
- A signed, up-to-date device report
- Submission details to an external research ethics committee, and a copy of their approval if available.
- An approved Data Transfer Agreement with a third party
- Specific advice/approval from a Data Steward or TU Delft Privacy Team regarding eg: a Data Privacy Impact Assessment – or (where data are potentially sensitive and Privacy Team advice has been sought) confirmation that no DPIA is required
- Specific advice/approval from an HSE representative regarding a specific experimental set-up.
- Other – please explain in the table below:

Document name	Brief description

Consensus in technology selection for Small Modular Reactors, MOT Master Thesis

Data Collection

What data will you collect or create?

The created data will be questionnaires and possible graphs deducted from the answers. The type of the data will be text sequences, scales and graphs. The data will be collected using Qualtrics. Qualtrics is chosen because it is widely used within TU Delft as surveying program. If a scale is asked, this will be analysed with MS Excel. No existing data sets will be used.

How will the data be collected or created?

Data collection will be organized through Qualtrics. Participants will receive a questionnaire which they are asked to fill in. File naming will be done according to the following options: xxx_rn_id_ddmmyy, with xxx being substituted by one of the following: questions, answers, results. rn will be the round number; id, will be the identifier number and ddmmyy will be the date the document is made or received. File naming will be the responsibility of the student.

Documentation and Metadata

What documentation and metadata will accompany the data?

The following metadata will be made per questionnaire: dates, identifier number.

The following personal data will be collected, but kept/stored private: name, job title, e-mail address.

The personal data will be stored in a separate file, so the questionnaire answers will remain anonymized. The seperate data will be stored locally. The laptop is only accessible by me.

Ethics and Legal Compliance

How will you manage any ethical issues?

Due to the nature of the delphi study, data will be anonymized. Participants have to give consent to sharing their anonymized (processed) data. Any answers given that might reveal an identity, company or position of a participant will be removed before sharing. The participant will be asked if he/she agrees with the changes made to his answer via e-mail.

How will you manage copyright and Intellectual Property Rights (IPR) issues?

This research is not linked to a company. The copyright of this data belongs to Luuk van Breugel. The data can be used as it is published in the thesis, via citation.

Storage and Backup

How will the data be stored and backed up during the research?

Data will be stored locally and backed up on a secure MS Teams environment, accessible by student and supervisors, after logging in with TU Delft accounts. Uploading to the MS Teams environment will be the responsibility of the student. Raw data will remain accessible via the Qualtrics account during the period of the project.

How will you manage access and security?

Access to the data will be provided by the student. Access will only be given to thesis supervisors. The data will only be accessible through the secure MS Teams environment, specially created for this thesis.

Selection and Preservation

Which data are of long-term value and should be retained, shared, and/or preserved?

The outcome of the various rounds of questionnaires will be preserved. The privacy related metadata will be deleted after the thesis is uploaded into the repository. The raw anonymized data might be useful at a later stadium. This data can be uploaded separately to the TU Delft repository.

What is the long-term preservation plan for the dataset?

The final data can be found in the thesis in the TU Delft Repository: https://repository.tudelft.nl.

Data Sharing

How will you share the data?

Raw data will not be shared with anyone. A new questionnaire is made out of the answers given by the participants. These answers can be included in the questionnaire, but these will be anonymized. The final results can be found in the thesis which will be available in the TU Delft repository, after the defense.

Are any restrictions on data sharing required?

Only anonymized data will be shared, after the participant has given his/her consent.

Responsibilities and Resources

Who will be responsible for data management?

The student (Luuk van Breugel) is responsible for implementation of the DMP and every other step related to it.

What resources will you require to deliver your plan?

No other resources are required for the DMP.

B.2 Informed Consent

The following message was displayed at the start both surveys:

Small modular reactors (SMRs) have the potential to become big parts of future energy generation around the world. With various countries worldwide investing in research and development of these reactors, they have shown to potentially be a source of clean energy generation. In our energy transition from fossil fuels to cleaner energy, there are also many alternatives available. As it stands now the SMR sector is at a breaking point. The technology shows that it can generate a lot of electricity and heat, that can be used for various purposes. Regulatory instances want to derive regulations of the first running SMRs, but the companies building them are being hold back by the high investment cost and uncertainty. Policy makers and the public have their concerns about safety. So the three parties are waiting for each other to make the first move.

The goal of this research is to create recommendations on the viability of SMRs with different choices of technology. This survey is answered by experts from different companies and instances. The given answers from every individual expert will be used to create follow up questions for a new survey. Therefore this survey will be followed up by a new survey. The results will be sent to the email addresses of everyone who participated in the research, and has shared their email address in the end of this first survey. The research is part of my (Luuk van Breugel) Master thesis for Management of Technology at Delft University of Technology in The Netherlands and is not affiliated with, or sponsored by, any company or instance. More information on the program can be found here: https://www.tudelft.nl/en/education/programmes/masters/mot/mot

This survey will take approximately 20 minutes. The survey does not need to be completed in one go. The link can be accessed as many times as needed to complete the survey. This survey will close on 13-DEC-2021. The data will be anonymized and used for this thesis and might possibly be used for future studies related to SMR development. As an expert in the SMR sector, your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any question.

We believe there are no known risks associated with this research study; however, as with any online related activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing data in closed TU Delft environments. Your answers will be stored under an identifier number and separate files will be used to relate this number to the participant. Answers given that might reveal personal data, or company specific information, will be erased. Privacy related data will be deleted after this thesis, so anonymized data can never be coupled with a participant after the thesis is finished.